# Non-invasive Brain Stimulation of the Cerebellum in Emotion

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## Abstract

Transcranial magnetic and direct current stimulation are non-invasive brain stimulation techniques that are used to investigate cerebellar functions in healthy and clinical populations. These approaches allow transient modulation of neural excitability of the human cerebellar cortex to directly examine phenomenological, behavioral, and physiological aspects of motivation and emotion. While cerebellar neurostimulation in the field of social and affective neuroscience is still in its initial phase, empirical evidence confirms the direct involvement of the cerebellum in motivation and emotion. Non-invasive stimulation of the cerebellum provides a unique experimental approach to study the relation between the cerebellum and emotions in humans.

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## 8.1 Introduction

Stimulation of the cerebellum has a long history that dates back to the eighteenth century. Luigi Rolando (1773–1831) was among the first to pioneer the use of electric currents to study cerebellar functions and observed that galvanic currents applied to the cerebellum of animals can elicit convulsions (Ponce et al. 2021). The administration of electric currents to examine cerebellar neurophysiology of motor functions in healthy and neurological populations was further pioneered in the subsequent centuries. The Italian scientist Giuseppe Moruzzi (1910–1986) used electric currents to show that the cerebellum is involved in emotions by providing evidence that autonomic activity associated with hypothalamic-induced sham rage in cats could be modulated by electrically stimulating the cerebellum (Zanchetti and Zoccolini 1954). The introduction of non-invasive brain stimulation techniques including transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) provided a novel safe and minimally invasive means to study the relationship between the cerebellum and emotions in humans (Cattaneo et al. 2021). While early research with weak electric currents was abandoned during the 1960s, partly due to the lack of systematicity of findings, empirical proof that tDCS can modulate neural excitability in a polarity-dependent fashion back in 2000 (Nitsche and Paulus 2000) triggered a renewed interest in this technique by researchers

and clinicians. The resurgence of tDCS in the last decades is actually due to TMS, a technique introduced in 1985, which was used to activate the corticospinal tract in order to show changes in motor-evoked potentials of the hand muscles following tDCS (Nitsche and Paulus 2000). In addition to targeting the cerebral cortical areas of the brain, the fact that the cerebellar cortex faces the cranium has led to an increasing number of non-invasive brain stimulation studies in basic and clinical neurosciences that explore the functional contributions of the cerebellum in motor, cognition, and, more recently, emotions. In this chapter technical and methodological aspects of cerebellar TMS and cerebellar tDCS in studying the cerebellar correlates of human emotions will be discussed and a brief overview of the scientific literature will be provided.

## 8.2 Cerebellar Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is a non-invasive brain stimulation technique that was developed at the Royal Hallamshire Hospital in Sheffield (England) (Barker et al. 1985). The technique is based on Faraday's law of electromagnetic induction which dictates that when a conductor is placed inside a rapidly varying magnetic field, an electric current will be created in the conductor. Therefore, whenever high amounts of stored energy in capacitors connected to a coil are released via an electronic switch, an electric current will start to flow through the coil. In keeping with Ørsted's law, the electric current will create a brief magnetic field that, unattenuated through the scalp and skull, causes a secondary electric current in the underlying conducting nerve tissue. When the electromagnetic pulse is strong enough, the secondary current will give rise to a transmembrane potential which depolarizes neurons and produces action potentials.

The first human study in which the cerebellum was targeted showed that single-pulse TMS induces brain responses located over anterior scalp regions as recorded with conventional electrodes (Amassian et al. 1992). These distal brain responses were explained by transsynaptic activation of the dentato-thalamo-cortical pathway through local activation of the cerebellar cortex. Subsequent studies demonstrated that high-intensity single-pulse TMS applied to the midpoint between the inion and the mastoid could elicits cerebellar inhibitory effects on the contralateral primary motor cortex (M1) (Ugawa et al. 1995). This cerebellar inhibitory effect is suggested to stem from TMS-induced activation of the inhibitory GABA-driven Purkinje cells that dampen the excitatory output of the deep cerebellar nuclei to M1 via ventral thalamic projections (Daskalakis et al. 2004).When 5–8 ms after a cerebellar TMS (conditioning) pulse, a single TMS (test) pulse is applied to M1, the motor-evoked potential (MEP) recorded from the hand muscles will be markedly smaller as compared to single-pulse TMS to M1 without the preceding cerebellar TMS pulse. The 5–8 ms latency concurs with the onset of anterior electroencephalographic (EEG) responses to contralateral cerebellar stimulation found earlier by Amassian et al. (1992). In addition, anterior EEG responses in the theta frequency range (4–7 Hz) were registered in response to single-pulse TMS administered over the cerebellar midline as compared to sham and occipital single-pulse TMS in healthy human volunteers (Schutter and van Honk 2006). In a more recent study, neuro-navigated single-pulse cerebellar TMS was interleaved with EEG recordings to examine associations between electrocortical responses and levels of (inhibitory) GABA and (excitatory) glutamate in the prefrontal cortex as measured with magnetic resonance spectroscopy (Du et al. 2018). Single-pulse cerebellar TMS over the midline induced bilateral anterior broadband synchronization in the theta-gamma frequency range (4–45 Hz) that was inversely associated with GABA concentrations in the medial frontal lobe. Subsequent analyses indicated that the higher EEG frequency range (9–45 Hz) contributed the most to this association. It has been proposed that increased availability of GABA facilitates local processing effects in the cerebral cortex that reduces phase locking of large neural

populations, consequently causing less EEG synchronization on the macroscopic level (Du et al. 2018). These studies among many others illustrate that magnetic stimulation is capable of inducing both local as well as distal neurophysiological effects, thereby establishing TMS as a viable probe to study cerebellar functions. While the effects of single-pulse TMS are short-lived, when applied in a repetitive (rTMS) or patterned fashion, like theta burst stimulation (TBS), neurophysiological effects typically outlast the stimulation period and can be used to transiently modulate neural excitability levels of the tissue that is being targeted. For example, 900 pulses delivered at 1 Hz over the right cerebellar cortex resulted in a significant reduction of cerebellar capacity to inhibit M1 output for at least 30 minutes after rTMS (Popa et al. 2010). In the same study, continuous TBS (cTBS), which consists of three-pulse bursts at 50 Hz repeated every 200 milliseconds for 40 seconds (600 pulses), also yielded significant reductions in cerebellar inhibition of M1 for at least 30 minutes. By contrast, the administration of three-pulse bursts at 50 Hz repeated every 200 milliseconds for 2 seconds separated by 8 seconds of no stimulation (a protocol known as intermittent TBS; iTBS) can enhance the inhibitory function of Purkinje cells for 30 minutes (Koch et al. 2008). The observation of changes in frontal resting-state EEG activity following fast-frequency rTMS applied to the cerebellum further suggests the efficacy of cerebellar TMS to modify local and distal neural activity (Garg et al. 2013; Schutter et al. 2003). While the precise mechanisms are still under investigation, the modulation of cerebellar excitability is suggested to involve complex local synaptic processes at the level of Purkinje cells associated with, on the one hand, long-term depression (LTD) from slow-frequency rTMS and cTBS, and, on the other hand, long-term potentiation (LTP) from fast-frequency rTMS and iTBS. Furthermore, selective facilitatory and inhibitory effects on excitatory granule cells and GABA-ergic interneurons with lower excitability thresholds have also been suggested to contribute to the mechanisms by which TMS modulates cerebellar physiology (Koch 2010).

Following the earlier intracranial electric stimulation studies in animals and humans that provided evidence for cerebellar involvement in the brain's emotion and motivation circuits (Berman et al. 1974; Heath et al. 1978, 1980; Zanchetti and Zoccolini 1954), the introduction of TMS and the possibility to effectively target the little brain offered a unique non-invasive and safe alternative to further explore the relation between the cerebellum and emotions in humans. Among the first attempts was a pilot study that investigated the effect of high-frequency repetitive transcranial magnetic (rTMS) stimulation over the medial cerebellum (Schutter et al. 2003). In a sham-controlled crossover design, healthy volunteers received a 20- minute stimulation regimen consisting of 80 trains of 10 seconds of 25 Hz rTMS followed by 5 seconds of no stimulation for a total of 20 minutes. On separate days and in varying order, participants received real rTMS over the midline cerebellum, lateral cerebellum, and occiput or sham rTMS over the medial cerebellum using an iron core coil (Epstein and Davey 2002). Figure 8.1a shows results of a computer simulation performed with SimNIBS software (Thielscher et al. 2015) of the electric field produced by the iron core coil over the medial cerebellum in a realistic head model.

Results showed that midline cerebellar rTMS as compared to placebo induced a significant shift in anterior asymmetry, from left to right dominance in the fast (30–50 Hz) EEG spectrum, whereas no effects were observed to occipital and lateral cerebellar rTMS. Interestingly, spontaneous reports of increased alertness and positive mood state were recorded exclusively after midline cerebellar rTMS.

In keeping with the early intracranial electrical stimulation studies in animals that demonstrated cerebellar connectivity to brain structures involved in cognitive and emotive functions, a subsequent sham-controlled crossover study in healthy volunteers was performed in which EEG responses to sixty single pulses of TMS over the medial cerebellum were recorded in healthy human volunteers (Schutter and van Honk
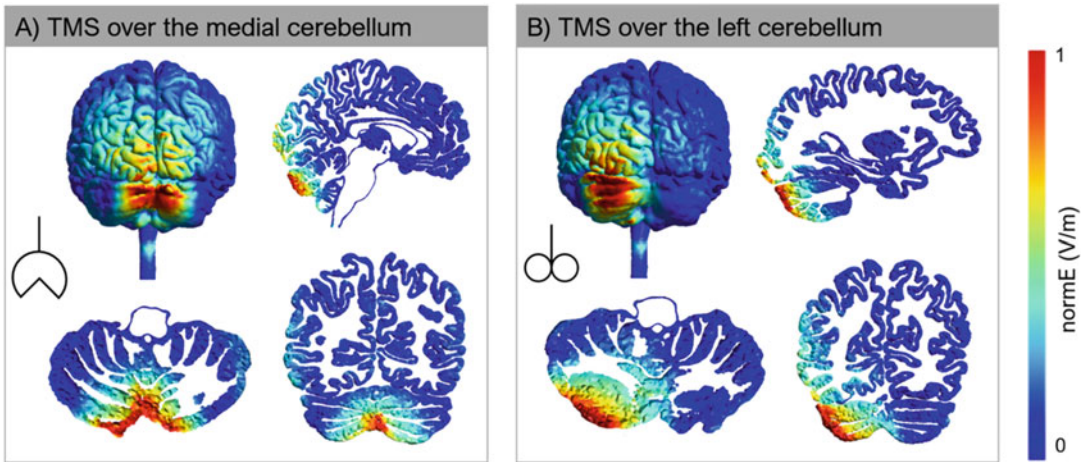
**Fig. 8.1** Distribution of the electric field induced by TMS (dI/dt = 1.00 × 1.0e6 A/s) over the medial cerebellum to target the vermis with an iron core coil (**a**) and the left posterior cerebellum with a conventional double winding 70 mm figure of eight-shaped coil on a realistic head model (**b**)

2006). Analyses showed a significant and frequency-specific increase of theta (4–7 Hz) activity to single-pulse medial cerebellar TMS as compared to sham and occipital TMS. Since animal and human research relates theta activity with the septo-hippocampal complex and anterior cingulate cortex, which are important limbic brain structures involved in cognition and emotion, it was speculated that, in addition to the cerebello-cortical connections found by previous studies, the cerebellum is part of the core neural limbic circuitry involved in emotions. The findings of both studies are in line with more recent research that has found evidence that cerebellar stimulation can entrain local field potentials in the frontal cortex and drive synchronization of cerebello-cortical and cortico-cortical networks (Tremblay et al. 2019). Results reported in this study do not only further substantiate the contributions of the medial cerebellum to large-scale synchronization in non-motor-related brain areas, but also provide indirect and incremental support for cerebellar involvement in the experience and regulation of emotions. The latter assumption is supported by a study that directly investigated the effects of cerebellar rTMS on emotion regulation in healthy volunteers (Schutter and van Honk 2009). In a randomized, counterbalanced within-subjects

design spanning across three experimental sessions, twelve healthy, young, right-handed volunteers received 20 minutes of continuous real 1 Hz rTMS over the midline cerebellum and occiput, and sham rTMS to the medial cerebellum. Mood state inventories were acquired prior to and immediately after rTMS and following an emotion regulation task (ERT). In the ERT, participants were instructed to either look at aversive and neutral scenes, or to suppress the negative feelings experienced while watching aversive scenes. No changes in baseline-corrected mood were observed immediately after rTMS. However, significant increases in baseline-corrected negative mood following the ERT were reported only after active cerebellar rTMS. This suggests that, arguably due to rTMS-related interference of cerebellar functioning, participants were less able to effectively regulate the emotional content associated with the aversive scenes causing an increase of negative mood. The findings concur with the existing evidence of emotion dysregulation in cerebellar patients and cerebellar abnormalities found in psychiatric patients with impaired emotion regulation (for a discussion see Chap. 17).

In another randomized, cross-over sham-controlled study, effects of 15 minutes of 20 Hz (i.e.,

90 trains of 5 seconds on and 5 seconds off) rTMS over the medial cerebellum on implicit processing of emotional faces were examined in healthy volunteers (Schutter et al. 2009). Implicit face processing was measured with the masked emotional faces response task which consists of 14 millisecond presentations of an emotional or neutral face directly followed by the presentation of a masking stimulus. The face and mask are presented in different colors and the participant is instructed to name the color of the ink in which the mask is printed. Performance in terms of slower or faster color naming of the emotional as compared to the neutral faces trials varies as a function of the participant's motivational state. For example, masked fearful faces more readily capture automated attention in anxious individuals which results in slower color naming of the mask in comparison to masked neutral faces. In other words, the motivational state of the individual is presumed to drive the implicit (pre-attentive) reactions to the emotional facial expressions and influence the color naming of the subsequent presentation of the mask. As compared to occipital or sham rTMS, high-frequency rTMS over the cerebellum was associated with significant increases in response times to masked happy, but not fearful or neutral facial expressions. The selectivity of the findings implied that the response to happy facial expressions could not be explained by a general effect of rTMS on motor responsivity. In addition, an objective awareness check confirmed that participants were not able to consciously identify the expression of the faces. No evidence for changes in self-reported mood was found. The slower color naming of the masking stimulus following happy facial expressions can be interpreted as indicative of an increased pre-attentive bias to positive stimuli as a result of increased appetitive motivation following high-frequency rTMS over the medial cerebellum.

To understand the complex changes in emotion regulation capacity and attentional processing following rTMS to the medial cerebellum, a role may be reserved for the processing and regulation of the sympathetic and parasympathetic nervous system. The link between the medial cerebellum and the autonomic nervous system (ANS) was explored by applying neuronavigated iTBS on three consecutive days to the vermis and left and right cerebellar hemispheres in healthy volunteers (Demirtas-Tatlidede et al. 2011). Results showed a significant increase in thirst and a trend toward increased appetite following vermal stimulation, signaling elevated approach- and reward-related motivation. These findings concur with the reports of increased responsivity to happy facial expressions after 20 Hz rTMS over the medial cerebellum (Schutter et al. 2009). Furthermore, iTBS to the posterior vermis induced a significant decrease in heart rate which indicates a cerebellar-mediated increase of parasympathetic input over the sympathetic branch of the ANS. In addition to the vermis, short bursts of high-frequency rTMS (20 Hz) to perturb left posterolateral cerebellar activity were found to impair the perception of emotional facial expressions during an incidental cognitive task in which participants were instructed to classify the faces as either male or female (Ferrari et al. 2018). Crucially, a control experiment showed no effects when participants were instructed to identify the sex of neutral faces exclusively. In addition to the cerebellar role in implicit emotion processing, interrupting cerebellar activity with TMS also reduced the sensitivity to correctly recognize the emotional expression of faces (Ferrari et al. 2018). These findings are in agreement with the idea that the posterolateral regions of the cerebellum play a role in perception and even imitation of emotional expressions (Schraa-Tam et al. 2012). Further evidence for the involvement of the cerebellum in emotion processing comes from a recent sham-controlled study in healthy volunteers that tested the effects of 15 minutes of 1 Hz cerebellar rTMS on corticospinal excitability in response to viewing fearful and neutral facial expressions (Ferrari et al. 2021). In another study the interfering effects of tripe-pulse TMS (20 Hz) with a 70-mm figure of eight-shaped coil over the prefrontal cortex (PFC) and right cerebellum on social attitudes were investigated in healthy volunteers (Gamond et al. 2017). The targeted

regions were localized by means of stereotaxic navigation on individual estimated magnetic resonance images (MRI) using a warping procedure aligning a high-resolution MRI template with the volunteer's scalp model and craniometric points. The targeted cerebellar site corresponded to cerebellar right Crus I. In two separate behavioral experiments, evidence was found that TMS administered to the PFC and right Crus I abolished the positive attentional bias to in-group members as evaluated with an attitude priming task. These findings indicate that, next to the PFC, the cerebellum is involved in mediating implicit socio-emotional attitudes and may be differentially involved across varying social contexts (Gamond et al. 2017). Figure 8.1b illustrates an estimation of the electric field induced by a figure-of-eight coil on a realistic head model. Corticospinal excitability was assessed by measuring the MEP from the left and right first dorsal interosseous muscle to a single pulse of TMS applied to the motor cortices. Results showed that real as compared to sham 1 Hz rTMS over the left posterolateral cerebellum lowered the MEP amplitude evoked by single-pulse TMS to right M1 during the presentation of fearful, but not neutral faces. In addition, the MEP amplitude evoked by single-pulse TMS to ipsilateral M1 was not affected after left-sided 1 Hz rTMS to the posterolateral cerebellum. Interestingly, the data cannot be explained by an inhibitory effect of 1-Hz rTMS on Purkinje cells, as this would have increased the excitability along the dentato-thalamo-cortical pathway, causing a net facilitatory effect on the fear-mediated MEP. Perhaps disruption of the cerebellum may have led to reductions in the processing of salient threat-related stimuli which normally would increase corticospinal excitability in preparation for action (Schutter et al. 2008). The latter explanation adds to the idea that the cerebellum interfaces with the limbic and motor areas of the brain in the perception and coordination of appropriate behavioral responses.

In addition to faces, body postures are another non-verbal source involved in emotional expressions (de Gelder et al. 2015). Research has demonstrated that body expressions signaling threat recruit brain areas dedicated to emotion, action observation, and preparation as shown by increases of corticospinal excitability to single-pulse TMS (Hortensius et al. 2016). To explore the contribution of the cerebellum to these processes, online disruptive rTMS was administered over the left posterior cerebellar region of healthy volunteers who were instructed to discriminate between pairs of body postures expressing positive and negative emotions presented on a computer screen (Ferrari et al. 2019). TMS administered to the cerebellum as compared to the visual cortex and vertex as control sites interfered with the ability to discriminate between pairs of body postures when one of the postures displayed threat. The findings show that the cerebellum is sensitive to different features of information that carries biologically relevant (e.g., threat) signals. It is therefore plausible to assume that the cerebellum is also involved in the processing of sounds and odors that signal threat-related information (Billot et al. 2017; Indovina et al. 2014). The latter idea fits the universal cerebellar transform (UCT) theory which posits that the cerebellum is able to perform computations and integrate signals from different modalities (Schmahmann et al. 2019).

## 8.3    Cerebellar Transcranial Direct Current Stimulation

Transcranial direct current stimulation (tDCS) is another commonly used technique to non-invasively modulate neuronal activity by administering a continuous weak electric current (1–2 mA) applied with two or more electrodes placed on the scalp. Unlike TMS, tDCS does not induce action potentials, but modulates resting state membrane potentials of neurons through polarization. Polarization changes the spontaneous firing of neurons and affects neural excitability as a function of the direction of the current flow in the underlying tissue (Priori 2003; Woods et al. 2016). For cerebellar tDCS, specifically, the induced electric field is suggested to polarize the superficial cortical layer that includes the large Purkinje cells (Grimaldi et al.

2016). In addition, tDCS will most likely also affect other neural elements in the cerebellar cortex, including granule and inhibitory cells, as well as climbing and mossy (axonal) fibers. The changes in the cerebellar cortex are complemented by transsynaptic modulation of the deep cerebellar nuclei, mainly through the inhibitory output of the Purkinje cells (Grimaldi et al. 2016). For motor cortex stimulation, tDCS-induced modulation of cortical excitability has been shown to differ as a function of the polarity of the electrodes. The positively charged anode causes neuronal depolarization in the underlying tissue and increases spontaneous neural firing and cortical excitability as measured by MEPs, while the negatively charged cathode causes neuronal hyperpolarization and reduces spontaneous neural firing and cortical excitability (Nitsche et al. 2008; Nitsche and Paulus 2000). While this polarity-dependent effect is often considered a generic mechanism by which tDCS establishes its effects in the cerebral cortex, marked differences in cytoarchitecture and morphology of the cortical regions outside the motor cortex illustrate that this polarity-dependent effect on neural tissue is not straightforward. As will be illustrated below, this mechanism is even less unequivocal for cerebellar tDCS (Ferrucci et al. 2015; Grimaldi et al. 2014; Oldrati and Schutter 2018; van Dun et al. 2016).

Neurophysiological effects of cerebellar tDCS can, for instance, be quantified by examining cerebellar brain inhibition (CBI), which arguably serves as an index of inhibitory connections between the cerebellar cortex and the dentate nucleus. As mentioned earlier in this chapter, applying a single conditioning TMS pulse over the cerebellum 5–8 seconds before applying a test pulse over the contralateral motor cortex reduces the observed MEP (Ugawa et al. 1995). In a series of experiments, Galea et al. (2009) measured the effects of 25 minutes of anodal, cathodal, or sham tDCS over the right cerebellum on CBI. In this study, the active electrode was placed over the right cerebellar cortex (3 cm lateral to the inion), while the return electrode was placed over the ipsilateral buccinator muscle. Across eight participants, cathodal tDCS significantly

decreased CBI relative to baseline (i.e., prior to stimulation) and relative to post-anodal and -sham tDCS, respectively. Further, this effect lasted up to 30 minutes post-stimulation, as demonstrated in a separate sample of six individuals. By contrast, the authors reported stimulation intensity-independent increase of CBI to anodal tDCS in another sample of eight participants. Overall, these findings were taken as evidence for a polarity-dependent effects of tDCS on cerebellar (and by proxy motor cortex) excitability. That is, cathodal tDCS decreases Purkinje cell excitability, resulting in a reduction of the inhibitory effect the conditioning TMS pulse exerts on the connection between the dentate nucleus and the motor cortex, whereas anodal tDCS increases Purkinje cell excitability and enhances the inhibitory connection. Importantly, however, a follow-up study which combined plasticity-inducing paired associative stimulation (PAS) with anodal, cathodal, or sham tDCS did not find evidence for polarity-specific effects (Hamada et al. 2012). Using similar tDCS parameters, the authors found the expected PAS-related increase in MEPs following sham tDCS, but no such effect was observed following anodal or cathodal tDCS. Overall, this suggests that while cerebellar tDCS is able to modulate cerebello-cortical pathways, the direction of the physiological effect is difficult to anticipate. To further address this issue, magnetic resonance spectroscopy (MRS) has been used to investigate the effects of tDCS on neurotransmitter concentrations in the cerebellum (Jalali et al. 2018; Moussa-Tooks et al. 2020). Jalali et al. (2018) found no evidence for changes in (excitatory) glutamate and (inhibitory) GABA concentrations in the right cerebellar hemisphere following 25 minutes of anodal tDCS at an intensity of 2 mA over the right cerebellum. Also, a study by Moussa-Tooks et al. (2020) did not yield consistent effects on neurotransmitter concentrations to 1.5 mA anodal or sham tDCS over the left cerebellar hemisphere for 20 minutes.

While our understanding of the mechanisms of tDCS and in particularly how transcranially applied electric current interacts with brain tissue

is still in its infancy, cerebellar tDCS does reliably induce behavioral and physiological modulation as evidenced by numerous controlled studies. However, the effects are typically small and results show large interindividual variability. It is therefore not surprising that the outcome of cerebellar tDCS is hard to predict. A meta-analysis examining the efficacy of cerebellar tDCS to modulate behavior in motor and cognitive tasks found significant absolute effects (i.e., not assuming a particular direction of the effect for anodal or cathodal tDCS) of cerebellar tDCS, with overall larger effect sizes for studies in the motor in comparison to the cognitive domain (Oldrati and Schutter 2018). Importantly, however, there was no evidence for polarity-*specific* effects for either anodal or cathodal tDCS.

Empirical studies employing cerebellar tDCS that specifically address affective processes in healthy volunteers are still limited. Ferrucci et al. (2012) were the first to demonstrate an effect of cerebellar tDCS on emotion recognition. In their study, healthy volunteers received anodal, cathodal, or sham tDCS (2 mA, 20 min) through two 6 × 7 cm electrodes placed over the medial cerebellum and the right deltoid muscle. Before and after stimulation, participants were presented with angry, sad, happy, and neutral faces and asked to indicate the depicted emotion. Following anodal and cathodal tDCS, reaction times in response to negative facial expressions were reduced compared to baseline, while performance on neutral or positive faces was not affected. Sham tDCS did not modulate performance, and no effects of active tDCS on self-reported mood and anxiety were found. These results were taken as evidence that the cerebellum is primarily involved in the processing of negative emotional content, in line with its reciprocal connections to the amygdala.

A recent study investigated the effect of both anodal and cathodal cerebellar tDCS on predicting social action sequences (Oldrati et al. 2021). In particular, participants were asked to decide whether short videos of people performing a given action would end in an individual action (e.g., a child eating an apple) or an interpersonal action (e.g., a child handing an apple to another

child). During the familiarization phase, implicit predictions were cued by random color combinations present in the videos, and it was subsequently investigated in a testing phase whether the processing of highly as opposed to lowly predictable social actions were modulated by cerebellar tDCS. For this, anodal, cathodal, and sham tDCS (2 mA, 20 min) were applied through two 5 × 5 cm electrodes placed over the right cerebellar hemisphere and ipsilateral buccinator muscle while participants performed the task. Results showed that anodal tDCS significantly improved task accuracy for low-expectancy trials, while cathodal tDCS decreased accuracy for high-expectancy trials. Crucially, these stimulation-specific effects were only observed during the actual testing phase, in which implicit predictions had already been established. Furthermore, confirming the domain-specific contribution of the cerebellum to the processing of social action scenes, no effects of tDCS on a control task using shapes as stimuli were observed. Overall, this supports the concept of a "social cerebellum" (Van Overwalle et al. 2020), in which the prediction of social events involves the (right) cerebellum.

In light of the cerebellum's reciprocal monosynaptic connections to the hypothalamic-pituitary-adrenal axis (Schutter 2012), another recent study investigated whether cerebellar tDCS can modulate self-reported mood and cortisol levels (Gheorghe et al. 2021). In forty-five volunteers, individual cortisol levels were measured before, immediately after, and 10 and 30 minutes after cerebellar tDCS. Additionally, subjective mood ratings were assessed before and after stimulation. The healthy participant sample was divided into three groups receiving either 2 mA anodal, cathodal, or sham tDCS for 15 min over the cerebellum, with the two 5 × 7 cm electrodes placed over the midline and the right deltoid muscle. None of the tDCS conditions affected cortisol levels at any of the time points. However, both anodal and cathodal tDCS resulted in improved self-reported mood relative to baseline, providing some tentative evidence about potential mood-regulating effects of cerebellar tDCS. In a similar vein, Newstead et al.

(2018) reported improved subject mood ratings in participants receiving a single or three consecutive 12-min sessions of active frontocerebellar tDCS at 2 mA relative to sham tDCS. In this study, two 5 × 5 cm electrodes were placed over the right cerebellum and the left dorsolateral prefrontal cortex (10–20 electrode position F3). Again no polarity-specific effects were observed, further adding to the notion that the cerebellum is not sensitive to polarity-dependent neuronal modulation. Interestingly, the mood improvement demonstrated an additive effect, with steadily increasing effects following each of the three stimulation sessions. In sum, the small number of available studies do provide preliminary evidence for the potential of cerebellar tDCS to modulate emotion processing (Ferrucci et al. 2012), social processing (Oldrati et al. 2021), and mood (Gheorghe et al. 2021; Newstead et al. 2018). Further research into the neurophysiological mechanisms of these effects is warranted.

To get a better understanding of the physiological mechanisms related to cerebellar tDCS, it is important to consider the unique cerebellar cell morphology. Early work in the turtle cerebellum showed that electrical stimulation affects different kinds of cerebellar cells depending on how their cell bodies are oriented relative to the applied electric field (Chan et al. 1988). Furthermore, the delicate folding of the cerebellar cortex likely causes large differences in polarization, which is determined by the angle between the electric field elicited by the injected current, and the somato-dendritic axis of the targeted cells (Rahman et al. 2014). Additionally, inconsistent findings may partly be caused by the large number of methodological degrees of freedom inherent to the application of cerebellar tDCS. Factors like stimulation intensity and duration as well as electrode positioning and size are not standardized for cerebellar tDCS. Computational field modeling studies have attempted to shed some light on the question of how strongly and focally the cerebellum can be targeted by tDCS (Gomez-Tames et al. 2019; Parazzini et al. 2014; Rezaee and Dutta 2019). While these studies have documented the potential of cerebellar

tDCS to target predominantly posterior regions of the cerebellum with sufficiently high field strengths, the focality of these elicited fields remained an open question. In a recent study, we therefore simulated electric fields induced by the commonly used montage, in which the return electrode is placed over the ipsilateral buccinator muscle in 20 individual brains (Klaus & Schutter 2021, Sci Rep). As demonstrated in Fig. 8.2a in one exemplary brain, this montage using 5 × 5 cm electrodes is successful in reaching the targeted cerebellar region, but crucially suffers from low focality, as indexed by significant current spread in extracerebellar regions. In an attempt to minimize this unwanted effect, we further simulated electric fields from six alternative montages in which smaller electrodes (3 × 3 cm) were placed in gradually higher vicinity to each other. Maximum focality was obtained by placing the electrodes approximately 2 cm below EEG positions I2 and P10 (Fig. 8.2b). Overall, this suggests that previous studies using the buccinator montage likely did not target the cerebellum in a focal way, precluding definitive conclusions about its isolated involvement in the function investigated. Future work will need to verify the behavioral and neurophysiological effect of the proposed alternative montage. Furthermore, acknowledging the special anatomical location of the cerebellum, individual differences in skull thickness and cerebrospinal fluid are likely to be important factors in determining efficacy within and across individuals.

Finally, an exciting avenue for cerebellar stimulation research is transcranial alternating current stimulation (tACS), in which applying alternating currents to the targeted area can entrain brain oscillations to a desired frequency. Recent work has shown the potential of cerebellar tACS to modulate CBI (Naro et al. 2016; Spampinato et al. 2021). Future studies will need to establish whether this technique is suitable for modulating emotional and affective processing as well.
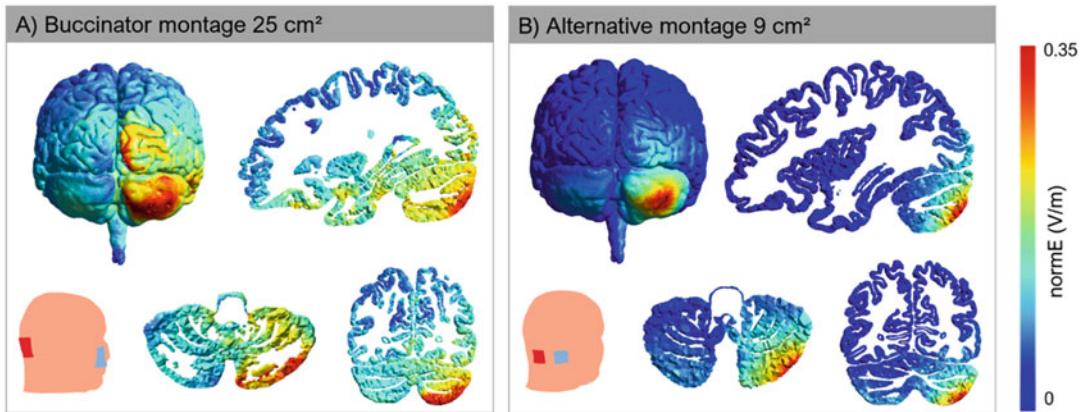
**Fig. 8.2** Distribution of the electric field induced by tDCS targeting the right posterior cerebellum placing two 5 × 5 cm electrodes over the right cerebellum and the right buccinator muscle (**a**) or placing two 3 × 3 cm electrodes 2 cm below electrode positions I2 and P10 (**b**). Simulations were performed with SimNIBS software (Thielscher et al. 2015)

## 8.4 Conclusion

Through its ability to transcranially manipulate superficial neural tissue with exogenous electromagnetic pulses and weak electric currents, non-invasive brain stimulation techniques provide a direct means to examine the involvement of the human cerebellum in emotions. The currently available empirical studies confirm that manipulating the cerebellum has a direct impact on the elicitation, experience, and regulation of emotions. These studies show that non-invasive brain stimulation techniques offer a unique and valuable approach in cerebellar neuroscientific research and potentially provide new directions in biologically oriented non-invasive treatments of psychological disorders (see Chap. 17).

The fact that the word emotion is derived from *emovere,* which is Latin for "move through" and "move out", illustrates the intimate conceptual link between perception, emotion, and action. The cerebellum may well lie at the heart of connecting these different facets which ultimately constitute emotional experience and drive human behavior. However, cerebellar non-invasive brain stimulation still faces several methodological and technical issues, particularly related to its physiological working mechanisms and spatial resolution/focality. These issues warrant further research to improve the applicability of TMS and tDCS in the cerebellar neurosciences of emotion.

**Conflict of Interest** The authors have no competing interests to declare.

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