Brain Stimulation 19 (2026) 103000

Contents lists available at ScienceDirect

Brain Stimulation

journal homepage: www.journals.elsevier.com/brain-stimulation

Time-dependent effect of left posterolateral cerebellar TMS in facial emotional processing

Dear Editor,

Understanding cognitive brain processes requires information about the timing of activation within and between different brain sites. Chronometric approaches, such as electroencephalography (EEG) and magnetoencephalography (MEG), have uniquely contributed to elucidating the neural dynamics supporting perceptual, memory, and emotional processes [1]. However, both EEG and MEG are challenging to implement in the cerebellum, which is now well-known for its role in cognitive, social, and emotional functions. Consistent evidence has shown that the posterior cerebellum is recruited during various socio-emotional tasks, from emotion perception to mentalizing, and that it is functionally connected to the salience and social networks [2]. Yet, the precise timing of cerebellar involvement in socioemotional processing remains unknown, limiting our understanding of its functional integration within broader brain networks that support these behaviors. Here, we employed chronometric transcranial magnetic stimulation (TMS), the only non-invasive chronometric approach applicable to the cerebellum, to investigate the temporal dynamics of the posterolateral cerebellum's involvement in facial emotional processing. We demonstrated that the left posterolateral cerebellum contributes to the processing of emotional faces between 220 and 320 ms after the onset of the emotional stimulus. Critically, this time-specific contribution is selective of the left posterolateral cerebellum and does not extend to the contralateral (right) cerebellum.

Twenty-four healthy right-handed Italian participants (7 males) indicated whether two consecutive emotional faces expressed the same or a different emotion while receiving neuronavigation-guided triple-pulse TMS (20 Hz) over the left and the right posterolateral cerebellum and the vertex (control site) (Fig. 1A/B). They were unaware of the study's scope and the TMS condition applied. TMS was delivered at three different time windows from target onset, namely 120- to 220 ms, 220- to 320-ms, and 320- to 420-ms, in order to cover the first ~500 ms of emotional face processing, in line with prior evidence showing that cortical responses to emotional faces extend to this temporal range [3]. These timings were used in our previous chronometric investigation of the paramedial cerebellum in emotional processing [4]. Further methodological details, including power analysis for definition of the sample size, are provided in the Supplementary Materials. We conducted a repeated-measures ANOVA with TMS site (right-posterolateral cerebellum, left-posterolateral cerebellum, and vertex) and TMS timing (120- to 220-ms time window, 220- to 320-ms time window, and 320- to 420-ms time window) as within-subjects variables on inverse efficiency (IE = mean correct RT/proportion of correct responses). Bonferroni-Holm correction was applied to multiple comparisons. The main effects of TMS site, $F\,(2, 46) = 1.53$, $p = .23$, and of TMS timing, $F\,(2, 46) = 1.20$, $p = .31$, were not significant. In turn, the interaction TMS site by TMS timing, $F\,(4, 92) = 2.71$, $p = .035$, $\eta_p^2 = .11$, reached significance (Fig. 1C) and was further examined by looking at the simple main effect of TMS site within each time window. When delivered in the 220- to 320-ms time window, TMS impaired performance, $F\,(2,46) = 5.93$, $p = .005$, $\eta_p^2 = .21$, with participants performing worse during TMS over the left-posterolateral cerebellum compared to the vertex, $t\,(23) = 2.49$, $p = .041$, and the right-posterolateral cerebellum, $t\,(23) = 3.19$, $p = .012$. TMS in the 220- to 320-ms time window over the right-posterolateral cerebellum did not affect performance compared to the control condition, $t\,(23) < 1$, $p = .91$. TMS over either the left or the right posterolateral cerebellum delivered in the 120- to 220-ms time window, $F\,(2, 46) = 1.14$, $p = .33$, and in the 320- to 420-ms time window, $F\,(2, 46) < 1$, $p = .96$, did not interfere with task performance compared to the control condition. Our findings suggest that the left (but not the right) posterolateral cerebellum is recruited in discriminating emotional faces in a specific time interval: from 220 ms to 320 ms after the onset of the to-be-evaluated emotional stimulus.

Consistent evidence suggests that the posterior cerebellum is a key region involved in socio-emotional processes. Here, we demonstrated for the first time that the left posterolateral cerebellum contributes to the discrimination of emotional faces selectively between 220 and 320 ms after the face onset. This result complements our previous chronometrical investigation of the paramedial cerebellum, which showed that this region is involved in emotional face processing earlier, between 100 and 220 ms after the face onset [4]. The difference in the time window of TMS-induced impairment between the paramedial and posterolateral cerebellum represents a unique temporal marker of the functional independence of these two regions, adding to previous neuroimaging and brain stimulation findings [5,6]. Critically, the timing of the biphasic pattern of cerebellar involvement in facial emotional processing we observed in our studies corresponds to that reported in the cerebrum by MEG investigations [7] that show a first amplification of emotional processing around 120–170 ms from the emotional cue onset in occipitotemporal regions, and a following one, around 220–310 ms, in anterior temporal lobe (ATL). This parallelism suggests a synergistic interaction between cerebral and cerebellar regions in supporting emotional processing, underscoring the need to incorporate the cerebellum into the well-established models of emotional face processing. According to the Internal Model Hypothesis, the cerebellum supports brain processing by generating predictive models based on previous experience [8]. We propose that during emotional processing, cerebellar-based predictive models play a pivotal role in two phases. Around 100 ms from the appearance of the emotional face, the paramedial cerebellum receives inputs from the posterior Superior Temporal Sulcus (pSTS). It generates perceptual predictive models that are sent back to the pSTS to facilitate its integration of visual information and attribution of socioemotional meanings to faces. STS sends inputs to ATL, which forwards information to the posterolateral cerebellum. This

https://doi.org/10.1016/j.brs.2025.103000
Received 24 June 2025; Received in revised form 17 November 2025; Accepted 1 December 2025
Available online 1 December 2025

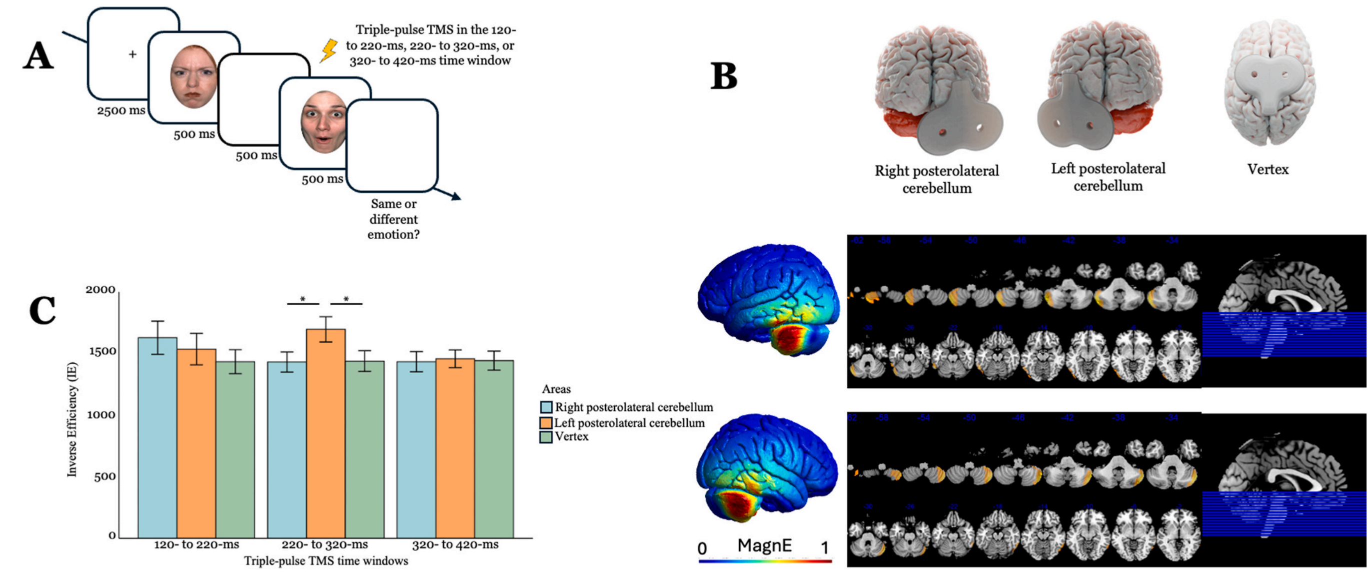

Fig. 1. A) Participants performed an emotion discrimination task that consisted of the presentation of a fixation cross (2500 ms), followed by the first face (500 ms), a blank screen (500 ms), and the target face (500 ms). Participants indicated whether the two faces expressed the same or different emotions by key pressing while receiving triple-pulse TMS over the left and right posterolateral cerebellum and the vertex as a control condition. B) A neuronavigation system guided localization and TMS coil positioning of the targeted sites, and the estimated electric field was calculated using SimNIBS. (C) The graph depicts Inverse Efficiency (IE) as a function of TMS site (right posterolateral cerebellum, left posterolateral cerebellum, and vertex) and TMS timing (120- to 220-ms, 220- to 320-ms, and 320- to 420-ms time window). Triple-pulse TMS over the left posterolateral cerebellum disrupted discrimination of facial emotions when delivered in the 220- to 320-ms time window. TMS over the right posterolateral cerebellum did not affect participants' performance in any of the TMS timing conditions. Error bars indicate 1 SEM. Asterisks indicate significant differences ($p < .05$) across conditions.

region creates memory-related predictive models based on this information and sends them back to ATL to facilitate the linking of perceptual face representations with person-specific, social, and emotional memories [9]. Our finding of the selective left cerebellar TMS-induced impairment further supports the hypothesized role of the posterolateral cerebellum in memory-related processes. Indeed, only the right (not the left) ATL to which the left posterolateral cerebellum is connected is associated with emotion and socially relevant memory [10]. There is also systematic evidence that during social tasks, the posterolateral cerebellum is functionally connected to the dorsomedial prefrontal cortex [11]. Therefore, an alternative hypothesis is that the posterolateral cerebellum mediates the generation of predictive models to implement high-order sociocognitive functions, i.e., mentalizing; a possibility that remains to be explored in future research.

Our finding of a selective contribution of the left posterolateral cerebellum is fully consistent with recent neuroimaging studies revealing stronger and more numerous effective connections from the left posterolateral cerebellum to right-hemispheric cortical social areas compared to left-hemispheric regions, in line with the well-established right-hemisphere dominance of socio-emotional networks in the cerebrum [11]. Further support for this left-cerebellar-right-cerebral organization in underpinning emotional processing comes from a recent TMS study demonstrating causal connectivity between the left paravermal cerebellum and the right pSTS during emotional processing [4]. Our findings also align with a consistent body of evidence, suggesting that the pattern of functional lateralization in the cerebellum broadly mirrors the organization of the cerebral hemispheres, as shown by the right cerebellar hemisphere being preferentially engaged in language-related functions, including linguistic prediction and phonological processing [5].

Our findings offer novel insights into the timing of cerebellar contribution to socio-emotional processing, adding to the emerging literature on cerebellar functional lateralization and structural asymmetries, an area that remains underexplored**.** Crucially, by temporally characterizing the cerebellum's role within the broader social brain network, our results help integrate this historically overlooked structure into current models of social cognition.

CRediT authorship contribution statement

Sonia Paternò: Writing – original draft, Visualization, Investigation. **Andrea Ciricugno:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization. **Zaira Cattaneo:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Chiara Ferrari:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2025.103000.

References

[1] Da Silva FL. EEG and MEG: relevance to neuroscience. Neuron 2013;80(5):1112–28.

[2] Van Overwalle F., Manto M., Cattaneo Z., Clausi S., Ferrari C., Gabrieli J.D., Guell X., Heleven E., Lupo M., Ma Q., Michelutti M., Olivito G., Pu M., Rice L.C., Schmahmann J.D., Siciliano L., Sokolov A.A., Stoodley C.J., van Dun K., … Leggio M. Consensus paper: cerebellum and social cognition. Cerebellum 19:833–868.

[3] Dima DC, Perry G, Messaritaki E, Zhang J, Singh KD. Spatiotemporal dynamics in human visual cortex rapidly encode the emotional content of faces. Hum Brain Mapp 2018;39(10):3993–4006.

[4] Ciricugno A, Ferrari C, Battelli L, Cattaneo Z. A chronometric study of the posterior cerebellum's function in emotional processing. Curr Biol 2024;34(9):1844–52.

[5] Stoodley CJ, Schmahmann JD. Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. Neuroimage 2009;44(2):489–501.

[6] Ferrari C, Ciricugno A, Arioli M, Cattaneo Z. Functional segregation of the human cerebellum in social cognitive tasks revealed by TMS. J Neurosci 2023;43(20):3708–17.
[7] Peyk P, Schupp HT, Elbert T, Junghöfer M. Emotion processing in the visual brain: a MEG analysis. Brain Topogr 2008;20:205–15.
[8] Ito M. Control of mental activities by internal models in the cerebellum. Nat Rev Neurosci 2008;9(4):304–13.
[9] Olson IR, Plotzker A, Ezzyat Y. The enigmatic temporal pole: a review of findings on social and emotional processing. Brain 2007;130(7):1718–31.
[10] Olson IR, McCoy D, Klobusicky E, Ross LA. Social cognition and the anterior temporal lobes: a review and theoretical framework. Soc Cognit Affect Neurosci 2013;8(2):123–33.
[11] Metoki A, Wang Y, Olson IR. The social cerebellum: a large-scale investigation of functional and structural specificity and connectivity. Cerebr Cortex 2022;32(5):987–1003.

Sonia Paternò[a,b], Andrea Ciricugno[c,*], Zaira Cattaneo[d], Chiara Ferrari[a,c]

[a] *Department of Humanities, University of Pavia, Pavia, Italy*
[b] *Department of Brain and Behavioral Sciences, University of Pavia, Pavia, Italy*
[c] *IRCCS Mondino Foundation, Pavia, Italy*
[d] *Department of Human and Social Sciences, University of Bergamo, Bergamo, Italy*

[*] Corresponding author.
E-mail address: andrea.ciricugno@mondino.it (A. Ciricugno).