Brain Stimulation 15 (2022) 999–1001

Contents lists available at ScienceDirect

Brain Stimulation

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

Cerebellar involvement in distributional semantic learning: Insights from a combined TMS-computational approach

Keywords:
Cerebellum
Semantic memory
Transcranial magnetic stimulation
Distributional-semantic models
Prediction

The cerebellum has been suggested to contribute to higher-order cognitive functions, including linguistic processing [1]. Cerebellar involvement in linguistic functions may hark back to its predictive nature, as probabilistic predictions on linguistic contextual information are pivotal during language comprehension. Yet, the extent to which words can be probabilistically predicted from language can vary depending on the level at which these computations operate. Accordingly, simple lexical-prediction processes (i.e., lexical surprisal) are neurally dissociable from processes building on the overall distributional history of words in linguistic context [2]. Here, we show that the right cerebellum is likely involved in this latter, arguably deeper semantic processing, rather than in surface-level linguistic predictions.

Forty healthy Italian right-handed [3] participants (14 males, mean age = 23.2 years, SD = 2.4) were asked to judge whether 140 Italian noun-adjective word-pairs (70 related and 70 unrelated) were semantically related or not (e.g., *red-apple* vs. *blue-banana*) while online 20-Hz triple-pulse transcranial magnetic stimulation (TMS) was administered over the right cerebellum or over the vertex (Fig. 1). The words were shown sequentially to investigate cerebellar involvement also from a chronometric point of view (i.e., TMS was administered at the onset of the noun for 20 participants and at the onset of the adjective for the other 20). Participants were told that they would have taken part in a language experiment. They were unaware of the scope of the study and of the characteristics of the TMS procedure applied.[1] Side effects were assessed by interviewing participants at the end of the experiment. Participants were asked whether they experienced discomfort or other side effects during TMS administration and none of them reported having experienced side effects.

Our dependent variables were participants' log-transformed correct reaction times (RTs) for the related word-pair trials. For each word-pair we computed lexical surprisal, an information-theoretic measure of the extent to which the occurrence of the second word is unexpected given the first word (operationalized as the inverse logarithm of the conditional probability of word2 given word1), as well as a measure quantifying the similarity of the distributional history of the two words in natural language usage (DisSim, operationalized as the distributional similarity between the words in the pair) by applying word-embeddings models [4].

A first mixed model was estimated including the interaction between TMS site (right cerebellum vs. vertex) and TMS timing (at the onset of the first vs second stimulus) as categorical predictors and words' surprisal as continuous predictor. Similarly, a second model was estimated, this time including DisSim as continuous predictor.

We next compared the two models in terms of Akaike information criterion (AIC), which returns an estimation of the quality of the model [5] and thus allows to select the model that provides the most accurate description of the data (i.e., the one with smaller AIC [6]). The resulting AICs were $AIC_{surprisal} = 82.12$ and $AIC_{DisSim} = 67.43$. Hence, the DisSim model outperformed the surprisal one with a $\Delta\ AIC = 14.69$.

In particular, we found a significant interaction TMS site by DisSim ($F(1,2199) = 7.99$, $p = .004$), indicating that the effect of DisSim was smaller during right cerebellar TMS compared with control stimulation (Fig. 1d). In particular, the higher the DisSim between the noun and the adjective, the shorter the reaction times, with this effect being significantly smaller during right cerebellar TMS, $t(128) = -1.59$, $p = .11$, b = -.21, compared with control stimulation, $t(123) = -3.82$, $p < .001$, b = -.50.

Then, we further probed whether the cerebellum treats the distributional proprieties of each word to be processed separately or is rather involved in active, automatic compositional operations inducing combined meanings from word pairs [7]. We computed compositional meanings for novel compounds (e.g., *redapple*) on the basis of their constituent word vectors (e.g., *red*, *apple* [8]). Then, we estimated a new model including additively two predictors indexing compositionality (together with their interactions with TMS timing and TMS site) and compared it with the previous one including DisSim. The resulting AICs were $AIC_{DisSim} = 67.43$ and $AIC_{compositionality} = 68.33$. Since the $\Delta\ AIC$ is < 2, the two models can be considered as statistically equivalent in explaining the process at hand; yet, in this case, the more parsimonious – that is the one comprising less predictors (i.e., the one including DisSim) – should be preferred. These results indicate that TMS stimulation over the cerebellum specifically interferes with the ability to extract associative information derived from the distributional pattern of individual words in language.

Previous studies have reported cerebellar involvement in several linguistic predictive processes [1]. Our findings elucidate

[1] This was confirmed by a brief individual interview at the end of the experiment, as none of the participants understood the real scope of the study.

https://doi.org/10.1016/j.brs.2022.07.004

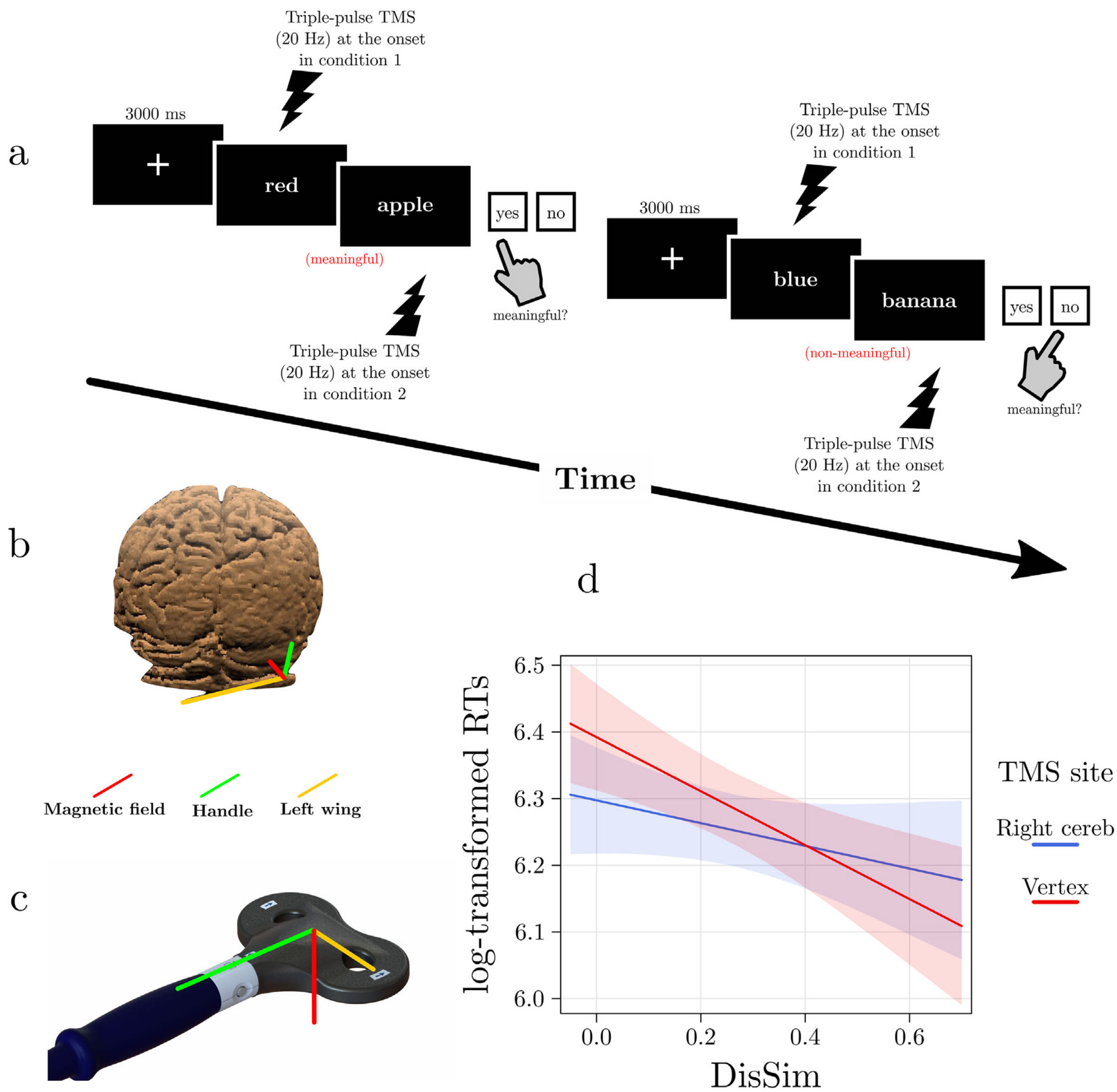

Fig. 1. Participants were asked to judge whether the word-pairs presented were semantically related (e.g., *red-apple*) or unrelated (e.g., *blue-banana*) while TMS was delivered (a). Right cerebellum was selected as a target site for TMS, while the vertex as a control site (not shown) (b); the green line indicates the handle orientation, the yellow one the left-wing of the coil and red one the magnetic field generated by the coil (c). Plot illustrating the significant interaction TMS site by DisSim (an index quantifying the distributional similarity of words in natural language); in particular, the effect of DisSim was smaller during right cerebellar TMS (blue line) compared with the control stimulation (red line) (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that cerebellar involvement in language prediction is specifically related to the processing of semantic associations, further supporting existing theories according to which the cerebellum acquires, stores and uses relations between co-occurring linguistic events [9]. The lack of an effect of TMS timing corroborates the involvement of the cerebellum in the same macro-process. Future neuroimaging studies will elucidate whether our findings reflect a direct involvement of the cerebellum or rather depend on indirect stimulation of other cortical areas.

This study supports neurocognitive models suggesting that the activity of the cerebellum can be traced back to a large-scale network that involves the prefrontal cortex and the temporo–parietal cortex [10]. Accordingly, the reduced reliance on DisSim observed during cerebellar TMS would reflect the disruption of the manipulation of the semantic association between words, while more complex semantic operations (i.e., compositionality) may possibly tap on areas primarily deputed to higher-level information.

In conclusion, our findings indicate that the cerebellum is involved not only in basic predictive functions, but also in more deep semantic functions linked to the process of semantic association in language.

Funding

This work was supported by funding from the Italian Ministry of University and Research (PRIN 2017 no. 201755TKFE) to TV, and from the Italian Ministry of Health (Ricerca Corrente 2022) to LR and TV.

Data availability

The data used in this study are reported as Supplementary Materials.

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.2022.07.004.

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10 June 2022
Available online 16 July 2022