tACS modulates comprehensions of structurally ambiguous sentences

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Introduction: Recent neuroimaging studies using rhythmic auditory linguistic stimuli reported that cortical entrainment, i.e., synchronization of brain activity with exogenous rhythmic stimuli, tracks hierarchical linguistic structures [1]. To further clarify the causal relationship between cortical tracking and sentence-structure building, we examined whether transcranial alternating current stimulation (tACS), a non-invasive brain stimulation method that can modulate cortical entrainment, can change the cortical tracking of hierarchical structures. We hypothesize that the tACS corresponding to the cortical tracking of the sentence structures would modulate sentence comprehension. To enhance the tACS effects on cortical tracking, we targeted structurally ambiguous sentences that can have two distinct structures.

Methods: We recruited 12 right-handed native speakers of Japanese (4 males, mean ± SD = 22.1±0.9 years), who had no history of neurological or psychiatric diseases. These participants were randomly assigned to two tACS groups: 0.5 Hz-tACS group and 1 Hz-tACS group (6 participants each). The same participants were tested for both tACS and sham sessions. We used three sentence conditions: Ambiguous, complex-sentence, and two-sentence conditions (150 sentences/condition). In the ambiguous condition, we presented a structurally ambiguous sentence that can be interpreted as a complex sentence or two simple sentences (e.g., *Otoko-o nagutta, Onna-o ketta.*; *Someone hit the man and someone kicked the woman* or *someone kicked the woman who hit the man*) in a phrase-by-phrase manner (500 ms/phrase). In the complex-sentence condition, we presented unambiguous complex sentences (e.g., *Otoko-o nagutta Onna-o, ketta.*; *Someone kicked the woman who hit the man*). Based on the pilot sentence comprehension experiments, we confirmed that the minimal difference between these conditions (i.e., inserting a comma after verbs or after nouns) modulated the structural ambiguity and sentence comprehension. In the two-sentence condition, we used sentences with periods after every verb (e.g., *Otoko-o nagutta. Onna-o ketta.*; *Someone hit the man. Someone kicked the woman.*). As the ambiguous sentences can be interpreted as four-word sentences (same as the complex-sentence condition) or two-word sentences (same as the two-sentence condition), we predict that 0.5 Hz-tACS, which corresponds to the duration of four-word sentences, facilitates complex-sentence comprehension, whereas 1 Hz-tACS, which corresponds to the duration of two-word sentences, enhances two-sentence comprehension. After the sentence presentation, we asked the participants to answer sentence-comprehension questions (e.g., *who hit the man?*) with four choices. We used a single-blinded, sham-controlled design. We used the MxN-5 tES system (Soterix Medical, USA) for the tACS and sham stimulation. We placed the electrodes on FC3, C5, FT7, F5, and FC56 according to the International 10-10 EEG system, which surrounded the left inferior frontal gyrus. For 0.5 and 1 Hz tACS, stimulation was given for 20 minutes (±2 mA). The participants performed the sentence comprehension task before and after the tACS and sham stimulations.

Results & Discussion: We found that 0.5 Hz-tACS significantly improved the task accuracy (p = .008, Wilcoxon signed-rank test), while 1 Hz-tACS and sham stimulation did not (1 Hz: p = .99, Sham: p = .18). These results indicate that 0.5 Hz-tACS facilitated complex-sentence comprehension, which is more demanding than two-sentence comprehension (Fig 1). We further tested whether the ratio between complex-sentence and two-sentence comprehension changed after 0.5 Hz- or 1 Hz-tACS (Chi-square test of independence). We found that the number of complex-sentence comprehensions increased, and two-sentence comprehensions decreased after 0.5 Hz stimulation (p < .001) (Table 1). In comparison, those of two-sentence comprehensions remained constant after 1 Hz stimulation (p = .38). These results further demonstrate that the tACS corresponding to the cortical tracking of the sentence structures (i.e., 0.5 Hz-tACS for complex-sentence comprehension and 1 Hz-tACS for two-sentence comprehension) modulated comprehensions of structurally ambiguous sentences.

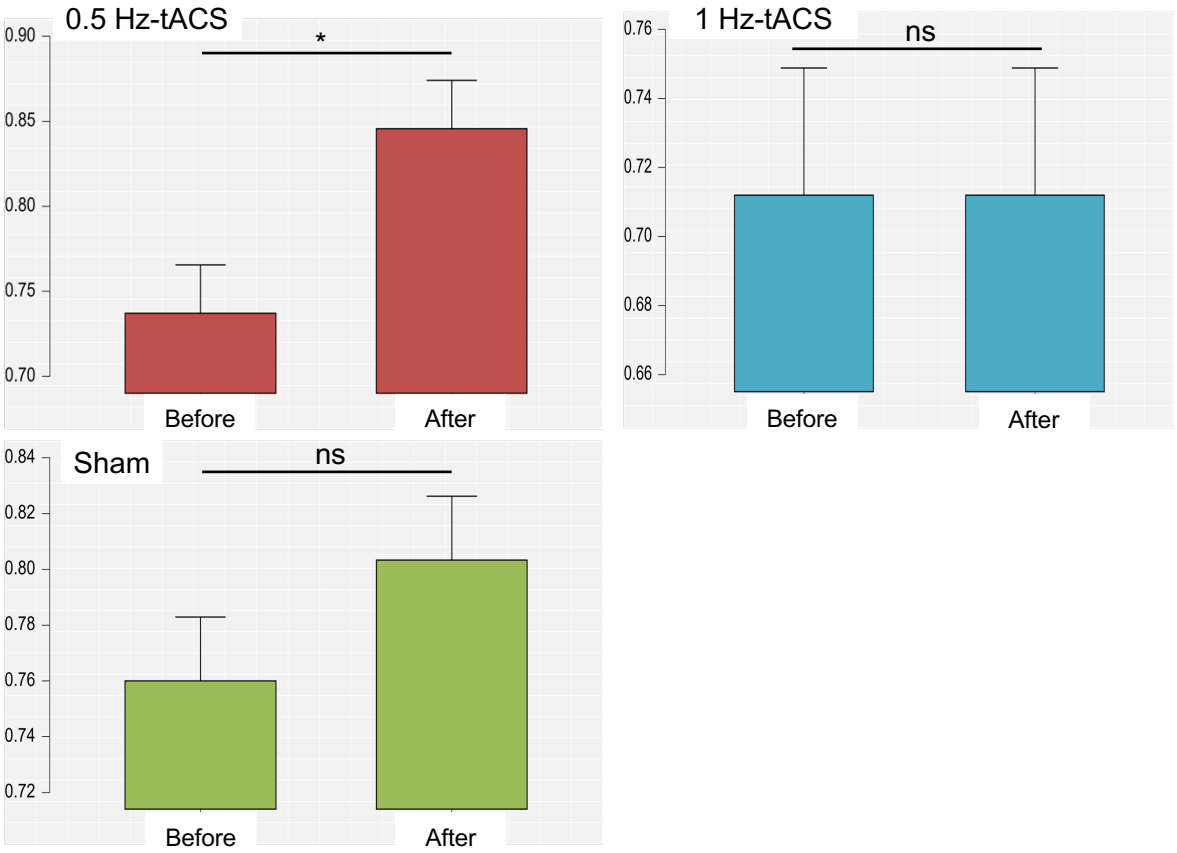

Figure 1. Accuracy before and after tACS. The 0.5 Hz-tACS significantly improved the accuracy, while 1 Hz-tACS and Sham stimulation did not. Error bars: SEM. *: $p < .05$.

Table 1. The number of comprehensions after tACS.

	Before 0.5 Hz-tACS	After 0.5 Hz-tACS	Before 1 Hz-tACS	After 1 Hz-tACS
Complex-sentence	57	124	63	80
Two-sentence	203	160	109	112

The number of complex-sentence comprehensions increased, and two-sentence comprehensions decreased after 0.5 Hz stimulation ($p < .001$), whereas those of two-sentence comprehensions remained constant after 1 Hz stimulation ($p = .38$).

References:

[1] Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2016) Cortical tracking of hierarchical linguistic structures in connected speech. *Nat. Neurosci.* 19(1):158-178.