Selective modulation of sentence comprehension by tACS over the left inferior frontal cortex

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Previous neuroimaging studies have proposed that the left inferior frontal gyrus (IFG) was crucial for constructing hierarchical syntactic structures (Ohta et al. 2013, Zaccarella et al. 2017). Moreover, another neuroimaging study has demonstrated the cortical activity of different frequency bands, which corresponded to syllabic, phrasal, and sentential rates, suggesting grammar-based internal construction of the hierarchical linguistic structure (Ding et al. 2016). Using transcranial alternating stimulation (tACS), which can modulate the specific frequency band of the cortical activity non-invasively (Antal & Paulus 2013), we examined whether the modulation of the cortical activity that corresponded to sentence structure construction changed sentence comprehension. We hypothesize that tACS at the sentential rate disrupts the internal construction of the hierarchical sentence structure, which may increase the difficulty of sentence comprehension.

We recruited 15 right-handed native speakers of Japanese (8 males, mean ± SD = 21.9 ± 0.8 years), who had no history of neurological or psychiatric diseases. The same participants were tested for both the tACS session and sham session (Fig. 1A). We used 96 Japanese sentences and 96 word-strings (total 192 stimuli). Each sentence stimulus consisted of three noun phrases and one verb, immediately followed by a question consisted of a subject and a verb (Fig. 1B). Each word list stimulus consisted of four noun or verb phrases, immediately followed by a pair of words (Fig. 1C). In the present experiment, we used a sentence comprehension task and a short-term memory task. In the sentence comprehension task, the participants judged whether the meaning of the sentence matched with the question by pressing one of two buttons, while in the short-term memory task, they judged which of the words in a word pair was included in the word string. We used a double-blinded sham-controlled design. Stimulation was delivered using DC-Stimulator Plus (NeuroConn, Germany). The two electrodes were placed over F7 and Fp2 according to the International 10-20 EEG system, which were right above the left IFG and the right forehead, respectively. For tACS, stimulation was given for 20 minutes (±2 mA, 0.5 Hz, 5 cm * 7 cm saline-soaked sponge electrodes, >10 kΩ). We used 0.5-Hz stimulation that corresponded to the sentential rate of the sentence comprehension task. Sham stimulation, which controls for the placebo effect, ramped up to ±2 mA over 10 s, remained at that level for 30 s, ramped back down over 10 s. In the sham session, the participants felt the initial ramp up event, which is the most noticeable in tACS, without receiving an effective stimulation in the tACS. Before and after the tACS and sham sessions, the participants performed the sentence comprehension and short-term memory tasks.

The participants showed high accuracies (>90%) and short reaction times to comprehension questions (RTs, <1000 ms) (Fig. 2). A two-way repeated-measures analysis of variance (Stimulation (baseline, tACS, and Sham) * task (sentence vs. memory)) for the accuracies did not show any significant effects (Stimulation: $F(2,28) = 0.78$, $p = 0.49$; Task: $F(1,14) = 0.48$, $p = 0.50$; interaction: $F(2,28) = 0.49$, $p = 0.62$). A two-way repeated-measures analysis of variance for the RTs did not show significant main effects (Stimulation: $F(2,28) = 2.6$, $p = 0.09$; Task: $F(1,14) = 1.5$, $p = 0.24$), while the interaction was significant ($F(2,28) = 4.5$, $p = 0.02$). To consider the random variabilities of participants and stimuli, we analyzed the RTs by using a linear mixed-effect model (lme4 and lmerTest packages on R). We found that the model with the effects of Stimulation (baseline vs. tACS vs. Sham) and Task (sentence vs. memory) (full model) was significantly better than the simpler model without the effect of Stimulation ($\chi^2(4) = 18$, $p = 0.0013$), suggesting the effect of tACS was significant (Table 1). Moreover, the sham stimulation over the left IFG significantly decreased the RTs of the sentence comprehension task ($t(2510) = -3.7$, $p = 0.0002$), indicating the learning effect. In contrast, the tACS over the left IFG did not show such effect ($t(2505) = -1.7$, $p = 0.08$) (Fig. 3). In the present tACS study, we demonstrated that the tACS over the left IFG disrupted the sentence comprehension task but not short-term memory task, suggesting the causal relationship between the left IFG activation and sentence structure constructions.

References: Antal & Paulus. *Front Hum Neurosci.*, 2013.; Ding et al. *Nat Neurosci.*, 2016.; Ohta et al. *PLoS ONE*, 2013.; Zaccarella et al. *Cereb Cortex*, 2017.

LME models:
Simple model: logRT ~ task + (stim + task | subject) + (1 | stimulus)
Full model: logRT ~ stim * task + (stim + task | subject) + (1 | stimulus)

Table 1. Model comparison between the full and simple models

Models	No. params	AIC	log-Likelihood	χ^2	df	*p* value
Simple	14	2789	−1381			
Full	18	2779	−13722	18	4	0.0013

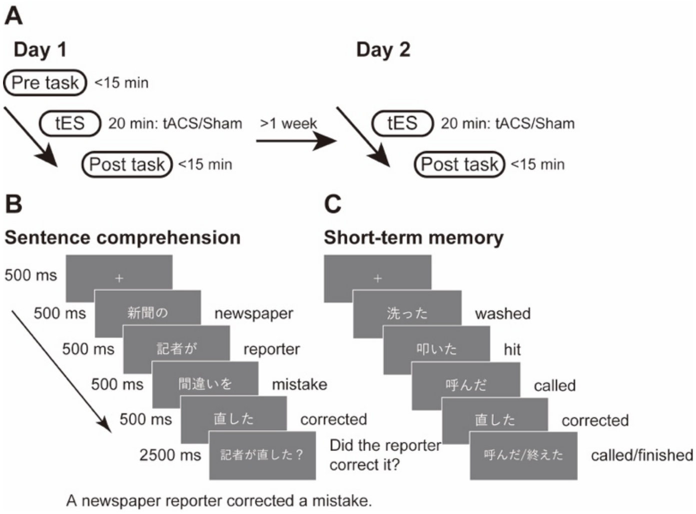

Fig. 1. Experimental design and tasks.

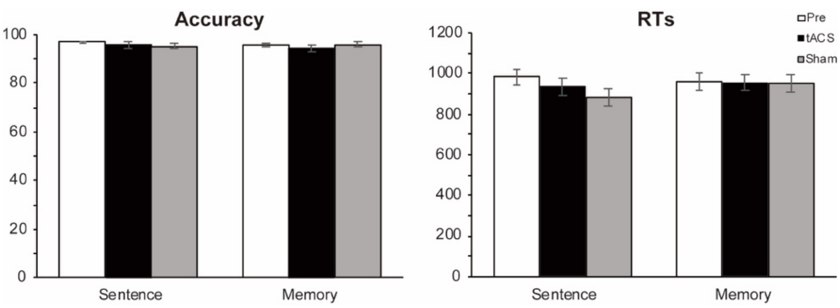

Fig. 2. Behavioral data. Mean ± SEM.

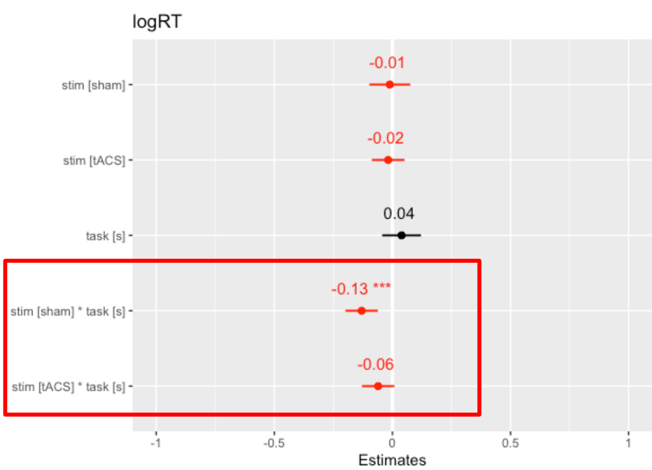

Fig. 3. Parameters of the full model.