Selective Modulation of Syntactic Processing by Anodal tDCS over the Left Inferior Frontal Region

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Previous neuroimaging studies have demonstrated that the left inferior frontal gyrus (IFG) is critical for syntactic processing. To test the causal relationship between the left IFG activation and syntactic processing, we examined whether anodal (i.e. excitatory) transcranial direct current stimulation (tDCS), a non-invasive brain stimulation technique applicable in humans, over the left IFG facilitates syntactic processing. We hypothesize that behavioral performance of sentences with additional syntactic loads (e.g. passive sentences) is improved by the anodal tDCS.

We recruited 20 right-handed native speakers of Japanese (10 males, mean ± SD = 22.5±0.8 years), who had no history of neurological or psychiatric diseases. The same participants were tested for both anodal stimulation session and sham session (Fig. 1A). We used 30 Japanese sentences for each of active intransitive (e.g., *Taro-to Hanako-ga aruita*, *Taro and Hanako walked*), active transitive (*Taro-ga Hanako-o tataita*, *Taro hit Hanako*), passive intransitive (*Hanako-ga Taro-ni arukareta*, *Hanako was adversely affected by Taro's walking*), and passive transitive sentences (*Hanako-ga Taro-ni tatakareta*, *Hanako was hit by Taro*) (total 120 stimuli). To examine the effect of active/passive voice as well as that of transitivity, we used these four sentence types. Note that the passive intransitive sentences, the so-called indirect passive, are grammatical in Japanese. Each sentence consisted of two noun phrases and one verb, immediately followed by a question consisted of a subject and a verb (e.g., *Taro-ga aruita?*, *Did Taro walk?*). In the present experiment, we used a sentence comprehension task, in which the participants were instructed to judge whether the meaning of the sentence matched with the question by pressing one of two buttons. We used a single-blinded sham-controlled design. Stimulation was delivered using DC-Stimulator Plus (NeuroConn GmbH, Germany). The anode and cathode electrodes were placed over F5 and F6 according to the International 10-20 EEG system, which were right above the left and right IFG, respectively. For anodal tDCS, stimulation was given for 20 minutes (1 mA, 5 cm * 7 cm saline-soaked sponge electrodes). Sham stimulation, which controls for the placebo effect, ramped up to 1 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 tDCS, without receiving an effective stimulation in the anodal tDCS. Before and after the anodal and sham stimulations, the participants performed the sentence comprehension task (Pre and Post task).

The participants showed high accuracies (> 90%) and short reaction times to comprehension questions (RTs, <1600 ms) for all of the four conditions (Fig. 1B, 1C). A three-way repeated-measures analysis of variance (rANOVA) (Stimulation*Condition*Pre/Post) for the accuracies showed significant main effects of Condition ($F(3,57)=11$, $p<.0001$) and Pre/Post ($F(1,19)=8.4$, $p=.009$), while the main effect of Stimulation and interactions were not significant ($p>.18$). The rANOVA for the RTs also showed significant main effects of Condition ($F(3,57)=42$, $p<.0001$) and Pre/Post ($F(1,19)=21$, $p=.0002$), as well as the interaction of these factors ($F(3,57)=3.7$, $p=.002$). These results suggest that the active intransitive condition was easiest, while the passive conditions were more demanding. The significant main effect of the Pre/Post also shows the learning effect. To consider the random variabilities of participants and stimuli, we further analyzed the RTs by using a linear mixed-effect model (lme4 and lmerTest packages on R). We found that the model with the effect of Stimulation was significantly better than the simpler model without such effect ($\chi^2(3)=38$, $p<.0001$), suggesting the effect of anodal tDCS. Moreover, the anodal stimulation over the left IFG significantly decreased the RTs of the passive sentences ($p=.002$, Fig 1D). In the present tDCS study, we demonstrated that the anodal tDCS over the left IFG facilitated the processing of syntactically more demanding passive sentences, suggesting the causal relationship between the left IFG activation and syntactic processing.

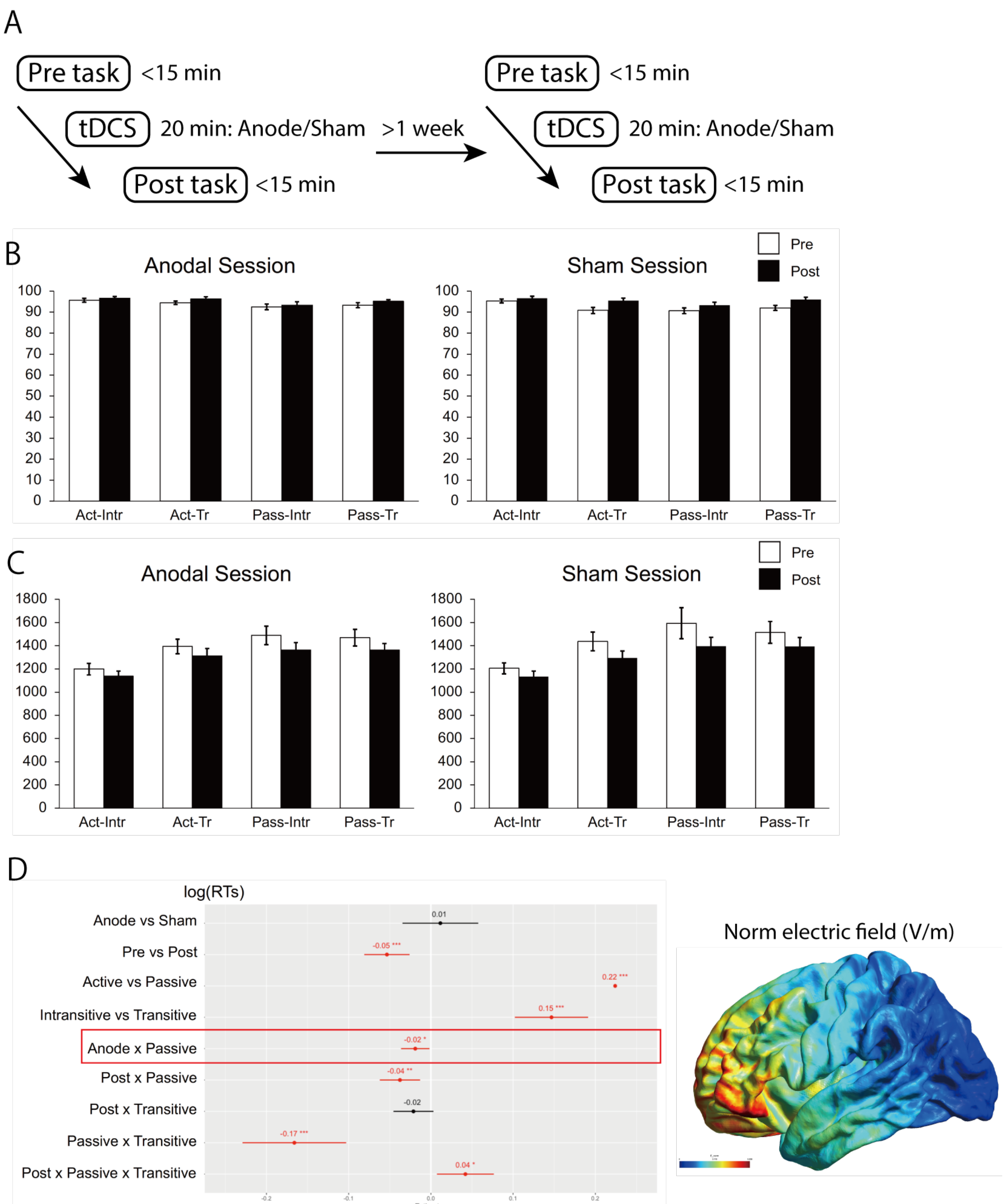

Figure. (A) Schematic illustration of the tDCS procedures, (B) accuracies to the comprehension questions, (C) reaction times to the comprehension questions, and (D) the LME results and estimated electric fields during anodal tDCS.