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Research article

The role of early stages of cortical visual processing in size and distance judgment: A transcranial direct current stimulation study

Thiago L. Costa [a,b,*], Marcelo F. Costa [a,c], Adsson Magalhães [a,c], Gabriel G. Rêgo [b], Balázs V. Nagy [a,c], Paulo S. Boggio [b], Dora F. Ventura [a,c]

[a] Departamento de Psicologia Experimental, Instituto de Psicologia da Universidade de São Paulo, São Paulo, Brazil
[b] Social and Cognitive Neuroscience Laboratory and Developmental Disorders Program, Mackenzie Presbyterian University, São Paulo, Brazil
[c] Núcleo de Neurociências e Comportamento e Neurociências Aplicada, Universidade de São Paulo, São Paulo, Brazil

HIGHLIGHTS

- tDCS of the early visual cortex affects size but not distance judgment.
- Increased visual cortex activity might interfere with size judgment.
- Size and distance judgment involves different mechanisms.

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ABSTRACT

Recent research suggests that V1 plays an active role in the judgment of size and distance. Nevertheless, no research has been performed using direct brain stimulation to address this issue. We used transcranial direct-current stimulation (tDCS) to directly modulate the early stages of cortical visual processing while measuring size and distance perception with a psychophysical scaling method of magnitude estimation in a repeated-measures design. The subjects randomly received anodal, cathodal, and sham tDCS in separate sessions starting with size or distance judgment tasks. Power functions were fit to the size judgment data, whereas logarithmic functions were fit to distance judgment data. Slopes and R^2 were compared with separate repeated-measures analyses of variance with two factors: task (size *vs.* distance) and tDCS (anodal *vs.* cathodal *vs.* sham). Anodal tDCS significantly decreased slopes, apparently interfering with size perception. No effects were found for distance perception. Consistent with previous studies, the results of the size task appeared to reflect a prothetic continuum, whereas the results of the distance task seemed to reflect a metathetic continuum. The differential effects of tDCS on these tasks may support the hypothesis that different physiological mechanisms underlie judgments on these two continua. The results further suggest the complex involvement of the early visual cortex in size judgment tasks that go beyond the simple representation of low-level stimulus properties. This supports predictive coding models and experimental findings that suggest that higher-order visual areas may inhibit incoming information from the early visual cortex through feedback connections when complex tasks are performed.

1. Introduction

Over the last decades, V1 has been proposed to play roles that are much more complex than what classic papers suggested [1,2]. More specifically, recent research has shed light on the involvement of this area in the processing of subjective size and distance judgment. For example, retinotopic V1 activity was better correlated with the perceived size of an object than with the retinal projection of the object [3–5]. This phenomenon was observed in different experiments. Functional magnetic resonance imaging (fMRI) showed a different spatial extent of V1 activation for stimuli of the same size that were perceived as close or distant [3]. In a different case, the same retinal afterimage led to greater V1 activation when the participant fixated on a distant background compared with a close background [4]. The actual size of the afterimage was the same in both conditions. In another imaging study, individual variations in the size of the surface area of V1 were significantly correlated with

* Corresponding author at: Rua Piauí, 181, 10º Andar, São Paulo, SP 01241-001, Brazil. Tel.: +55 11 2114 8878.
E-mail address: e.thiagocosta@gmail.com (T.L. Costa).

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the magnitude of the Ebbinghaus illusion, a fact that further supports the active involvement of this area in subjective size judgment [6].

These experiments raised numerous questions about the role of V1 in this kind of visual processing. To date, research has relied on psychophysical methods and fMRI. We argue that brain stimulation techniques should also be used to better understand the role of this area in size and distance processing. The level of causality that non-invasive brain stimulation may help establish between the early stages of cortical visual processing and behavior cannot be achieved with brain imaging alone. Brain stimulation allows interfering with brain activity, whereas MRI is restricted to imaging brain activity. Here, we propose using transcranial direct-current stimulation (tDCS) to directly interfere with the early stages of cortical visual processing, with the goal of modulating mostly V1 activity, during size and distance magnitude estimation tasks. The use of these magnitude estimation tasks allows us to discuss subjective size and distance perception because the participants have to judge a stimulus magnitude by comparing it to an always-present reference stimulus. tDCS is a noninvasive brain modulation technique that may increase or decrease brain excitability, depending on stimulation polarity [7]. It was also shown to be effective in modulating V1 activity [8,9]. Therefore, coupling tDCS and magnitude estimation psychophysics allows for a better understanding of how increased or decreased V1 activity affects size and distance judgment.

2. Methods

We used a repeated-measures protocol whereby anodal, cathodal, and sham tDCS were delivered to a group of 14 healthy volunteers (eight female, 25 ± 4.3 years old, all naive to the task and hypotheses) in separate sessions (one for each tDCS variation, for a total of three sessions) with an interval of at least 48 h. The session order was randomized between participants. In each session, the participants received 5 min of tDCS at rest before starting the tasks, except during the sham condition, in which the current was gradually turned off for 10 s after 30 s of stimulation, following standards in the field [10]. tDCS was applied through rubber electrodes that were covered with saline-soaked sponges (25 cm^2) to Oz, with return electrodes to Cz (10–20 International System). The current density was set to 0.06 mA/cm^2.

In each tDCS session, size judgment and distance judgment tasks were performed in a randomized order. In both tasks, a circle (50 mm diameter; 5° of visual angle from a viewing distance of 57 cm) was presented at the left side of the screen in all of the trials. The task was to judge the size or distance of a circle at the right side of the screen, considering that the size of the reference circle was always 50 (which was also the actual size of this stimulus in millimeters; Fig. 1).

For the size judgment task, the stimuli were presented on a black background (Fig. 1A). For the distance judgment task, the stimuli were presented on a background with a depth clue surface (Fig. 1B). The circles had a luminance of 40 cd/m^2. For the size judgment task, the subjects were instructed to judge the size of the circle at the right side, considering that the left circle had a size of 50 units. For the distance judgment task, the subjects were instructed to judge the distance of the right stimulus, considering that the left stimulus had a distance of 50 units from the beginning of the depth clue surface (Fig. 1B) and that both circles had the same size. In both experiments, 33 trials with stimuli that ranged from 11 to 100 mm diameter were presented. For a detailed methodological explanation, see Costa et al. [11]. The subjects had to judge the size or distance of the stimuli at each stimulus presentation. Sixteen target stimuli were smaller than the reference circle. Sixteen target stimuli were larger than the reference circle. One target stimulus was equal to the reference circle (*i.e.*, 50 mm). The stimuli differed from each other by 3 mm, and the order of presentation was random in each test session.

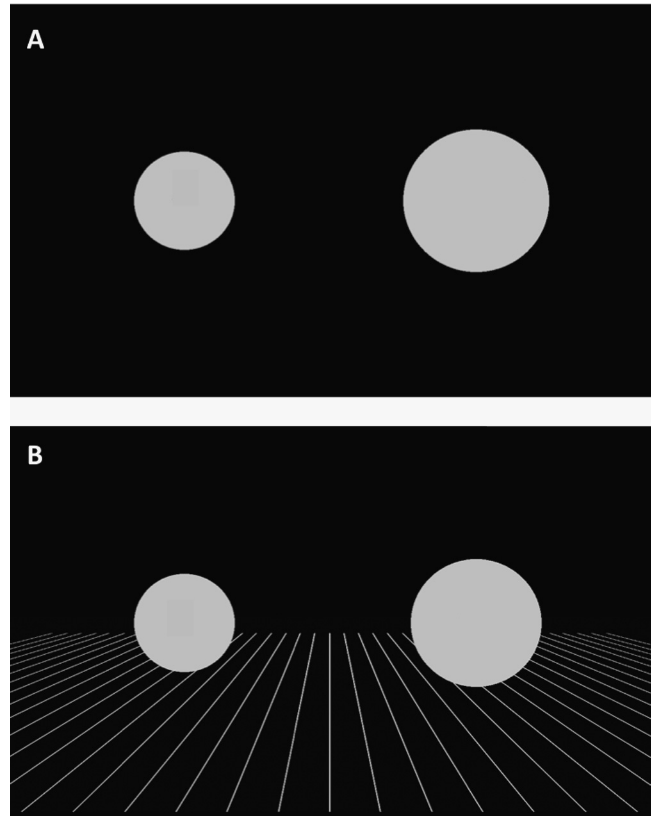

Fig. 1. Examples of stimuli used in the size judgment task (A) and distance judgment task (B). The task was to judge the size or distance of the right circle, considering that the left circle had a value of 50. Test stimuli ranged from 11 to 100 mm diameter.

For the size judgment task, a power function was fit to responses for each of the subjects in each session (Fig. 2). For the distance judgment task, a logarithmic function was fit to the responses of each of the subjects in each session. Slopes and R^2 for the functions of each subject in each task and each tDCS session were calculated. Increases in slope represent an expansive judgment (*i.e.*, the participants judge differences as larger than they are), and decreases in slope represent a compressive judgment (*i.e.*, the participants underestimate stimulus differences). High R^2 values represent a good correlation between perceived size and stimulus size, whereas low R^2 values represent low correlations.

The use of different functions to fit size and distance judgment data is rooted in previous studies which suggested that judgments might be made on a prothetic continuum (judgment based on *how much*) or metathetic continuum (judgment based on *what kind* or *where*) [12]. We chose to analyze the distance judgment results using a logarithmic scale for two reasons. First, the logarithmic function was the best fit to the data (higher R^2 values compared with alternative fits with power functions). Second, classic authors in this field suggest that size judgments lay on a prothetic continuum and their magnitudes should fit a power function [12], although some have argued that distance judgment results should be fit by a logarithmic function (see Anderson and Zahorik [13] for a debate).

3. Results

The data were analyzed using two repeated-measures ANOVAs: one for slope and one for R^2. Each ANOVA had two within-subjects