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Brain stimulation to left prefrontal cortex modulates attentional orienting to gaze cues

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Brain stimulation to left prefrontal cortex modulates attentional orienting to gaze cues

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MEDIA SUMMARY

Social robots are increasingly becoming a part of everyday life, and researchers are confronted with the challenge of how to make them sufficiently social for humans to accept them as social companions. Previous research has shown that the effect of nonverbal signals like changes in gaze direction on social-cognitive processes in human-robot interaction depends on the degree to which the robot is perceived as "having a mind". In using brain stimulation, the paper shows that this modulatory effect of mind perception on social-cognitive processes in human-robot interaction likely originates from left prefrontal brain areas.

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ABSTRACT

In social interactions, we rely on nonverbal cues like gaze direction to understand the behavior of others. How we react to these cues is determined by the degree to which we believe that they originate from an entity with a mind capable of having internal states and showing intentional behavior, a process called *mind perception*. While prior work has established a set of neural regions linked to mind perception, research has just begun to examine how mind perception affects social-cognitive mechanisms like gaze processing on a neuronal level. In the current experiment, participants performed a social attention task (i.e., attentional orienting to gaze cues) with either a human or a robot agent (i.e., manipulation of mind perception) while transcranial direct current stimulation (tDCS) was applied to prefrontal and temporo-parietal brain areas. The results show that temporo-parietal stimulation did not modulate mechanisms of social attention, neither in response to the human nor the robot agent, whereas prefrontal stimulation enhanced attentional orienting in response to human gaze cues and attenuated attentional orienting in response to robot gaze cues. The findings suggest that mind perception modulates low-level mechanisms of social cognition via prefrontal structures, and that a certain degree of mind perception is essential in order for prefrontal stimulation to affect mechanisms of social attention.

INTRODUCTION

People are seeing a day-to-day increase in the number of robot agents in their lives that could assist them in various domains [1]. Although evidence of positive outcomes of human-robot interactions exist [2–4], designing social robots that elicit natural human responses can be challenging due to people’s negative perceptions about having social robots be a part of their everyday life [5,6]. To remedy this and design robots that are able to elicit social responses, we must understand how the human brain processes social information in interactions with others and whether nonhuman agents are able to activate these networks to a similar extent as human interaction partners (and if so, under which conditions). Following this approach, we can identify physical and behavioral agent features that reliably activate brain areas involved in social-cognitive processes and investigate whether robots that elicit activation in these networks lead to more acceptance and trust, as well as improved performance in human-robot interaction [58].

Meaningful social interactions require the ability to infer internal states of others, such as intentions (i.e., mentalizing) and emotions (i.e., empathizing) [7], and to use this information to predict future behavior [8]. For that purpose, the human brain is equipped with neural networks specialized in processing information relevant to social interactions (i.e., *social brain*; [8–10]) that involve posterior areas like the temporo-parietal junction (TPJ), the superior temporal sulcus (STS) and the fusiform gyrus (FG), as well as anterior areas like the anterior cingulate cortex (ACC) and the ventromedial and dorsolateral prefrontal cortex (vmPFC, dlPFC) [8,11–16]. TPJ is involved in inferring higher-order action goals [17–25] and mental and spatial perspective taking [22,24,26], while STS and FG are involved in processing biological motion and

face identity, respectively [8,15]. PFC is involved in making inferences about enduring dispositions such as preferences or beliefs [14,23,27,28], and activation in medial PFC is positively correlated with the amount of background knowledge we have about others [18,29]. ACC is activated in social interactions requiring mentalizing in real-time [25,30], and is more strongly activated when interacting with human versus machine agents (i.e., computers; [31]).

Critically for human-robot interaction, most current social robot platforms underactivate the social brain network [31,41,44], which negatively impacts social (e.g., joint attention), emotional (e.g., empathy) and cognitive (e.g., trust) processes that would be essential in order for humans to socially interact with robot agents. Fortunately, for social roboticists, social brain activation depends on the degree to which an interaction partner is perceived as “having a mind” (i.e., *mind perception* [32]), with the general capability of making changes in the environment (i.e., *agency*; [33]), and experiencing internal states, such as emotions and intentions (i.e., *experience*), and as such can presumably be triggered by design. Whereas mind is easily perceived in other human agents [34], the degree to which nonhuman entities like robots trigger mind perception depends on whether their physical and behavioral characteristics are perceived as sufficiently human-like [35–38]. Mind perception is in fact a highly effortless process that activates social brain networks in a bottom–up or reflexive fashion [133–136], triggered by human-like facial features and relations (i.e., spatial arrangement of eye-nose-mouth configurations) [131,132, 134, 135, 137], as well as biological motion and/or predictable behavior [49].

Due to its reflexive nature, mind perception allows observers to differentiate intentional from non-intentional agents within a few hundred milliseconds [135, 136], and even just

passively viewing stimuli that trigger mind perception is sufficient in order to induce activation in a wide range of social brain networks [126], which varies parametrically as a function of the agent's physical human-likeness (i.e., increases as the agent's face or body becomes more human-like in appearance) [57, 84]. Brain areas related to variations in mind perception involve anterior social brain areas, such as the left ACC [12, 25, 43], as well as posterior areas, such as the left TPJ [90]. Left ACC is activated when others are treated as intentional agents [43, 141], and responds more strongly during social decision making tasks that involve intentional versus non-intentional agents [43, 141]; activation within left TPJ is associated with attributing human-likeness and intentionality to non-human agents [138-140], and gray matter volume in left TPJ corresponds to individual differences in anthropomorphizing non-human entities, in particular animals [90]. The degree to which agents trigger mind perception not only modulates activation in social brain areas, it also determines how we feel about them [39-42], behave towards them [31,43-46] and interact with them [47-50], and as such has the potential to impact acceptance, trust and performance in human-robot interactions. Mind perception affects higher-order social-cognitive processes like prosociality, morality and economic decision-making [46,49], and also modulates low-level social-cognitive processes, such as face perception [51] and social attention [52-55]. The effect of mind perception on social cognition is so profound that the mere belief that observed behavior may reflect the actions of an agent "with a mind" makes people interpret pre-programmed behaviors as intentional and motivates them to attune their actions accordingly [44,54-56].

Although the neural link between mind perception and social brain activation [27,57], as well as the behavioral link between mind perception and social-cognitive processes are

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relatively well understood [58], research has just begun to examine how mind perception modulates social cognition on a neural level (i.e., activation of which brain areas modulates social cognition as a function of mind perception) [44]. To address this important issue, we use transcranial direct current stimulation (tDCS) to investigate the link between activation of social brain areas implicated in mind perception and low-level social cognitive processes, such as social attention (i.e., the degree to which changes in gaze direction are followed) [67]. TDCS is a non-invasive electrical stimulation technique that can be applied without disrupting the participant during task execution, and has been proven to be effective in modulating a wide range of cognitive processes in previous studies (e.g., memory, attention, decision-making, perception; [59–62]). Social attention, or the tendency to follow changes in others’ gaze direction, was chosen for the present study, as it is a basic, yet essential, social-cognitive mechanism that allows for initiating and coordinating communication [63–65], establishing joint attention between two interaction partners and an object of interest in the environment [66], and an important precursor for developing a theory of mind [66].

Social attention can be examined using a gaze-cueing paradigm, where a face-like stimulus is presented centrally on a screen that first looks straight and then changes gaze direction to the left or right side of the screen. This so-called *gaze cue* is followed by the presentation of a target stimulus (e.g., F or T) that either appears at the cued location (i.e., valid trial) or an uncued (i.e., invalid trial) location and triggers shifts of the observer’s attention to the gazed-at location. As a result, reaction times on valid trials are usually shorter than reaction times on invalid trials, with the difference in reaction times between invalid and valid conditions constituting the *gaze-cueing effect* [67]. Although it is widely accepted that social

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3 attention has a strong bottom-up component (i.e., attention is shifted reflexively to the cued
4 location; [66]), there is accumulating evidence that it can be top-down controlled by higher-
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6 order social-cognitive processes when context information is available that increases the social
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8 relevance of observed gaze signals (e.g., gazer is similar or known to the observer; [54,68–77]).
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11 With particular relevance to the current study, manipulating the degree to which a gazer is
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13 perceived as an intentional being “with a mind” has been shown to modulate social attention,
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15 such that gaze-cueing effects are larger in response to human (i.e. intentional) versus machine
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17 (i.e., pre-programmed) gazers [54,55,78,79]. That this top-down modulation is specifically
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19 related to mind perception is supported by experiments showing that although individuals on
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21 the autism spectrum reflexively attend to gaze signals, they do not show the reported
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23 enhancement of gaze-cueing effects for human agents but an enhancement in attentional
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25 orienting in response to robot gaze cues (potentially due to difficulties with inferring internal
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27 states underlying human gaze behavior but an increased interest in machine behavior) [79].
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35 While modulatory effects of mind perception on social attention have been examined
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37 behaviorally [46,48], how mind perception modulates lower-level social-cognitive mechanisms
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39 like gaze cueing at the neuronal level still remains an open question. In particular, it is unclear
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41 whether anterior or posterior parts of the social brain network are more strongly involved in
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43 modulating social cognition via mind perception. On the one hand, Oezdem et al. showed that
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45 believing that an agent’s eye movements are human-controlled (i.e., intentional) as opposed to
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47 pre-programmed (i.e., non-intentional) modulated activation in bilateral TPJ (but not prefrontal
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49 networks), and enhanced attentional orienting to gaze cues [44]. On the other hand, Wiese et
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51 al. showed that although variations in social attention in response to human versus robot
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gazers correlated with activation in anterior (i.e., ventromedial PFC) and posterior social brain areas (i.e., TPJ), only activation in bilateral vmPFC correlated with both variations in mind perception and social attention, suggesting that vmPFC might be involved in the top-down control of social attention via mind perception [57]. Taken together, these findings show that although there is convincing evidence that social attention can be modulated via mind perception, the exact source of this modulatory effect still needs to be identified.

To address inconsistencies of previous studies and to examine whether anterior and/or posterior areas of the social brain network implicated in mind perception are causally involved in modulating social attention, in the current study we compare gaze-cueing effects induced by agents “with a mind” (i.e., human) to agents “without a mind” (i.e., robot), with and without tDCS stimulation to left prefrontal and left temporo-parietal areas. This manipulation was chosen for two reasons: First, previous studies showed that sophisticated minds are attributed to agents with human-like appearance but not to agents with a robot-like appearance (i.e., mind ratings increase as a function of physical human-likeness [33,81–83]), which allows us to experimentally manipulate mind perception via physical human-likeness. Second, since mind perception increases activation in social brain networks [84–87] and has been shown to modulate social-cognitive processes like gaze cueing on a behavioral level [55,88], using tDCS in the context of a social attention paradigm seems suitable to investigate the outlined research goal. Left prefrontal and left temporo-parietal areas were chosen as sites for tDCS stimulation for the following reasons: First, both areas have been implicated in mind perception in previous studies [27, 44, 57, 43, 141], and activation in both areas has been shown to correlate with variations in social attention (i.e., gaze cueing) [44, 57]. Second, both areas are located distant

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3 enough from each other to minimize the risk of accidental stimulation of the respective other
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5 site during stimulation (i.e., prefrontal vs. temporo-parietal). Third, previous studies suggest
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7 that active stimulation is superior to sham stimulation as a control, as it controls for side effects
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9 of stimulation that are not directly associated to brain functionality like stimulation sensations,
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11 and allows for drawing specific inferences regarding the origin of the modulation in terms of
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13 location, as permitting by the low spatial resolution of tDCS targeting [92,93].
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20 **METHODS AND MATERIALS**

21 **Participants**

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23 Eighty-two undergraduate students from George Mason University (57 females, $M = 19.84$, $SD =$
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25 2.35 , range: 18-29 years) participated in the current study for course credit. All participants
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27 were right-handed, had normal or corrected-to-normal vision, had no known neurological or
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29 psychological deficits, were not taking any medications known to affect the central nervous
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31 system at the time of the experiment, and had no history of migraines, seizures, or head
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33 injuries. All participants provided written consent to participation and were debriefed at the
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35 end of the study. Collection and handling of participant data were in accordance with the IRB
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37 guidelines (obtained prior to data collection). Data of participants whose accuracy rate in the
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39 gaze cueing task during baseline was below 85% (6 participants), who did not follow the
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41 instructions properly (2 participants), or did not complete the study (2 participants) were
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43 excluded from data analysis (13% of participants in total). The remaining 72 participants were
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45 quasi-randomly assigned to the experimental condition, that is: active stimulation of the left
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47 *prefrontal cortex* (**PFA**; $n = 36$, 23 females), or the control condition, that is: stimulation of the
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left *temporo-parietal cortex* (**TPA**; $n = 36$, 27 females). To determine the sample size needed for the study, an a priori power analysis was conducted in G*power for a mixed-effects repeated measures design (i.e., one between factor and one within factor). Since mixed-effects repeated measures designs in G*power can only handle two-factorial designs, the sample size was determined for an ANOVA with a 2-level between factor and a 4-level within factor (i.e., the two within variables were combined). The analysis was based on an alpha of ($\alpha = .05$), the power set to ($1 - \beta = .95$), and the assumption of a small-to-medium effect size (Cohen's $d = .17$). The analysis showed that an approximate sample size of 76 participants would be sufficient for both experimental groups. Since the current version of G*power cannot test for a 3-way factorial design but only a 2-way factorial design, another power analysis was conducted using R for the general linear model, which is a more generic test. The analysis was done for a 2x2x2 factorial model that contains three main effects and their interactions (i.e., three 2-way interactions and one 3-way interaction) using the same alpha ($\alpha = .05$), beta ($1 - \beta = .95$), and effect size (Cohen's $d = .17$) as the previous analysis. The analysis for the general linear model revealed that the study needed a total of 83 participants.

Apparatus

Stimuli were presented on a Dell 1703FP monitor with the refresh rate set at 85 Hz. RT measures were based on standard keyboard responses. Participants were seated approximately 57 cm from the monitor, and the experimenter ensured that participants were centered with respect to the monitor. The experiment was controlled by *Experiment Builder* (SR Research Ltd., Ontario, Canada).

TDCS stimulation

An ActivaDose II, ActivaTek system was used to administer the 2mA stimulation. Although there is not a universal and ideal level of current stimulation for any one montage, we selected 2mA because it is a commonly used level that is within human safety limits [94]. Electrode placement followed the 10–5 EEG system [95], and tDCS was delivered via two 5 × 5 cm saline soaked sponges in rubber housing (resulting in a sponge contact area of 3 × 3 cm). For PFA stimulation, the anode was placed on the scalp over F9 and the cathode was placed over Fz. For TPA stimulation, the anode was placed on the scalp over P5 and the cathode was placed extracephalically on the right [96,97]. This montage was chosen to minimize erroneous stimulation of non-targeted cortical areas based on brain modeling (see Brain Modeling; for more details).

Brain Modeling

Stimulation parameters were modeled using Finite Element Models (FEM) within the HD Explore brain modeling software (Soterix Medical, NY, USA). Brain models were obtained based on conductivities from Datta et al., [98]. The brain models for PFA and TPA stimulation were created for 5 x 5 cm sponges (as required by Soterix software). However, since the sponges were reduced to 3 x 3 cm due to the usage of sponge housings, we used a 160-channel EEG cap to measure the number of electrodes that were not targeted by the 3 x 3 cm sponges in order to correct the initial brain models by reducing the number of electrodes stimulated in the brain modeling software to provide the best approximation of the stimulation intensity at each area.

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PFA stimulation reached multiple prefrontal structures, including the left medial prefrontal cortex (lMPFC), dorsolateral prefrontal cortex (lDLPFC), dorsomedial prefrontal cortex (lDMPFC), ventromedial prefrontal cortex (lVMPFC), and anterior cingulate cortex (lACC): Soterix showed an average peak stimulation intensity of 0.34 V/m per 1 mA. For TPA stimulation, structures that received stimulation included the left temporo-parietal junction (lTPJ), left superior temporal sulcus (lSTS), left precuneus (lPRC), and left fusiform face area (lFFA): Soterix showed an average peak stimulation intensity of 0.33 V/m per 1 mA (see **Figure 1** for brain models and **Supplementary Materials** for exact stimulation intensities of each structure).

Although multiple models were evaluated, the electrode montages for PFA and TPA stimulation reported under “tDCS stimulation” demonstrated the greatest peak stimulation intensity over the targeted brain regions, with the least amount of stimulation to non-target brain regions. Specifically, FEM modeling illustrated that using an extracephalic cathodal electrode reduces erroneous stimulation for non-targeted cortical areas in the TPA stimulation condition. It is important to note that although recent evidence suggests that an extracephalic electrode may reduce the magnitude of the stimulation effect when compared to scalp placements [99], this is not the case in the current experiment as FEM models suggest that similar stimulation intensities were achieved for PFA and TPA stimulation (0.34 V/m vs 0.33 V/m per 1 mA).

Figure 1. Brain Models illustrate the field intensities of stimulation in V/m per mA. Darker red areas illustrate higher stimulation intensities compared to blue areas. The circled regions in the Left Lateral pane show the PFA region and the TPA region, respectively. Please see **Figure 1** for brain models and **Supplementary Materials** for exact stimulation intensities of each structure.

Stimuli

Gaze cueing requires participants to detect, locate or identify targets that are looked-at or looked-away from by a gazer [67], which in the current study is either a human (mind perception high) or a robot (mind perception low). In the human condition, the digitized photo of a female face was used as a gazer, which can be found in the Karolinska Directed Emotional Faces database, while in the robot condition the photo of a humanoid robot was used as a gazer (EDDIE; developed by the Technical University of Munich, Germany). The gazing stimuli were 6.4° wide and 10.0° high, depicted on a white background and presented in full frontal orientation with eyes positioned on the central horizontal axis of the screen (**Figure 2**). For left-

and rightward gaze, irises and pupils of the human and the robot gazer were shifted with Photoshop and deviated 0.4° from direct gaze. The target stimulus was a black capital letter (F or T; measuring 0.8° in width and 1.3° in height), which participants had to discriminate by pressing assigned keys on a regular keyboard. The target letters appeared on the horizontal axis of the screen and were located 6.0° left or right from the center of the screen.

Figure 2. Human and Robot Stimuli: the human agent is represented by a female face taken from the Karolinska Directed Emotional Faces (KDEF) database (F07; written informed consent from Karolinska Institute was received to use the photograph for experimental investigations and illustrations). The robot agent is the robot EDDIE (developed at the Technical University of Munich).

Procedure

At the beginning of the experiment, participants gave informed consent and completed the Snellen near-sightedness exam to test their eye vision. They then answered a set of questionnaires to assess their perception of robots from the Godspeed measure [100], attitudes towards robots from the Negative Attitude towards Robots questionnaire [101], and autistic traits from the Autism quotient [102]. Upon completion of the questionnaires, participants were instructed how to perform the gaze cueing task, and were informed that the experiment consisted of two parts: a first part where they would perform the gaze cueing task

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3 without stimulation, and a second part, where they would perform the gaze cueing task under
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5 stimulation, with a break for setting up the tDCS equipment in between.
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8   After completing the baseline block, which took 20 minutes, the researcher started
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10 setting up the tDCS equipment, which took about 10 minutes. As soon as the current reached
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12 its maximum value of 2.0 mA, participants completed a sensation questionnaire to monitor
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14 their comfort levels. They were given an unrelated video-game experience questionnaire
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16 following the first sensation questionnaire. The unrelated video game questionnaire was
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18 administered to ensure that the timing of the stimulation was similar to previous studies that
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20 successfully modulated cognitive processes using tDCS [96,103–106]. This was an important
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22 step as there is no unified standard for the use of tDCS modulation of cognitive tasks [107].
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24 After completing the unrelated videogame questionnaire, participants completed a second
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26 sensation questionnaire. Next, subjects started the stimulation gaze-cueing block, which also
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28 took 20 minutes. After the stimulation gaze-cueing block, a third sensation questionnaire was
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30 administered, the electrodes were removed, the GSM and NARS questionnaire were
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32 administered again, and the participants were debriefed. The timing of the experiment can be
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34 viewed in **Figure 3**.
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Figure 3. Timing of the Experimental Procedure: The experiment started with participants completing the baseline gaze-cueing task. Next the researcher set up the tDCS machine and participants completed a questionnaire about their sensations. The participants then completed a decoy survey, which asked about their video-game experience. Participants then completed a second sensation questionnaire followed by a gaze-cueing task under stimulation. After the stimulation gaze cueing task was completed, a final sensation questionnaire was administered and the tDCS stimulation was stopped (set-up image was adapted from Dayan et al., 2013).

The sequence of events on a given trial of gaze cueing is illustrated in **Figure 4**. The beginning of each trial was signaled by a fixation cross at the center of the screen. Between 700-1000 ms later, one of the agents (i.e., human or robot) appeared on the screen looking straight (and with the fixation cross remaining in its position). After a random time interval of 700-1000 ms, the gazer shifted its gaze either left- or rightwards, which constituted the gaze cue. After a stimulus onset asynchrony (SOA; i.e., time interval between gaze cue and target onset) of 400-600 ms, a target letter (F or T) appeared on the left or the right side of the screen, and participants were asked to respond as fast and accurately as possible to the identity of the

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3 target [67].¹ Gaze cue and target letter remained on the screen until a response was given or
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5 after a timeout of 1200 ms was reached, whichever came first. The next trial started after an
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7 inter-trial-interval (ITI) of 680 ms.
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10 Participants were instructed to fix their gaze on the fixation cross at the beginning of a
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12 trial, and to not make any eye movements during the trial. They were also instructed that after
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14 the fixation cross the image of a social agent would appear in the center of the screen, which
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16 would first look at them (*mutual gaze*), and then after some time make an eye movement to
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18 look to the left or right side of the screen (*averted gaze*). Participants were further advised that
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20 the change in gaze direction would be followed by the appearance of a target letter (F or T),
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22 which would appear either at the gazed-at location or opposite of the gazed-at location.
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24 Participants were asked to indicate as quickly and accurately as possible whether “F” or “T” was
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26 shown on the screen by pressing the respective response key: For one half of the participants
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28 “F” was assigned to the “D” key and “T” to the “K” key on a regular keyboard, while for the
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30 other half of participants stimulus-response mapping was reversed. The original key labels were
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32 covered with a sticker to prevent interference effects with the actual letters on the keyboard.
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34 All instructions were given in written form.
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42 Gaze direction (left, right), target location (left, right), target identity (F, T) and agent
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44 type (human, robot) were selected pseudo-randomly; every combination appeared with equal
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46 frequency throughout the experiment. Gaze direction was manipulated orthogonal to target
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50 ¹ The SOAs were jittered to prevent preparedness effects on the participant’s side. Please note
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52 that this is in line with previous studies (e.g., [55]) and should not affect attentional orienting,
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54 since no qualitative differences in attentional orienting have been reported in this time frame
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56 (i.e., both reflexive and voluntary shifts of attention occur in the 400-600 ms SOA range, and
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58 not inhibition of return effects have been reported) [66].
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location: in half of the trials, the target was validly cued, and in the other half of the trials, the target was invalidly cued. Each experimental session was composed of 220 trials, with a block of 20 practice trials preceding two gaze-cueing blocks of 100 trials of gaze cueing each (i.e., 220 trials for the stimulation baseline and 220 trials for the stimulation block). Participants first completed one block of gaze cueing without stimulation, and were then assigned to either the group that received active stimulation to left PFA or the group that received active stimulation to left TPA. Stimulation was applied for 30 minutes, during which participants completed the second block of gaze cueing.

Figure 4. Sequence of events on a trial of gaze cueing: participants first fixated on a fixation cross for 700-1000 ms and were then presented with the gazing agent (human vs. robot) looking straight for 700-1000 ms, followed by a change in gaze direction (either to the left or right side of the screen). After an SOA of 400-600 ms, the target letter (F or T) appeared either where the face was looking or opposite of where the face was looking. The target remained on the screen until a response was given or a timeout of 1200 ms was reached.

RESULTS

Questionnaires

We used the Godspeed Measure (GSM; [100]) and the Negative Attitude towards Robots Scale (NARS; [101]) to determine whether participants in the two different stimulation conditions differed in their perception of and attitudes towards robots. Both questionnaires were administered at the beginning of the experiment (to capture potential a-priori individual differences), as well as after the completion of the experiment (to assess whether attitudes changed). The short version of the Autism Quotient (AQ-short; [102]) was administered once, at the beginning of the experiment, to measure participants' autistic traits. A 10-point sensation questionnaire was also administered three times to monitor participant's comfort levels during the experiment [96,97]. Participants were told that a reporting a "7" would illustrate unbearable sensations. The questionnaire was administered as soon as stimulation started, before the start of the stimulation block, and after completing the stimulation block. Participants in the PFA and the TPA stimulation did not differ in terms of their perception of robots (GSM; $F(1, 69) = .09$, $p = .75$; $\eta^2 < .001$), attitudes towards robots (NARS; $F(1, 69) = .2$, $p = .65$; $\eta^2 < .01$) or autistic traits (AQ score; $t(69) = -1.66$, $p = .09$). Comparison of the GSM and NARS pre-post ratings did not reveal differences between the two stimulation conditions (GSM: $F(1,69) = 1.19$, $p = .27$, $\eta^2 < .01$; NARS: $F(1,69) = .04$, $p = .84$, $\eta^2 < .001$); see **Tables S1** and **S2** in the **Supplementary Materials** for the full report of the inference statistics. Two participants indicated sensation levels of above "7", which indicated that they were uncomfortable and did not continue the experiment (see participants section).

Behavioral Data

To determine whether active PFA and/or TPA stimulation had a modulatory effect on gaze cueing, we conducted a 2 x 2 x 2 mixed ANOVA on gaze cueing effects (i.e., mean reaction times for invalid - valid trials) with *Agent Type* (human vs. robot) and *Session* (baseline vs. stimulation) as within-participants factors, and *Brain Site* (left PFA vs. TPA) as between-participants factor. The descriptive statistics of this analysis are depicted in **Figure 5**.

Before examining the results of the statistical models, we tested the normality of the residuals using the Kolmogorov-Smirnov test (and not the more commonly used Shapiro-Wilk test as is it not recommended for larger sample sizes; [108,109]). The Kolmogorov-Smirnov test revealed a non-significant effect ($D = .07$, $p = .42$), showing that the residuals of our data did not differ significantly from a normal distribution (i.e., the normality of the residuals assumption of parametric tests was not violated).

The ANOVA revealed no main effect of *Agent Type* ($F(1, 70) = .2$, $p = .64$, $\eta^2 = <.001$), indicating that across stimulation sites and sessions, there were no significant differences in gaze-cueing effects for the human agent compared to the robot agent (Human: 8.22 ms vs. Robot: 7.20 ms). The main effect of *Session* ($F(1, 70) < .001$, $p = .98$, $\eta^2 < .001$) was also not significant, showing that across stimulation sites and agent types gaze cueing effects did not differ between baseline and stimulation (Baseline: 7.69 ms vs. Stimulation: 7.74 ms). The main effect of *Brain Site* ($F(1, 70) < .001$, $p = .98$, $\eta^2 < .001$) was also not significant, showing that across agent types and sessions, no differences in gaze cueing effects were found between the two stimulation sites (PFA: 7.69 ms vs. TPA: 7.74 ms). All two-way interactions were also not significant (*Agent Type* x *Session*: $F(1, 70) = .61$, $p = .43$, $\eta^2 < .001$; *Agent Type* x *Brain Site*: ($F(1,$

70) = 2.24, $p = .13$, $\eta^2 < .01$); *Session* x *Brain Site*: ($F(1, 70) = .17$, $p = .67$, $\eta^2 < .001$). Most importantly, however, the three-way interaction of *Agent Type* x *Session* x *Brain Site* was significant ($F(1, 70) = 4.50$, $p = .03$, $\eta^2 = .12$) indicating that tDCS stimulation affected gaze cueing effects differently for the human versus the robot condition under left PFA but not left TPA stimulation.

To examine the significant three-way interaction effect further, two 2 x 2 post-hoc ANOVAs with *Agent Type* (Human vs. Robot) and *Session* (Baseline vs. Stimulation) were conducted, one for left PFA stimulation and one for left TPA stimulation. The ANOVA for the PFA stimulation condition showed no main effects of *Agent Type* ($F(1, 35) = 2.21$, $p = .14$, $\eta^2 = .01$) or *Session* ($F(1, 35) = .08$, $p = .77$, $\eta^2 < .001$), but a significant *Agent Type* x *Session* interaction ($F(1, 35) = 5.51$, $p = .02$, $\eta^2 = .02$). Post-hoc paired t-tests revealed that there was no significant difference in gaze cueing effects between the human and robot agents at baseline (Human: 7.47 ms vs. Robot: 8.66 ms; $p = .75$), but significantly larger cueing effects for the human versus the robot gazer under stimulation (Human: 12.25 ms vs. Robot: 2.34 ms; $p = .02$). In contrast, the ANOVA for the TPA stimulation condition revealed neither main effects of *Agent Type* ($F(1, 35) = .47$, $p = .49$, $\eta^2 < .01$) or *Session* ($F(1, 35) = .09$, $p = .76$, $\eta^2 < .01$), nor a significant *Agent Type* x *Session* interaction ($F(1, 35) = .72$, $p = .39$, $\eta^2 < .01$). This suggests that while PFA stimulation modulated gaze cueing effects with significantly larger gaze-cueing effects for the human versus the robot agent under stimulation, TPA stimulation did not have such a modulatory effect on gaze cueing (i.e., no differences in gaze cueing at baseline and under stimulation). Post-hoc t-tests were corrected using the false discovery rate procedure (FDR).

A separate 2 x 2 x 2 mixed ANOVA was conducted on accuracy ratings of participants. The ANOVA revealed no significant main effects or interaction effects. See the **Behavioral Results** section of the **Supplementary Materials** for inference statistics. All data and materials can be publicly viewed on <https://osf.io/s8ewg/>.

Figure 5. Gaze-cueing effects (in ms) as a function of *Brain Site* (left PFA, left TPA), *Session* (Baseline, Stimulation), and *Agent Type* (Human, Robot). There was a significant change in gaze cueing for active PFA stimulation, with no differences in gaze cueing between human and robot at baseline, but significantly larger gaze-cueing effects for the human versus the robot agent under stimulation. Active TPA stimulation did not have significant effects on gaze cueing (* $p < .05$).

DISCUSSION

Previous studies have shown that activation in left prefrontal [10,31,43,57,110,111] and temporo-parietal [25,27,43,90] areas is related to mind perception and the modulation of low-level social-cognitive processes like gaze cueing [44,57,58]. The goal of the current experiment was to examine the causal involvement of left prefrontal and left temporo-parietal areas in the top-down modulation of social attention via mind perception. To address this issue, we asked participants to perform a gaze-cueing task with a human and a robot agent (i.e., manipulation of mind perception via physical human-likeness) while applying tDCS to left prefrontal and left temporo-parietal areas. The findings show that stimulating left prefrontal had a modulatory effect on social attention, such that gaze cues of intentional agents (i.e., human) were followed significantly more strongly than gaze cues of machine agents (i.e., robot) under stimulation of prefrontal areas. Left temporo-parietal stimulation, in contrast, did not significantly modulate gaze-cueing effects for either of the two agents. These results are in line with previous studies showing that experimental manipulations of mind perception enhance the degree to which gaze signals are followed [44,54,55]. In particular, it was shown that interpreting gaze signals as intentional or human-controlled augments sensory processing of stimuli presented at gazed-at locations [54], and increases the social relevance of observed gaze signals [53,55,79,112]. The results are also in line with studies showing a correlational relationship between activation in left prefrontal areas related to mind perception and modulation of social attention when performing an orthogonal gaze cueing task outside the fMRI scanner [57], as well as tDCS studies showing that temporo-parietal areas are causally involved in social-cognitive processes

like imitation and perspective taking but might not be causally involved in mind perception [113–115].

The current experiment adds to previous findings by localizing the source of top-down modulation of social attention via mind perception to left prefrontal areas, including areas like the ACC and vmPFC. These areas are associated with mentalizing [14,31], and involved in impression formation in social interaction [116,117]. In particular, activation in MPFC is linked to retrieving stereotypical knowledge about other people [118–120], and associated with retrieving script-based social knowledge [121,122]. Medial prefrontal areas are also more strongly activated when mentalizing about the internal states of similar than dissimilar others [117,123–125], as well as when viewing social scenes that contain human versus nonhuman agents [126]. The current experiment adds to the literature by indicating that prefrontal areas might not only is involved in the modulation of higher-order social-cognitive processes like decision-making [31,43], but might also exert modulatory effects on low-level social cognitive processes like social attention.

Please note that the current experiment does not show the previously reported difference in gaze cueing between human and robot gazer at baseline [55]. This can be due to several reasons: First, in previous experiments, the gazers were introduced as “human” versus “robot” via instruction, which provided participants with explicit labels as to how to treat them in terms of mind perception (i.e., “human/has a mind” and “robot/has no mind”). In contrast, in the current experiment, the gazers were introduced more neutrally as “agents” and their mind status had to be inferred from physical appearance, which makes the mind perception manipulation more implicit. Although this certainly increases the external validity of the

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3 experimental manipulation, it is possible that participants did not pay enough attention to the
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5 gazers' mind status, which could wash out effects between the two agents at baseline. Second,
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7 since mind perception was manipulated via physical appearance in the current experiment, it is
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9 also possible that individual differences in anthropomorphism [89, 90] attenuated differences
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11 in gaze cueing between the human and robot gazer at baseline. However, since baseline effects
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13 are comparable for both stimulation conditions and since the current paper is mainly interested
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15 in the modulation of social attention via mind perception, insignificant differences in gaze
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17 cueing at baseline should not have impacted the reported findings. Nevertheless, in order to
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19 validate the robustness of the reported findings, future experiments should be conducted to
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21 determine to which degree they might be influenced by individual differences in
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23 anthropomorphism.
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31 The question remains why stimulation of left temporo-parietal networks did not
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33 significantly modulate low-level mechanisms of social cognition despite previous reports
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35 showing a correlational relationship between mechanisms of social attention and bilateral TPJ
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37 activation [44]. One explanation for the lack of a significant effect of left temporo-parietal
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39 stimulation on gaze cueing is that it is possible that processes related to mind perception and
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41 social attention are not sufficiently interconnected at the level of the left TPJ in order to exert a
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43 top-down modulatory effect on attentional orienting to gaze cues. This interpretation would be
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45 in line with previous reports showing that social functions within the TPJ are lateralized [17],
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47 and that an overlap between attentional orienting and mentalizing is found within the right but
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49 not left TPJ [11,127,128]. In contrast, left TPJ lesions have been shown to cause selective
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51 deficits in false belief reasoning [89,91], which does require mentalizing but no orientation of
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social attention. In support of this notion, it has been shown that early posterior ERP components like the N170 are sensitive to the intentionality of an agent without being responsive to the congruency or social outcome of its gaze cues [112], whereas later anterior ERP components like the P350 are sensitive to *both* an agent’s intentionality and the congruency of gaze cues [78] (i.e., significant difference in P350 amplitudes for invalid vs. valid trials for human vs. computer-controlled conditions), suggesting that the integration of mind perception related processes and social attention might be instantiated in prefrontal (but not temporo-parietal) areas.

Another possible explanation is that prefrontal and temporo-parietal brain regions might process information about an agent’s mind on different levels, with TPJ activation being related to inferring *particular* internal *states* from observed behaviors [11,19,27,110] (e.g., observing an agent smile leads to the inference that the agent is currently in a state of happiness), and MPFC and VMPFC activation being related to reasoning based on *stereotypical* assumptions regarding general *traits* associated with intentional agents [129] (e.g., agent that looks like a child might like toys). It would be possible that studies that manipulate mind perception via instruction of particular beliefs (i.e., “eye movements are intentional”) engage the posterior mind perception network [44], while studies that manipulate mind perception via physical appearance (i.e., the agent looks human) more strongly activate stereotypical assumptions about human behavior, thereby engaging the anterior mind perception network involving the MPFC and VMPFC [118–120]. This interpretation is particularly plausible given that attentional orienting to gaze cues is a fast-acting process [67], which requires information from a readily available source in order to be top-down controlled. Since stereotypical

information about an agent is more readily available than the outcomes of mentalizing processes about particular internal states, a stronger involvement of prefrontal areas in the top-down modulation of fast processes like social attention seems tenable.

A third explanation is that the observed modulation of gaze cueing is not specific to mind perception, but due to other (related) functions associated with the left prefrontal cortex. One aspect of the experimental design that could have affected social attention in addition to the gazer's physical appearance is the non-predictivity of gaze cues in the current experiment (i.e., targets appear with equal frequency at validly and invalidly cued locations). Previous studies have shown that stimuli whose behavior is hard to predict are more likely anthropomorphized, and that evaluating unpredictable stimuli is associated with increased activation in medial prefrontal areas, and specifically the VMPFC and ACC [49]. In consequence, it is possible that one's sensitivity to the predictability of gaze cues had an impact on the degree to which the gazer was anthropomorphized and prefrontal brain areas were activated during gaze cueing. For the current experiment, this means that stimulating prefrontal areas may have specifically enhanced the social relevance of human gaze cues, leading to longer processing times on invalid trials [78] and larger gaze-cueing effects (i.e., difference in reaction times between invalid and valid trials), while temporo-parietal stimulation may not have affected the perceived social relevance of human gaze cues².

Alternatively, the VMPFC has been shown to track feelings of eeriness towards nonhuman agents in a parametric fashion [129] and has been labeled the potential neural

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² Please note that the conducted a-priori power analysis was based on a small-to-medium effect size, which leaves the possibility that very small-to-small effects might not have been detected with the current sample size.

correlate of the *uncanny valley* [130] (i.e., nonhuman agents with human-like appearance induce feelings of eeriness if they are not perfectly human). If that were the case, stimulation of prefrontal areas could have enhanced feelings of eeriness towards the robotic agent, leading to a disengagement from robot gaze cues together with an increased engagement in attending to human gaze cues (i.e., eeriness of robot cues made human gaze cues more “desirable”). Effects related to non-social prefrontal functions such as working memory, executive functioning or abstract reasoning are less likely to have influenced gaze cueing, since one would expect comparable effects of stimulation for human and nonhuman agents. Whether prefrontal stimulation modulated gaze cueing directly via mind perception or via processes affected by mind perception, such as perception of uncertainty [78] or emotional reactions to uncanny agents [129], cannot ultimately be answered based on the current data and requires follow-up studies. It can also not be clearly determined — due to the lack of spatial specificity of tDCS — which prefrontal brain area(s) ultimately caused the observed top-down modulation of social attention (i.e., areas directly implicated in mind perception such as the left ACC, or areas that are indirectly involved in mind perception such as the left MPFC, VMPFC or DLPFC).

CONCLUSIONS

Previous studies have shown that the degree to which we attend to social cues depends on the degree to which we perceive mind in the entity sending the cues. The neural correlates of mind perception have been localized to prefrontal and temporo-parietal structures in previous studies, but the causal involvement of these areas in the modulation of low-level social-cognitive processes like gaze cueing has not been determined yet. The current study shows that

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3 stimulation to prefrontal areas increases the degree to which human gaze is followed compared
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5 to the degree to which robot gaze is followed, while stimulation to temporo-parietal regions
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7 does not seem to have a measurable modulatory effect on gaze cueing. Since the effect of
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9 prefrontal stimulation is only observable for human gazers, it is tenable that prefrontal
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11 stimulation does not simply lead someone to perceive “more” mind in others, but rather seems
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13 to enhance the social relevance of signals coming from agents “with a mind”. In other words,
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15 prefrontal stimulation does not seem to make participants perceive more human-likeness in
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17 non-human agents, which makes it unlikely that the observed effect is related to
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19 anthropomorphism. Instead, prefrontal stimulation seems to help discriminate agents “with a
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21 mind” from agents “without a mind”, as evidenced by an increased difference in gaze cueing
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23 between the human and the robot gazer under stimulation, indicating that stimulation of
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25 prefrontal areas enhances the importance of social signals coming from human agents. Taken
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27 together, this study shows a causal link between prefrontal stimulation and mechanisms of
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29 social attention, and dissociation between the anterior and posterior part of the social brain
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31 network in terms of top-down modulation of social-cognitive processes. Whether the effect is
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33 specific to mind perception or related to processes indirectly affected by mind perception
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35 needs to be determined in future studies.
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Figure 1. Brain Models illustrate the field intensities of stimulation in V/m per mA. Darker red areas illustrate higher stimulation intensities compared to blue areas. Please see Supplementary Materials for exact stimulation intensities of each structure.

338x190mm (300 x 300 DPI)

Figure 2. Human and Robot Stimuli: the human agent is represented by a female face taken from the Karolinska Directed Emotional Faces (KDEF) database (F07; written informed consent from Karolinska Institute was received to use the photograph for experimental investigations and illustrations). The robot agent is the robot EDDIE (developed at the Technical University of Munich).

84x62mm (300 x 300 DPI)

Figure 3. Timing of the Experimental Procedure: The experiment started with participants completing the baseline gaze-cueing task. Next the researcher set up the tDCS machine and participants completed a questionnaire about their sensations. The participants then completed a decoy survey, which asked about their video-game experience. Participants then completed a second sensation questionnaire followed by a gaze-cueing task under stimulation. After the stimulation gaze cueing task was completed, a final sensation questionnaire was administered and the tDCS stimulation was stopped (set-up image was adapted from Dayan et al., 2013).

270x152mm (300 x 300 DPI)

Figure 4. Sequence of events on a trial of gaze cueing: participants first fixated on a fixation cross for 700-1000 ms and were then presented with the gazing agent (human vs. robot) looking straight for 700-1000 ms, followed by a change in gaze direction (either to the left or right side of the screen). After an SOA of 400-600 ms, the target letter (F or T) appeared either where the face was looking or opposite of where the face was looking. The target remained on the screen until a response was given or a timeout of 1200 ms was reached.

279x215mm (300 x 300 DPI)

Figure 5. Gaze-cueing effects (in ms) as a function of Brain Site (left PF, left TP), Session (Baseline, Stimulation), and Agent Type (Human, Robot). There was a significant change in gaze cueing for active PF stimulation, with no differences in gaze cueing between human and robot at baseline, but significantly larger gaze-cueing effects for the human versus the robot agent under stimulation. Active TP stimulation did not have significant effects on gaze cueing (* $p < .05$).

156x163mm (300 x 300 DPI)

Brain stimulation to left prefrontal cortex modulates attentional orienting to gaze cues

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MEDIA SUMMARY

Social robots are increasingly becoming a part of everyday life, and researchers are confronted with the challenge of how to make them sufficiently social for humans to accept them as social companions. Previous research has shown that the effect of nonverbal signals like changes in gaze direction on social-cognitive processes in human-robot interaction depends on the degree to which the robot is perceived as "having a mind". In using brain stimulation, the paper shows that this modulatory effect of mind perception on social-cognitive processes in human-robot interaction likely originates from left prefrontal brain areas.

ABSTRACT

In social interactions, we rely on nonverbal cues like gaze direction to understand the behavior of others. How we react to these cues is determined by the degree to which we believe that they originate from an entity with a mind capable of having internal states and showing intentional behavior, a process called *mind perception*. While prior work has established a set of neural regions linked to mind perception, research has just begun to examine how mind perception affects social-cognitive mechanisms like gaze processing on a neuronal level. In the current experiment, participants performed a social attention task (i.e., attentional orienting to gaze cues) with either a human or a robot agent (i.e., manipulation of mind perception) while transcranial direct current stimulation (tDCS) was applied to prefrontal and temporo-parietal brain areas. The results show that temporo-parietal stimulation did not modulate mechanisms of social attention, neither in response to the human nor the robot agent, whereas prefrontal stimulation enhanced attentional orienting in response to human gaze cues and attenuated attentional orienting in response to robot gaze cues. The findings suggest that mind perception modulates low-level mechanisms of social cognition via prefrontal structures, and that a certain degree of mind perception is essential in order for prefrontal stimulation to affect mechanisms of social attention.

INTRODUCTION

People are seeing a day-to-day increase in the number of robot agents in their lives that could assist them in various domains [1]. Although evidence of positive outcomes of human-robot interactions exist [2–4], designing social robots that elicit natural human responses can be challenging due to people’s negative perceptions about having social robots be a part of their everyday life [5,6]. To remedy this and design robots that are able to elicit social responses, we must understand how the human brain processes social information in interactions with others and whether nonhuman agents are able to activate these networks to a similar extent as human interaction partners (and if so, under which conditions). Following this approach, we can identify physical and behavioral agent features that reliably activate brain areas involved in social-cognitive processes and investigate whether robots that elicit activation in these networks lead to more acceptance and trust, as well as improved performance in human-robot interaction [58].

_____ Meaningful social interactions require the ability to infer internal states of others, such as intentions (i.e., mentalizing) and emotions (i.e., empathizing) [7], and to use this information to predict future behavior [8]. For that purpose, the human brain is equipped with neural networks specialized in processing information relevant to social interactions (i.e., *social brain*; [8–10]) that involve posterior areas like the temporo-parietal junction (TPJ), the superior temporal sulcus (STS) and the fusiform gyrus (FG), as well as anterior areas like the anterior cingulate cortex (ACC) and the ventromedial and dorsolateral prefrontal cortex (vmPFC, dlPFC) [8,11–16]. TPJ is involved in inferring higher-order action goals [17–25] and mental and spatial perspective taking [22,24,26], while STS and FG are involved in processing biological motion and

face identity, respectively [8,15]. PFC is involved in making inferences about enduring dispositions such as preferences or beliefs [14,23,27,28], and activation in medial PFC is positively correlated with the amount of background knowledge we have about others [18,29]. ACC is activated in social interactions requiring mentalizing in real-time [25,30], and is more strongly activated when interacting with human versus machine agents (i.e., computers; [31]).

Critically for human-robot interaction, most current social robot platforms underactivate the social brain network [31,41,44], which negatively impacts social (e.g., joint attention), emotional (e.g., empathy) and cognitive (e.g., trust) processes that would be essential in order for humans to socially interact with robot agents. Fortunately, for social roboticists, social brain activation depends on the degree to which an interaction partner is perceived as “having a mind” (i.e., *mind perception* [32]), with the general capability of making changes in the environment (i.e., *agency*; [33]), and experiencing internal states, such as emotions and intentions (i.e., *experience*), and as such can presumably be triggered by design. Whereas mind is easily perceived in other human agents [34], the degree to which nonhuman entities like robots trigger mind perception depends on whether their physical and behavioral characteristics are perceived as sufficiently human-like [35–38]. Mind perception is in fact a highly effortless process that activates social brain networks in a bottom–up or reflexive fashion [133–136], triggered by human-like facial features and relations (i.e., spatial arrangement of eye-nose-mouth configurations) [131,132, 134, 135, 137], as well as biological motion and/or predictable behavior [49].

Due to its reflexive nature, mind perception allows observers to differentiate intentional from non-intentional agents within a few hundred milliseconds [135, 136], and even just

passively viewing stimuli that trigger mind perception is sufficient in order to induce activation in a wide range of social brain networks [126], which varies parametrically as a function of the agent's physical human-likeness (i.e., increases as the agent's face or body becomes more human-like in appearance) [57, 84]. Brain areas related to variations in mind perception involve anterior social brain areas, such as the left ACC [12, 25, 43], as well as posterior areas, such as the left TPJ [90]. Left ACC is activated when others are treated as intentional agents [43, 141], and responds more strongly during social decision making tasks that involve intentional versus non-intentional agents [43, 141]; activation within left TPJ is associated with attributing human-likeness and intentionality to non-human agents [138-140], and gray matter volume in left TPJ corresponds to individual differences in anthropomorphizing non-human entities, in particular animals [90]. The degree to which agents trigger mind perception not only modulates activation in social brain areas, it also determines how we feel about them [39-42], behave towards them [31,43-46] and interact with them [47-50], and as such has the potential to impact acceptance, trust and performance in human-robot interactions. Mind perception affects higher-order social-cognitive processes like prosociality, morality and economic decision-making [46,49], and also modulates low-level social-cognitive processes, such as face perception [51] and social attention [52-55]. The effect of mind perception on social cognition is so profound that the mere belief that observed behavior may reflect the actions of an agent "with a mind" makes people interpret pre-programmed behaviors as intentional and motivates them to attune their actions accordingly [44,54-56].

Although the neural link between mind perception and social brain activation [27,57], as well as the behavioral link between mind perception and social-cognitive processes are

relatively well understood [58], research has just begun to examine how mind perception modulates social cognition on a neural level (i.e., activation of which brain areas modulates social cognition as a function of mind perception) [44]. To address this important issue, we use transcranial direct current stimulation (tDCS) to investigate the link between activation of social brain areas implicated in mind perception and low-level social cognitive processes, such as social attention (i.e., the degree to which changes in gaze direction are followed) [67]. TDCS is a non-invasive electrical stimulation technique that can be applied without disrupting the participant during task execution, and has been proven to be effective in modulating a wide range of cognitive processes in previous studies (e.g., memory, attention, decision-making, perception; [59–62]). Social attention, or the tendency to follow changes in others’ gaze direction, was chosen for the present study, as it is a basic, yet essential, social-cognitive mechanism that allows for initiating and coordinating communication [63–65], establishing joint attention between two interaction partners and an object of interest in the environment [66], and an important precursor for developing a theory of mind [66].

Social attention can be examined using a gaze-cueing paradigm, where a face-like stimulus is presented centrally on a screen that first looks straight and then changes gaze direction to the left or right side of the screen. This so-called gaze cue is followed by the presentation of a target stimulus (e.g., F or T) that either appears at the cued location (i.e., valid trial) or an uncued (i.e., invalid trial) location and triggers shifts of the observer’s attention to the gazed-at location. As a result, reaction times on valid trials are usually shorter than reaction times on invalid trials, with the difference in reaction times between invalid and valid conditions constituting the *gaze-cueing effect* [67]. Although it is widely accepted that social

attention has a strong bottom-up component (i.e., attention is shifted reflexively to the cued location; [66]), there is accumulating evidence that it can be top-down controlled by higher-order social-cognitive processes when context information is available that increases the social relevance of observed gaze signals (e.g., gazer is similar or known to the observer; [54,68–77]). With particular relevance to the current [study](#), manipulating the degree to which a gazer is perceived as an intentional being “with a mind” has been shown to modulate social attention, such that gaze-cueing effects are larger in response to human (i.e. intentional) versus machine (i.e., pre-programmed) gazers [54,55,78,79]. That this top-down modulation is [specifically](#) related to mind perception is supported by experiments showing that [although](#) individuals [on the autism spectrum reflexively attend to gaze signals, they do not show the reported](#) enhancement of gaze-cueing effects for human agents but an enhancement in attentional orienting in response to robot gaze cues (potentially due to difficulties with inferring internal states underlying human gaze behavior but an increased interest in machine behavior) [79].

While modulatory effects of mind perception on social attention have been [examined](#) behaviorally [46,48], how mind perception modulates [lower-level social-cognitive mechanisms like gaze cueing](#) at the neuronal level still remains an open question. [In particular, it is unclear whether anterior or posterior parts of the social brain network are more strongly involved in modulating social cognition via mind perception.](#) On the [one](#) hand, [Oezdem et al.](#) showed that believing that an agent’s eye movements are human-controlled (i.e., intentional) [as opposed to](#) pre-programmed (i.e., non-intentional) [modulated](#) activation in bilateral TPJ (but not prefrontal [networks](#)), and enhanced attentional orienting to gaze cues [\[44\]](#). [On the other hand, Wiese et al. showed that although variations in social attention in response to human versus robot](#)

gazers correlated with activation in anterior (i.e., ventromedial PFC) and posterior social brain areas (i.e., TPJ), only activation in bilateral vmPFC correlated with both variations in mind perception and social attention, suggesting that vmPFC might be involved in the top-down control of social attention via mind perception [57]. Taken together, these findings show that although there is convincing evidence that social attention can be modulated via mind perception, the exact source of this modulatory effect still needs to be identified.

To address inconsistencies of previous studies and to examine whether anterior and/or posterior areas of the social brain network implicated in mind perception are causally involved in modulating social attention, in the current study we compare gaze-cueing effects induced by agents “with a mind” (i.e., human) to agents “without a mind” (i.e., robot), with and without tDCS stimulation to left prefrontal and left temporo-parietal areas. This manipulation was chosen for two reasons: First, previous studies showed that sophisticated minds are attributed to agents with human-like appearance but not to agents with a robot-like appearance (i.e., mind ratings increase as a function of physical human-likeness [33,81–83]), which allows us to experimentally manipulate mind perception via physical human-likeness. Second, since mind perception increases activation in social brain networks [84–87] and has been shown to modulate social-cognitive processes like gaze cueing on a behavioral level [55,88], using tDCS in the context of a social attention paradigm seems suitable to investigate the outlined research goal. Left prefrontal and left temporo-parietal areas were chosen as sites for tDCS stimulation for the following reasons: First, both areas have been implicated in mind perception in previous studies [27, 44, 57, 43, 141], and activation in both areas has been shown to correlate with variations in social attention (i.e., gaze cueing) [44, 57]. Second, both areas are located distant

enough from each other to minimize the risk of accidental stimulation of the respective other site during stimulation (i.e., prefrontal vs. temporo-parietal). Third, previous studies suggest that active stimulation is superior to sham stimulation as a control, as it controls for side effects of stimulation that are not directly associated to brain functionality like stimulation sensations, and allows for drawing specific inferences regarding the origin of the modulation in terms of location, as permitting by the low spatial resolution of tDCS targeting [92,93].

METHODS AND MATERIALS

Participants

Eighty-two undergraduate students from George Mason University (57 females, $M = 19.84$, $SD = 2.35$, range: 18-29 years) participated in the current study for course credit. All participants were right-handed, had normal or corrected-to-normal vision, had no known neurological or psychological deficits, were not taking any medications known to affect the central nervous system at the time of the experiment, and had no history of migraines, seizures, or head injuries. All participants provided written consent to participation and were debriefed at the end of the study. Collection and handling of participant data were in accordance with the IRB guidelines (obtained prior to data collection). Data of participants whose accuracy rate in the gaze cueing task during baseline was below 85% (6 participants), who did not follow the instructions properly (2 participants), or did not complete the study (2 participants) were excluded from data analysis (13% of participants in total). The remaining 72 participants were quasi-randomly assigned to the experimental condition, that is: active stimulation of the left *prefrontal cortex* ([PFA](#); $n = 36$, 23 females), or the control condition, that is: stimulation of the

left *temporo-parietal cortex* (**TPA**; $n = 36$, 27 females). To determine the sample size needed for the study, an a priori power analysis was conducted in G*power for a mixed-effects repeated measures design (i.e., one between factor and one within factor). Since mixed-effects repeated measures designs in G*power can only handle two-factorial designs, the sample size was determined for an ANOVA with a 2-level between factor and a 4-level within factor (i.e., the two within variables were combined). The analysis was based on an alpha of ($\alpha = .05$), the power set to ($1 - \beta = .95$), and the assumption of a small-to-medium effect size (Cohen's $d = .17$). The analysis showed that an approximate sample size of 76 participants would be sufficient for both experimental groups. Since the current version of G*power cannot test for a 3-way factorial design but only a 2-way factorial design, another power analysis was conducted using R for the general linear model, which is a more generic test. The analysis was done for a 2x2x2 factorial model that contains three main effects and their interactions (i.e., three 2-way interactions and one 3-way interaction) using the same alpha ($\alpha = .05$), beta ($1 - \beta = .95$), and effect size (Cohen's $d = .17$) as the previous analysis. The analysis for the general linear model revealed that the study needed a total of 83 participants.

Apparatus

Stimuli were presented on a Dell 1703FP monitor with the refresh rate set at 85 Hz. RT measures were based on standard keyboard responses. Participants were seated approximately 57 cm from the monitor, and the experimenter ensured that participants were centered with respect to the monitor. The experiment was controlled by *Experiment Builder* (SR Research Ltd., Ontario, Canada).

TDCS stimulation

An ActivaDose II, ActivaTek system was used to administer the 2mA stimulation. Although there is not a universal and ideal level of current stimulation for any one montage, we selected 2mA because it is a commonly used level that is within human safety limits [94]. Electrode placement followed the 10–5 EEG system [95], and tDCS was delivered via two 5 × 5 cm saline soaked sponges in rubber housing (resulting in a sponge contact area of 3 × 3 cm). For PFA stimulation, the anode was placed on the scalp over F9 and the cathode was placed over Fz. For TPA stimulation, the anode was placed on the scalp over P5 and the cathode was placed extracephalically on the right [96,97]. This montage was chosen to minimize erroneous stimulation of non-targeted cortical areas based on brain modeling (see Brain Modeling; for more details).

Brain Modeling

Stimulation parameters were modeled using Finite Element Models (FEM) within the HD Explore brain modeling software (Soterix Medical, NY, USA). Brain models were obtained based on conductivities from Datta et al., [98]. The brain models for PFA and TPA stimulation were created for 5 x 5 cm sponges (as required by Soterix software). However, since the sponges were reduced to 3 x 3 cm due to the usage of sponge housings, we used a 160-channel EEG cap to measure the number of electrodes that were not targeted by the 3 x 3 cm sponges in order to correct the initial brain models by reducing the number of electrodes stimulated in the brain modeling software to provide the best approximation of the stimulation intensity at each area.

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[PFA](#) stimulation reached multiple prefrontal structures, including the left medial prefrontal cortex (lMPFC), dorsolateral prefrontal cortex (lDLPFC), dorsomedial prefrontal cortex (lDMPFC), ventromedial prefrontal cortex (lVMPFC), and anterior cingulate cortex (lACC): Soterix showed an average peak stimulation intensity of 0.34 V/m per 1 mA. For [TPA](#) stimulation, structures that received stimulation included the left temporo-parietal junction (lTPJ), left superior temporal sulcus (lSTS), left precuneus (lPRC), and left fusiform face area (lFFA): Soterix showed an average peak stimulation intensity of 0.33 V/m per 1 mA (see **Figure 1** for brain models and **Supplementary Materials** for exact stimulation intensities of each structure).

Although multiple models were evaluated, the electrode montages for [PFA](#) and [TPA](#) stimulation reported under “tDCS stimulation” demonstrated the greatest peak stimulation intensity over the targeted brain regions, with the least amount of stimulation to non-target brain regions. Specifically, FEM modeling illustrated that using an extracephalic cathodal electrode reduces erroneous stimulation for non-targeted cortical areas in the [TPA](#) stimulation condition. It is important to note that although recent evidence suggests that an extracephalic electrode may reduce the magnitude of the stimulation effect when compared to scalp placements [99], this is not the case in the current experiment as FEM models suggest that similar stimulation intensities were achieved for [PFA](#) and [TPA](#) stimulation (0.34 V/m vs 0.33 V/m per 1 mA).

Figure 1. Brain Models illustrate the field intensities of stimulation in V/m per mA. Darker red areas illustrate higher stimulation intensities compared to blue areas. The circled regions in the Left Lateral pane show the PFA region and the TPA region, respectively. Please see **Figure 1** for brain models and **Supplementary Materials** for exact stimulation intensities of each structure.

Stimuli

Gaze cueing requires participants to detect, locate or identify targets that are looked-at or looked-away from by a gazer [67], which in the current study is either a human (mind perception high) or a robot (mind perception low). In the human condition, the digitized photo of a female face was used as a gazer, which can be found in the Karolinska Directed Emotional Faces database, while in the robot condition the photo of a humanoid robot was used as a gazer (EDDIE; developed by the Technical University of Munich, Germany). The gazing stimuli were 6.4° wide and 10.0° high, depicted on a white background and presented in full frontal orientation with eyes positioned on the central horizontal axis of the screen (**Figure 2**). For left-

and rightward gaze, irises and pupils of the human and the robot gazer were shifted with Photoshop and deviated 0.4° from direct gaze. The target stimulus was a black capital letter (F or T; measuring 0.8° in width and 1.3° in height), which participants had to discriminate by pressing assigned keys on a regular keyboard. The target letters appeared on the horizontal axis of the screen and were located 6.0° left or right from the center of the screen.

Figure 2. Human and Robot Stimuli: the human agent is represented by a female face taken from the Karolinska Directed Emotional Faces (KDEF) database (F07; written informed consent from Karolinska Institute was received to use the photograph for experimental investigations and illustrations). The robot agent is the robot EDDIE (developed at the Technical University of Munich).

Procedure

At the beginning of the experiment, participants gave informed consent and completed the Snellen near-sightedness exam to test their eye vision. They then answered a set of questionnaires to assess their perception of robots from the Godspeed measure [100], attitudes towards robots from the Negative Attitude towards Robots questionnaire [101], and autistic traits from the Autism quotient [102]. Upon completion of the questionnaires, participants were instructed how to perform the gaze cueing task, and were informed that the experiment consisted of two parts: a first part where they would perform the gaze cueing task

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3 without stimulation, and a second part, where they would perform the gaze cueing task under
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5 stimulation, with a break for setting up the tDCS equipment in between.
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8   After completing the baseline block, which took 20 minutes, the researcher started
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10 setting up the tDCS equipment, which took about 10 minutes. As soon as the current reached
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12 its maximum value of 2.0 mA, participants completed a sensation questionnaire to monitor
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14 their comfort levels. They were given an unrelated video-game experience questionnaire
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16 following the first sensation questionnaire. The unrelated video game questionnaire was
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18 administered to ensure that the timing of the stimulation was similar to previous studies that
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20 successfully modulated cognitive processes using tDCS [96,103–106]. This was an important
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22 step as there is no unified standard for the use of tDCS modulation of cognitive tasks [107].
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24 After completing the unrelated videogame questionnaire, participants completed a second
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26 sensation questionnaire. Next, subjects started the stimulation gaze-cueing block, which also
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28 took 20 minutes. After the stimulation gaze-cueing block, a third sensation questionnaire was
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30 administered, the electrodes were removed, the GSM and NARS questionnaire were
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32 administered again, and the participants were debriefed. The timing of the experiment can be
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34 viewed in **Figure 3**.
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Figure 3. Timing of the Experimental Procedure: The experiment started with participants completing the baseline gaze-cueing task. Next the researcher set up the tDCS machine and participants completed a questionnaire about their sensations. The participants then completed a decoy survey, which asked about their video-game experience. Participants then completed a second sensation questionnaire followed by a gaze-cueing task under stimulation. After the stimulation gaze cueing task was completed, a final sensation questionnaire was administered and the tDCS stimulation was stopped (set-up image was adapted from Dayan et al., 2013).

The sequence of events on a given trial of gaze cueing is illustrated in **Figure 4**. The beginning of each trial was signaled by a fixation cross at the center of the screen. Between 700-1000 ms later, one of the agents (i.e., human or robot) appeared on the screen looking straight (and with the fixation cross remaining in its position). After a random time interval of 700-1000 ms, the gazer shifted its gaze either left- or rightwards, which constituted the gaze cue. After a stimulus onset asynchrony (SOA; i.e., time interval between gaze cue and target onset) of 400-600 ms, a target letter (F or T) appeared on the left or the right side of the screen, and participants were asked to respond as fast and accurately as possible to the identity of the

target [67].¹ Gaze cue and target letter remained on the screen until a response was given or after a timeout of 1200 ms was reached, whichever came first. The next trial started after an inter-trial-interval (ITI) of 680 ms.

Participants were instructed to fix their gaze on the fixation cross at the beginning of a trial, and to not make any eye movements during the trial. They were also instructed that after the fixation cross the image of a social agent would appear in the center of the screen, which would first look at them (*mutual gaze*), and then after some time make an eye movement to look to the left or right side of the screen (*averted gaze*). Participants were further advised that the change in gaze direction would be followed by the appearance of a target letter (F or T), which would appear either at the gazed-at location or opposite of the gazed-at location. Participants were asked to indicate as quickly and accurately as possible whether “F” or “T” was shown on the screen by pressing the respective response key: For one half of the participants “F” was assigned to the “D” key and “T” to the “K” key on a regular keyboard, while for the other half of participants stimulus-response mapping was reversed. The original key labels were covered with a sticker to prevent interference effects with the actual letters on the keyboard. All instructions were given in written form.

Gaze direction (left, right), target location (left, right), target identity (F, T) and agent type (human, robot) were selected pseudo-randomly; every combination appeared with equal frequency throughout the experiment. Gaze direction was manipulated orthogonal to target

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¹ The SOAs were jittered to prevent preparedness effects on the participant’s side. Please note that this is in line with previous studies (e.g., [55]) and should not affect attentional orienting, since no qualitative differences in attentional orienting have been reported in this time frame (i.e., both reflexive and voluntary shifts of attention occur in the 400-600 ms SOA range, and not inhibition of return effects have been reported) [66].

location: in half of the trials, the target was validly cued, and in the other half of the trials, the target was invalidly cued. Each experimental session was composed of 220 trials, with a block of 20 practice trials preceding two gaze-cueing blocks of 100 trials of gaze cueing each (i.e., 220 trials for the stimulation baseline and 220 trials for the stimulation block). Participants first completed one block of gaze cueing without stimulation, and were then assigned to either the group that received active stimulation [to](#) left PFA or the group that received active stimulation [to](#) left TPA. Stimulation was applied for 30 minutes, during which participants completed the second block of gaze cueing.

Figure 4. Sequence of events on a trial of gaze cueing: participants first fixated on a fixation cross for 700-1000 ms and were then presented with the gazing agent (human vs. robot) looking straight for 700-1000 ms, followed by a change in gaze direction (either to the left or right side of the screen). After an SOA of 400-600 ms, the target letter (F or T) appeared either where the face was looking or opposite of where the face was looking. The target remained on the screen until a response was given or a timeout of 1200 ms was reached.

RESULTS

Questionnaires

We used the Godspeed Measure (GSM; [100]) and the Negative Attitude towards Robots Scale (NARS; [101]) to determine whether participants in the two different stimulation conditions differed in their perception of and attitudes towards robots. Both questionnaires were administered at the beginning of the experiment (to capture potential a-priori individual differences), as well as after the completion of the experiment (to assess whether attitudes changed). The short version of the Autism Quotient (AQ-short; [102]) was administered once, at the beginning of the experiment, to measure participants' autistic traits. A 10-point sensation questionnaire was also administered three times to monitor participant's comfort levels during the experiment [96,97]. Participants were told that a reporting a "7" would illustrate unbearable sensations. The questionnaire was administered as soon as stimulation started, before the start of the stimulation block, and after completing the stimulation block.

Participants in the PFA and the TPA stimulation did not differ in terms of their perception of robots (GSM; $F(1, 69) = .09$, $p = .75$; $\eta^2 < .001$), attitudes towards robots (NARS; $F(1, 69) = .2$, $p = .65$; $\eta^2 < .01$) or autistic traits (AQ score; $t(69) = -1.66$, $p = .09$). Comparison of the GSM and NARS pre-post ratings did not reveal differences between the two stimulation conditions (GSM: $F(1,69) = 1.19$, $p = .27$, $\eta^2 < .01$; NARS: $F(1,69) = .04$, $p = .84$, $\eta^2 < .001$); see **Tables S1** and **S2** in the **Supplementary Materials** for the full report of the inference statistics. Two participants indicated sensation levels of above "7", which indicated that they were uncomfortable and did not continue the experiment (see participants section).

Behavioral Data

To determine whether active PFA and/or TPA stimulation had a modulatory effect on gaze cueing, we conducted a 2 x 2 x 2 mixed ANOVA on gaze cueing effects (i.e., mean reaction times for invalid - valid trials) with *Agent Type* (human vs. robot) and *Session* (baseline vs. stimulation) as within-participants factors, and *Brain Site* (left PFA vs. TPA) as between-participants factor. The descriptive statistics of this analysis are depicted in **Figure 5**.

Before examining the results of the statistical models, we tested the normality of the residuals using the Kolmogorov-Smirnov test (and not the more commonly used Shapiro-Wilk test as is it not recommended for larger sample sizes; [108,109]). The Kolmogorov-Smirnov test revealed a non-significant effect ($D = .07$, $p = .42$), showing that the residuals of our data did not differ significantly from a normal distribution (i.e., the normality of the residuals assumption of parametric tests was not violated).

The ANOVA revealed no main effect of *Agent Type* ($F(1, 70) = .2$, $p = .64$, $\eta^2 = <.001$), indicating that across stimulation sites and sessions, there were no significant differences in gaze-cueing effects for the human agent compared to the robot agent (Human: 8.22 ms vs. Robot: 7.20 ms). The main effect of *Session* ($F(1, 70) < .001$, $p = .98$, $\eta^2 < .001$) was also not significant, showing that across stimulation sites and agent types gaze cueing effects did not differ between baseline and stimulation (Baseline: 7.69 ms vs. Stimulation: 7.74 ms). The main effect of *Brain Site* ($F(1, 70) < .001$, $p = .98$, $\eta^2 < .001$) was also not significant, showing that across agent types and sessions, no differences in gaze cueing effects were found between the two stimulation sites (PFA: 7.69 ms vs. TPA: 7.74 ms). All two-way interactions were also not significant (*Agent Type* x *Session*: $F(1, 70) = .61$, $p = .43$, $\eta^2 < .001$; *Agent Type* x *Brain Site*: ($F(1,$

70) = 2.24, $p = .13$, $\eta^2 < .01$); *Session* x *Brain Site*: ($F(1, 70) = .17$, $p = .67$, $\eta^2 < .001$). Most importantly, however, the three-way interaction of *Agent Type* x *Session* x *Brain Site* was significant ($F(1, 70) = 4.50$, $p = .03$, $\eta^2 = .12$) indicating that tDCS stimulation affected gaze cueing effects differently for the human versus the robot condition under left PFA but not left TPA stimulation.

To examine the significant three-way interaction effect further, two 2 x 2 post-hoc ANOVAs with *Agent Type* (Human vs. Robot) and *Session* (Baseline vs. Stimulation) were conducted, one for left PFA stimulation and one for left TPA stimulation. The ANOVA for the PFA stimulation condition showed no main effects of *Agent Type* ($F(1, 35) = 2.21$, $p = .14$, $\eta^2 = .01$) or *Session* ($F(1, 35) = .08$, $p = .77$, $\eta^2 < .001$), but a significant *Agent Type* x *Session* interaction ($F(1, 35) = 5.51$, $p = .02$, $\eta^2 = .02$). Post-hoc paired t-tests revealed that there was no significant difference in gaze cueing effects between the human and robot agents at baseline (Human: 7.47 ms vs. Robot: 8.66 ms; $p = .75$), but significantly larger cueing effects for the human versus the robot gazer under stimulation (Human: 12.25 ms vs. Robot: 2.34 ms; $p = .02$). In contrast, the ANOVA for the TPA stimulation condition revealed neither main effects of *Agent Type* ($F(1, 35) = .47$, $p = .49$, $\eta^2 < .01$) or *Session* ($F(1, 35) = .09$, $p = .76$, $\eta^2 < .01$), nor a significant *Agent Type* x *Session* interaction ($F(1, 35) = .72$, $p = .39$, $\eta^2 < .01$). This suggests that while PFA stimulation modulated gaze cueing effects with significantly larger gaze-cueing effects for the human versus the robot agent under stimulation, TPA stimulation did not have such a modulatory effect on gaze cueing (i.e., no differences in gaze cueing at baseline and under stimulation). Post-hoc t-tests were corrected using the false discovery rate procedure (FDR).

A separate 2 x 2 x 2 mixed ANOVA was conducted on accuracy ratings of participants. The ANOVA revealed no significant main effects or interaction effects. See the **Behavioral Results** section of the **Supplementary Materials** for inference statistics. All data and materials can be publicly viewed on <https://osf.io/s8ewg/>.

Figure 5. Gaze-cueing effects (in ms) as a function of *Brain Site* (left PFA, left TPA), *Session* (Baseline, Stimulation), and *Agent Type* (Human, Robot). There was a significant change in gaze cueing for active PFA stimulation, with no differences in gaze cueing between human and robot at baseline, but significantly larger gaze-cueing effects for the human versus the robot agent under stimulation. Active TPA stimulation did not have significant effects on gaze cueing (* $p < .05$).

DISCUSSION

Previous studies have shown that activation in left prefrontal [10,31,43,57,110,111] and temporo-parietal [25,27,43,90] areas is related to mind perception and the modulation of low-level social-cognitive processes like gaze cueing [44,57,58]. The goal of the current experiment was to examine the causal involvement of left prefrontal and left temporo-parietal areas in the top-down modulation of social attention via mind perception. To address this issue, we asked participants to perform a gaze-cueing task with a human and a robot agent (i.e., manipulation of mind perception via physical human-likeness) while applying tDCS to left prefrontal and left temporo-parietal areas. The findings show that stimulating left prefrontal had a modulatory effect on social attention, such that gaze cues of intentional agents (i.e., human) were followed significantly more strongly than gaze cues of machine agents (i.e., robot) under stimulation of prefrontal areas. Left temporo-parietal stimulation, in contrast, did not significantly modulate gaze-cueing effects for either of the two agents. These results are in line with previous studies showing that experimental manipulations of mind perception enhance the degree to which gaze signals are followed [44,54,55]. In particular, it was shown that interpreting gaze signals as intentional or human-controlled augments sensory processing of stimuli presented at gazed-at locations [54], and increases the social relevance of observed gaze signals [53,55,79,112]. The results are also in line with studies showing a correlational relationship between activation in left prefrontal areas related to mind perception and modulation of social attention when performing an orthogonal gaze cueing task outside the fMRI scanner [57], as well as tDCS studies showing that temporo-parietal areas are causally involved in social-cognitive processes

like imitation and perspective taking but might not be causally involved in mind perception [113–115].

The current experiment adds to previous findings by localizing the source of top-down modulation of social attention via mind perception to left prefrontal areas, including areas like the ACC and vmPFC. These areas are associated with mentalizing [14,31], and involved in impression formation in social interaction [116,117]. In particular, activation in MPFC is linked to retrieving stereotypical knowledge about other people [118–120], and associated with retrieving script-based social knowledge [121,122]. Medial prefrontal areas are also more strongly activated when mentalizing about the internal states of similar than dissimilar others [117,123–125], as well as when viewing social scenes that contain human versus nonhuman agents [126]. The current experiment adds to the literature by indicating that prefrontal areas might not only is involved in the modulation of higher-order social-cognitive processes like decision-making [31,43], but might also exert modulatory effects on low-level social cognitive processes like social attention.

Please note that the current experiment does not show the previously reported difference in gaze cueing between human and robot gazer at baseline [55]. This can be due to several reasons: First, in previous experiments, the gazers were introduced as “human” versus “robot” via instruction, which provided participants with explicit labels as to how to treat them in terms of mind perception (i.e., “human/has a mind” and “robot/has no mind”). In contrast, in the current experiment, the gazers were introduced more neutrally as “agents” and their mind status had to be inferred from physical appearance, which makes the mind perception manipulation more implicit. Although this certainly increases the external validity of the

experimental manipulation, it is possible that participants did not pay enough attention to the gazers' mind status, which could wash out effects between the two agents at baseline. Second, since mind perception was manipulated via physical appearance in the current experiment, it is also possible that individual differences in anthropomorphism [89, 90] attenuated differences in gaze cueing between the human and robot gazer at baseline. However, since baseline effects are comparable for both stimulation conditions and since the current paper is mainly interested in the modulation of social attention via mind perception, insignificant differences in gaze cueing at baseline should not have impacted the reported findings. Nevertheless, in order to validate the robustness of the reported findings, future experiments should be conducted to determine to which degree they might be influenced by individual differences in anthropomorphism.

The question remains why stimulation of left temporo-parietal networks did not significantly modulate low-level mechanisms of social cognition despite previous reports showing a correlational relationship between mechanisms of social attention and bilateral TPJ activation [44]. One explanation for the lack of a significant effect of left temporo-parietal stimulation on gaze cueing is that it is possible that processes related to mind perception and social attention are not sufficiently interconnected at the level of the left TPJ in order to exert a top-down modulatory effect on attentional orienting to gaze cues. This interpretation would be in line with previous reports showing that social functions within the TPJ are lateralized [17], and that an overlap between attentional orienting and mentalizing is found within the right but not left TPJ [11,127,128]. In contrast, left TPJ lesions have been shown to cause selective deficits in false belief reasoning [89,91], which does require mentalizing but no orientation of

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3 social attention. In support of this notion, it has been shown that early posterior ERP
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5 components like the N170 are sensitive to the intentionality of an agent without being
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7 responsive to the congruency or social outcome of its gaze cues [112], whereas later anterior
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9 ERP components like the P350 are sensitive to *both* an agent’s intentionality and the
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11 congruency of gaze cues [78] (i.e., significant difference in P350 amplitudes for invalid vs. valid
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13 trials for human vs. computer-controlled conditions), suggesting that the integration of mind
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15 perception related processes and social attention might be instantiated in prefrontal (but not
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17 temporo-parietal) areas.
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23 Another possible explanation is that prefrontal and temporo-parietal brain regions
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25 might process information about an agent’s mind on different levels, with TPJ activation being
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27 related to inferring *particular* internal *states* from observed behaviors [11,19,27,110] (e.g.,
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29 observing an agent smile leads to the inference that the agent is currently in a state of
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31 happiness), and MPFC and VMPFC activation being related to reasoning based on *stereotypical*
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33 assumptions regarding general *traits* associated with intentional agents [129] (e.g., agent that
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35 looks like a child might like toys). It would be possible that studies that manipulate mind
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37 perception via instruction of particular beliefs (i.e., “eye movements are intentional”) engage
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39 the posterior mind perception network [44], while studies that manipulate mind perception via
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41 physical appearance (i.e., the agent looks human) more strongly activate stereotypical
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43 assumptions about human behavior, thereby engaging the anterior mind perception network
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45 involving the MPFC and VMPFC [118–120]. This interpretation is particularly plausible given
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47 that attentional orienting to gaze cues is a fast-acting process [67], which requires information
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49 from a readily available source in order to be top-down controlled. Since stereotypical
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information about an agent is more readily available than the outcomes of mentalizing processes about particular internal states, a stronger involvement of prefrontal areas in the top-down modulation of fast processes like social attention seems tenable.

A third explanation is that the observed modulation of gaze cueing is not specific to mind perception, but due to other (related) functions associated with the left prefrontal cortex. One aspect of the experimental design that could have affected social attention in addition to the gazer's physical appearance is the non-predictivity of gaze cues in the current experiment (i.e., targets appear with equal frequency at validly and invalidly cued locations). Previous studies have shown that stimuli whose behavior is hard to predict are more likely anthropomorphized, and that evaluating unpredictable stimuli is associated with increased activation in medial prefrontal areas, and specifically the VMPFC and ACC [49]. In consequence, it is possible that one's sensitivity to the predictability of gaze cues had an impact on the degree to which the gazer was anthropomorphized and prefrontal brain areas were activated during gaze cueing. For the current experiment, this means that stimulating prefrontal areas may have specifically enhanced the social relevance of human gaze cues, leading to longer processing times on invalid trials [78] and larger gaze-cueing effects (i.e., difference in reaction times between invalid and valid trials), while temporo-parietal stimulation may not have affected the perceived social relevance of human gaze cues².

Alternatively, the VMPFC has been shown to track feelings of eeriness towards nonhuman agents in a parametric fashion [129] and has been labeled the potential neural

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² Please note that the conducted a-priori power analysis was based on a small-to-medium effect size, which leaves the possibility that very small-to-small effects might not have been detected with the current sample size.

correlate of the *uncanny valley* [130] (i.e., nonhuman agents with human-like appearance induce feelings of eeriness if they are not perfectly human). If that were the case, stimulation of prefrontal areas could have enhanced feelings of eeriness towards the robotic agent, leading to a disengagement from robot gaze cues together with an increased engagement in attending to human gaze cues (i.e., eeriness of robot cues made human gaze cues more “desirable”). Effects related to non-social prefrontal functions such as working memory, executive functioning or abstract reasoning are less likely to have influenced gaze cueing, since one would expect comparable effects of stimulation for human and nonhuman agents. Whether prefrontal stimulation modulated gaze cueing directly via mind perception or via processes affected by mind perception, such as perception of uncertainty [78] or emotional reactions to uncanny agents [129], cannot ultimately be answered based on the current data and requires follow-up studies. It can also not be clearly determined — due to the lack of spatial specificity of tDCS — which prefrontal brain area(s) ultimately caused the observed top-down modulation of social attention (i.e., areas directly implicated in mind perception such as the left ACC, or areas that are indirectly involved in mind perception such as the left MPFC, VMPFC or DLPFC).

CONCLUSIONS

Previous studies have shown that the degree to which we attend to social cues depends on the degree to which we perceive mind in the entity sending the cues. The neural correlates of mind perception have been localized to prefrontal and temporo-parietal structures in previous studies, but the causal involvement of these areas in the modulation of low-level social-cognitive processes like gaze cueing has not been determined yet. The current study shows that

stimulation to prefrontal areas increases the degree to which human gaze is followed compared to the degree to which robot gaze is followed, while stimulation to temporo-parietal regions does not seem to have a measurable modulatory effect on gaze cueing. Since the effect of prefrontal stimulation is only observable for human gazers, it is tenable that prefrontal stimulation does not simply lead someone to perceive “more” mind in others, but rather seems to enhance the social relevance of signals coming from agents “with a mind”. In other words, prefrontal stimulation does not seem to make participants perceive more human-likeness in non-human agents, which makes it unlikely that the observed effect is related to anthropomorphism. Instead, prefrontal stimulation seems to help discriminate agents “with a mind” from agents “without a mind”, as evidenced by an increased difference in gaze cueing between the human and the robot gazer under stimulation, indicating that stimulation of prefrontal areas enhances the importance of social signals coming from human agents. Taken together, this study shows a causal link between prefrontal stimulation and mechanisms of social attention, and dissociation between the anterior and posterior part of the social brain network in terms of top-down modulation of social-cognitive processes. Whether the effect is specific to mind perception or related to processes indirectly affected by mind perception needs to be determined in future studies.

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