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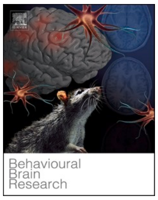

Research report

The contribution of the supplementary motor area to explicit and implicit timing: A high-definition transcranial Random Noise Stimulation (HD-tRNS) study

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ABSTRACT

It is becoming increasingly accepted that timing tasks, and underlying temporal processes, can be partitioned on the basis of whether they require an explicit or implicit temporal judgement. Most neuroimaging studies of timing associated explicit timing tasks with activation of the supplementary motor area (SMA). However, transcranial magnetic stimulation (TMS) studies perturbing SMA functioning across explicit timing tasks have generally reported null effects, thus failing to causally link SMA to explicit timing. The present study probed the involvement of SMA in both explicit and implicit timing tasks within a single experiment and using High-Definition transcranial Random Noise Stimulation (HD-tRNS), a previously less used technique in studies of the SMA. Participants performed two tasks that comprised the same stimulus presentation but differed in the received task instructions, which might or might not require explicit temporal judgments. Results showed a significant HD-tRNS-induced shift of perceived durations (i.e., overestimation) in the explicit timing task, whereas there was no modulation of implicit timing by HD-tRNS. Overall, these results provide initial non-invasive brain stimulation evidence on the contribution of the SMA to explicit and implicit timing tasks.

1. Introduction

The ability to process time in the millisecond-to-seconds range is critical to virtually all of our daily-life activities, such as driving, dancing, playing sports, and music. Considerable controversy, however, remains on how the brain measures time in this temporal range, with some theories positing the existence of dedicated timing networks hosting an internal “clock” [1-3], and others arguing for the distribution of timing across neural circuits [4]. What, instead, seems more consistent across neuroimaging studies of time is the involvement of the supplementary motor area (SMA) in timing tasks. For example, one meta-analysis of fMRI experiments reported a significant association of SMA activity with temporal processing regardless of the nature (motor or non-motor) of the timing tasks and the duration (subsecond or suprasecond) of the intervals to be timed [5], a finding confirmed by additional meta-analyses [6-8].

A critical taxonomy that is also gaining prominence in the temporal literature fractionates timing tasks, and underlying cognitive processes, into *explicit* and *implicit* types, according to whether task goals entail explicit or implicit temporal judgments [9]. The question of whether the SMA is equally involved in both forms of timing is still elusive.

In explicit timing tasks, participants are instructed to attend to stimulus duration, which itself is the main focus of the task. For example, explicit timing tasks include the time bisection task, in which participants are first trained on a “short standard” and a “long standard” duration and then required to classify some intermediate durations as being more similar to the short or to the long standard ([10,11]; see also [12]). A variant of the time bisection task, described below, was our measure of explicit timing.

Unlike explicit timing tasks, implicit timing tasks do not require any

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overt temporal judgment, but because timing is incidental to the (non-temporal) task to be performed, its processing will nonetheless shape behaviour. One example of implicit timing tasks is a simple reaction time (RT) task in which a target is separated from a warning signal by time intervals (i.e., foreperiod) of variable durations (i.e., the "variable foreperiod task"; [13-16]). Participants are not asked to judge the duration of the foreperiod, but to simply make a fast response to the target onset. However, in a design with equally probable foreperiods, if the target does not occur at the shortest foreperiod, the probability that it will occur at the longest foreperiod reaches 100%. Implicitly exploiting the passage of time will hence shorten RTs at the longest foreperiod trials, an effect known as "the foreperiod effect". The foreperiod effect is formally described by the hazard function, that is, the conditional probability that an event will occur given that it has not yet occurred [17-20]. The foreperiod effect was our measure of implicit timing (e.g., [21-23]).

According to Coull and Nobre's [9] original review of neuroimaging studies, explicit timing is preferentially associated with basal ganglia, right prefrontal cortex, cerebellar, and SMA areas, whereas implicit timing with left inferior parietal cortex and premotor areas. Support for the specific involvement of the SMA in explicit timing comes from the above-mentioned meta-analysis by Wiener et al. [5], reporting significant SMA activity in all of the included explicit timing tasks. Furthermore, a follow-up meta-analysis by the same group on implicit timing tasks confirmed the preferential involvement of the left inferior parietal cortex in implicit timing [24]. In contrast to these findings, other meta-analyses of neuroimaging studies related SMA activity to both explicit and implicit temporal processes [6,25,8]. For example, Nani et al. [6] showed that the SMA was the only brain area with the greatest overlap (100%) in a conjunction analysis of all the explicit and implicit timing conditions considered in their meta-analysis (i.e., motor and non-motor, below or above the 1-sec range). This result aligns well with further fMRI data showing increased SMA activity during foreperiod tasks ([26,27]; see also [28]). There is also evidence that the SMA is a fundamental "hub" of a cortico-basal-thalamo-cortical network involved in the internal (implicit) timing of voluntary planning/execution in complex sequences, such as speech (see [29,30]).

Summarizing the main neuroimaging findings introduced above, the involvement of the SMA seems to be less controversial for explicit than implicit timing. However, the picture of explicit timing and SMA drastically changes when moving from neuroimaging studies to non-invasive brain stimulation ones. Indeed, a causal role for the SMA in explicit timing has been found so far either weak (i.e., effects restricted to participants' variability or sensitivity to interval duration without changes in accuracy; [31,32], respectively) or not at all support [33-36] in transcranial magnetic stimulation (TMS) experiments perturbing SMA functioning across explicit timing tasks (see [37,38], for reviews). Regarding implicit timing, we are not aware of any TMS study targeting the SMA in a variable foreperiod task such as the one used here (see [39], for a review).

In addition to TMS, transcranial electric stimulation (tES) techniques, including transcranial Direct Current Stimulation (tDCS), transcranial Alternating Current Stimulation (tACS), and transcranial Random Noise Stimulation (tRNS), are rapidly growing in the investigation of the neural correlates of time perception (see [37], for a review) and sensorimotor processes (see [30]). Although the majority of tES studies on explicit timing tasks (e.g., temporal discrimination, temporal reproduction, and temporal bisection tasks) have mainly used tDCS [40-43], it should be noted that the commonly assumed cathodal/inhibition and anodal/facilitation tDCS effects on the motor system are not so clear in the cognitive domain [44-46]. In contrast to tDCS, both tACS (where a fixed frequency is used) and tRNS (where the current alternates at random frequencies) have no constraint of current flow direction sensitivity [47-50]. Another advantage of tRNS and tACS, over tDCS, is that they are more appropriate for placebo-controlled studies because of the smaller amount of sensory sensations usually reported as compared to tDCS ([51]; Antal and Hermann, 2016).

To date, only a few studies have used either tACS or tRNS over different brain areas in explicit timing tasks, with mixed results (e.g., [52-56]). Narrowing down the focus on time bisection studies, it has been found that tRNS delivery over the auditory cortex [53] or the right posterior parietal cortex [54] led participants to over-estimate durations in visual and auditory time bisection tasks, with no effects on temporal variability (i.e., resolution at which time intervals are perceived, as commonly observed with tDCS; [41,43]). An overestimation of durations was also reported by Wiener et al. [56] after applying tACS at beta frequencies over the SMA. In that study, participants performed a variant of the time bisection task, i.e., the "partition method" [57], which consists in classifying visually-presented stimuli into short- and long-duration categories on the basis of a running average of the durations encountered on previous trials rather than previously memorized standard durations.

Extending the above-mentioned studies, here, we sought to further explore the contribution of the SMA not only to explicit but also to implicit timing in the same experiment and group of participants. To this end, we used two timing tasks that might or might not require explicit temporal judgments [21], and relied on High-Definition tRNS (HD-tRNS) to deliver a more focal stimulation and to decrease the functional relevance of the reference electrodes (see [44], for a review). Our time bisection task was similar to the partition method used by Wiener et al. [56]. This version of the time bisection task enables, indeed, a better-balanced setting to compare explicit and implicit timing given the lack of previous exposure to standard durations, as for the implicit timing task.

In sum, the present study adopted for the first time a non-invasive brain stimulation approach in a "within-subjects comparison" of explicit and implicit timing tasks, a crucial test to probe the causal contribution of SMA to both temporal processes.

2. Method

2.1. Participants

Forty-eight university students (16 males, mean age: 23.31 years, *SD* = 1.63, range: 20–28 years) voluntarily participated in the study. The sample size was adequate to detect a medium effect size (d = 0.48) with a power of.9 in a paired-sample *t*-test with a two-sided alpha level of 0.05 (G*Power 3 software; [58]). Moreover, it allowed us to complete the counterbalance order of tasks and experimental conditions between participants (see below). Participants were recruited and tested at the Department of General Psychology, University of Padova (Italy), had a normal or corrected-to-normal vision, and all signed informed consent before participation in accordance with the Declaration of Helsinki. All of them met the criteria for the application of tRNS [59]. The experiment was approved by the Ethics Committee of the Department of General Psychology at the University of Padova (protocol n. 3069).

2.2. Procedure and task

Fig. 1 illustrates the schematic of implicit and explicit timing tasks and the experimental procedure. The tasks were the same as in our previous study [21], except for the partition method in the time bisection task. As introduced above, in this variant of the time bisection task no previous standard durations are presented, but participants estimate "short" and "long" durations on the basis of their own subjective feeling [56]. Participants were seated in a quiet room approximately 60 cm from the computer screen (15.6'') that produced and recorded experimental events via PsychoPy Software [60].

Explicit and implicit timing tasks comprised the same stimulus material and general procedure, differing only in the specific task instructions given to participants [9]. For both tasks, stimuli consisted of a grey circle and a grey cross presented in the centre of a lighter grey

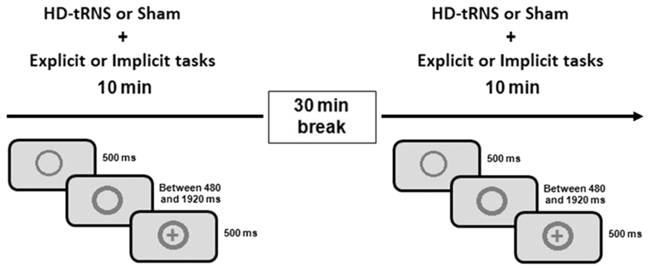

Fig. 1. **:** Graphical representation of the experimental procedure for each session. All participants performed the explicit and implicit timing task with or without electric stimulation (HD-tRNS or sham).

background screen. A thin circle was initially displayed for 500 ms, followed by a thicker circle that could assume one of the following durations: 480, 720, 960, 1200, 1440, 1680, or 1920 ms. After the duration elapsed, a cross appeared in the centre of the circle for 500 ms. In the *explicit timing task*, participants were instructed to estimate whether the temporal interval elapsing from the onset of the thicker circle to the onset of the cross was displayed for a “short” or “long” interval according to their own perception. Responses were given by pressing two response keys (“S” and “L” on the computer keyboard), which were covered with the labels “B” and “L” (i.e., “Breve” and “Lungo”, respectively, meaning short and long in Italian); response keys were counterbalanced across participants. In the *implicit timing task*, participants were instructed to press the space bar as fast as possible whenever the cross appeared inside the thicker circle. For both explicit and implicit timing tasks, no information about stimulus durations was given to participants.

The experiment consisted of a total of ten blocks (5 blocks for each timing task) of 42 trials each (6 repetitions for each temporal interval). HD-tRNS and sham stimulations (each lasting 10 min, see below) were counterbalanced between participants and performed in two different sessions, separated by 48 h. Half of the participants started with the explicit timing task followed by the implicit one, whereas the remaining participants started with the implicit timing task followed by the explicit task. The same block order was used for the two sessions. Explicit and implicit timing tasks were separated by a 30-min break to allow participants a brief rest before undergoing the second task. Before each session, participants familiarized themselves with both timing tasks by performing a short block of 14 training trials (2 repetitions per duration). No feedback was provided in either of the two timing tasks. Overall, each session lasted approximately 60 min considering the whole setup.

2.3. *Sensation experienced questionnaire*

A questionnaire about the sensations experienced by the participant during the two types of stimulation (HD-tRNS, sham) was included [61]. The questionnaire was composed of 7 possible sensations commonly experienced during stimulation (i.e., fatigue, heat, pain, burning, pinching, itching, and iron taste), and participants had to report how much they experienced that sensation on a scale ranging from not experienced = 0 to very much = 4. The questionnaire allowed us to evaluate whether unspecific stimulation effects could account for differences in behavioural performance. A total score was calculated by summing up the scores from all the questions included. Data from the Sensation experienced questionnaire were analysed with non-parametric statistics using Wilcoxon matched-pair signed rank test for stimulation (HD-tRNS vs. sham) separately for the explicit and implicit timing tasks.

2.4. *Stimulation setting*

HD-tRNS was applied through a StarStim8 device, a hybrid wireless neuro-stimulation system for simultaneous EEG/tACS recording, controlled by Neuroelectrics Instrument Controller (NIC 2.0; Neuroelectrics, Barcelona, Spain; http://www.neuroelectrics.com/products/software/nic2/) software. The system included 8 channels that could be located in 64 possible scalp positions through a neoprene head cap according to the international 10–20 system. For the present study, 5 PISTIM Ag/AgCl electrodes with a 1 cm radius were active electrods for stimulation, whereas the remaining three electrodes were not used. The stimulation electrode was placed in FCz, while the 4 return electrodes were placed in AFz, FC3, FC4, and CPz. Stimulation intensity was set at 1 mA (milliAmpere), and the frequencies ranged randomly from 0 to 500 Hz, lasting 10 min for each timing task [59]. The whole frequency band was used as it has been shown to be the most effective in enhancing neural excitability [62,63].

The sham condition consisted of 20-sec ramp-up and 20-sec ramp-down, and 20 s of stimulation at the beginning and the end of the tasks. After each stimulation (HD-tRNS and sham) and each timing task (explicit and implicit), participants filled in the sensation questionnaire [61].

2.5. *Data analysis*

A similar analytical approach was used for statistical inference in the two tasks. For the explicit timing task, the probability of *long* responses was modelled by means of a probit regression implemented in the *glmer* function (i.e., a generalized linear mixed model, GLMM, with probit-link function) in the *lme4* library [64] under the R environment (http://www.R-project.org/). For the implicit timing task, log-transformed reaction times (log-RTs) were analyzed by means of a linear regression implemented by using the *lmer* function (i.e., a linear mixed model, LMM) in *lme4* library.

The GLMM, for the explicit timing task, and the LMM, for the implicit timing task, included the same fixed- and random-effects. In particular, the fixed-effect terms were the thicker circle duration as a continuous variable (centred and standardized using Z-score to improve the fit of the model and the interpretation of the variable), stimulation type as a factor (HD-tRNS vs sham stimulation), and their interaction. The random structure included correlated by-subject (ID) random intercepts and slopes for duration, stimulation and their interaction.

For the analysis of RTs in the implicit timing task, trials with anticipations ($RT < 150$ ms) or missed responses were excluded from the analysis (mean excluded trials: 1.96, range: 0–12). Following Baayen and Milin [65], once the model was fitted, trials with absolute standardized residuals higher than 2.5 SD were considered outliers and removed (2.7% of the trials). After outlier removal, the model was refitted. The advantage of this approach over repeated-measures ANOVA is that it is not restricted to predictors with categorical levels, thereby preserving the continuous status of the stimulus duration variable.

In addition to the GLMM analysis, for the explicit timing task, we also computed more conventional indexes (to aid comparison with previous studies) such as the participants’ Bisection Points (BPs) and the Just Noticeable Difference (JNDs) and compared them between the two stimulation conditions using paired-sample t-tests. The BP (also known as the point of subjective equality) is the duration value at which participants are equally likely to classify the stimulus duration as short or long. The just noticeable difference (JND) is a measure of discrimination sensitivity defined as the minimal physical difference between two stimuli that a participant can just notice [66]. A general linear model (GLM) with probit-link function and including stimulus duration, stimulation and their interaction as predictors (these terms were specified as in the GLMM analysis) was fitted for each participant. From the GLM results, the BPs for the sham and tRNS conditions were computed as

$-\beta_0/\beta_1$ and $-(\beta_0+\beta_2)/(\beta_1+\beta_3)$, respectively, where β_0 is the intercept term, β_1 is the slope associated with duration, β_3 is the main effect of stimulation, and β_4 is the interaction term between duration and stimulation. The JNDs for the two stimulation conditions were computed at the 84th percentile of the normal distribution as $0.9944/\beta_1$ and $0.9944/(\beta_1+\beta_3)$. Finally, for completeness, the Supplementary material also reports the RT data from the explicit timing task.

3. Results

As concerns the results from the sensation questionnaire, there was no difference between HD-tRNS and sham stimulation for either explicit ($Z = 0.23$, $p = .819$) or implicit ($Z = 1.57$, $p = .116$) timing tasks, indicating that participants reported a similar level of aversive sensation after HD-tRNS or sham (Explicit HD-tRNS mean = 0.16, SD = 0.19; Explicit sham mean = 0.17, SD = 0.21; Implicit HD-tRNS mean = 0.21, SD = 0.20; Implicit sham mean = 0.17, SD = 0.29).

The GLMM results for the explicit timing task (marginal $R^2 = .57$, conditional $R^2 = .70$) are reported in Table 1. The significant main effects of duration and stimulation were significant, whereas their interaction was not significant. As shown in Fig. 2, there was a shift of the probit curve to the left (i.e., overestimation) in the HD-tRNS as compared to sham stimulation. Results from BPs analysis were consistent with the GLMM results. Mean BPs were lower in the HD-tRNS condition (mean = −0.04, SD = 0.35) compared to the sham condition (mean = 0.02, SD = 0.39), with this difference reaching statistical significance ($t(47) = 2.01$, $p = 0.0497$). JND for sham (mean = 0.71, SD = 0.22) and HD-tRNS condition (mean = 0.71, SD = 0.23) were not significantly different ($t(47) = -0.21$, $p = 0.836$).

The results of the LMM for the implicit timing task (marginal $R^2 = .07$, conditional $R^2 = .46$) are reported in Table 2. There was a significant main effect of duration, whereas the effect of stimulation and its interaction with duration were not significant. Fig. 3 shows that log-RTs decreased as stimulus duration increased, in line with common findings from variable foreperiod tasks.

4. Discussion

This study tested whether the application of HD-tRNS over the SMA had similar effects on performance in explicit and implicit timing tasks. To this end, we implemented a previous paradigm from our group in which implicit and explicit timing tasks were equated in terms of stimulus material but differed in terms of temporal requirements [21]. In the explicit timing task, participants categorized stimulus durations into short and long categories, whereas in the implicit timing task, they simply responded to target onset with no judgement of interval duration (foreperiod). Our results showed that delivering HD-tRNS during the explicit timing task resulted in an overestimation bias relative to sham stimulation. Conversely, we found no effect of HD-tRNS on performance in the implicit timing task, as the foreperiod effect (i.e., shorter responses with longer foreperiods) did not differ between HD-tRNS and sham condition.

As concerns the explicit timing task, our findings dovetail with recent non-invasive electric stimulation studies using classic time bisection tasks with standard durations. Mioni [53] applied tRNS over auditory (A1) and visual (V1) areas while participants performed visual and auditory versions of the time bisection task. Relative to sham stimulation, the application of tRNS over A1 produced a temporal overestimation bias in both visual and auditory tasks. When tRNS was delivered over V1, the effect only emerged for the visual task. In another study from the same group, temporal overestimation for both auditory and visual time bisection tasks was also found when tRNS was applied over the right posterior parietal cortex [54]. Regardless of these specific modality effects, what is interesting to note here is the observed pattern of temporal overestimation as a consequence of tRNS stimulation. Our results are consistent with these findings in the context of a different visual time bisection task and extend them by targeting a different brain area – the SMA. Collectively, findings from these previous studies and the present one support the existence of a distributed network of areas, encompassing the SMA, in explicit time processing.

The reported HD-tRNS-induced overestimation is also in line with the results from a different tES technique. As noted in the Introduction,

Table 1
Summary output of the GLMM on the “long” response probability in the explicit timing task.

Predictors	Risk Ratios	CI	p
(Intercept)	0.99	0.83 – 1.16	0.863
Duration	4.46	3.94 – 5.05	**< 0.001**
Stimulation [HD-tRNS]	1.11	1.01 – 1.21	**0.026**
Duration × Stimulation	0.98	0.89 – 1.08	0.729

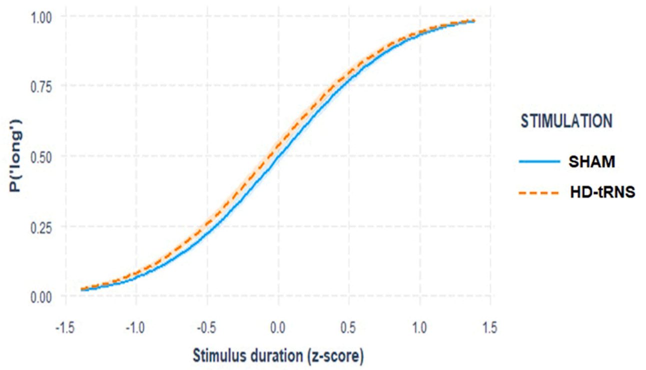

Fig. 2. Interaction plot of the effects of stimulus duration and stimulation on the probability of “long” responses in the explicit timing task. The figure shows the conditional probability of “long responses” given stimulus duration for Sham (blue continuous lines) and HD-tRNS (orange dashed line) stimulations. Shaded error bars indicate Standard Errors of estimated marginal means.

Table 2
Summary output of the LMM on log-RTs in the implicit timing task.

Predictors	Estimates	CI	p
(Intercept)	5.73	5.7 – 5.76	< 0.001
Duration	-0.05	-0.06– – 0.05	< 0.001
Stimulation [tRNS]	-0.01	-0.03– 0.02	0.65
Duration × Stimulation	0	-0.01– 0.01	0.761

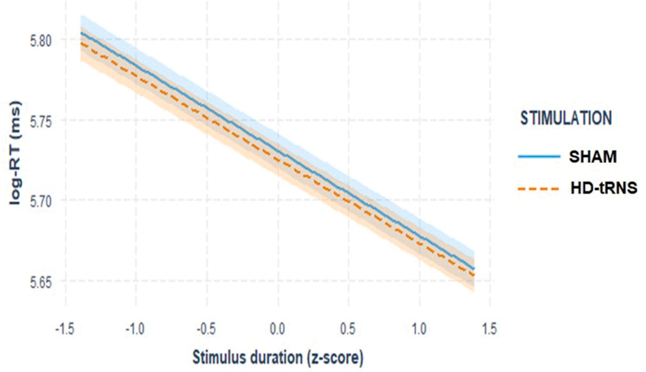

Fig. 3. Interaction plot of the effects of stimulus duration and stimulation on log-RTs in the implicit timing task. The figure shows the conditional effect of stimulus duration on log-RTs for Sham (blue continuous lines) and HD-tRNS (orange dashed line) stimulations. Shaded error bars indicate Standard Errors of estimated marginal means.

the application of beta tACS over SMA led participants to report durations as lasting longer [56]. Like here, the time bisection task in Wiener and colleagues required classifying stimulus durations into short and long categories by comparing them with a running average of the durations encountered in previous trials. In this case, it is assumed that participants gradually create an internal standard duration for making their own temporal judgments across trials, a process that would specifically stress memory encoding/retention and decision-making for stimulus durations. It seems, then, likely that both tACS and tRNS techniques might interfere with such memory and decision-making processes linked to timing operations thought to be reflected by SMA activity (e.g., [67,56,68]).

There is also evidence in the literature for the null effects of tRNS over SMA during explicit timing tasks [52]. Using a duration categorization task, tRNS had no influence on the participants' ability to decide whether a given dot had been presented for a short or long period. One might wonder whether this discrepancy reflects a difference in the used tRNS set-up (e.g., extra-cephalic reference electrode or less focality due to a normal tRNS montage in Dormal and colleagues' study) or it is due to the temporal variable under observation in the two studies. In particular, in Dormal and colleagues (2016), participants' performance was measured in terms of the distance effect by classifying durations as "easy" (i.e., 500 or 900) or "difficult" (600 or 800 ms) on the basis of whether they were or were not at the lower or upper extreme of the range. In such a case, the temporal task did not stress memory processes for durations. In keeping with the above line of reasoning, it seems plausible to suggest that while in our study the SMA was particularly critical to the encoding and retention of the internal standard for making a temporal decision, such processes were less stressed in Dormal and colleagues (2016). This hypothesis, however, remains speculative and should be directly tested in future studies. It is also important to further investigate the adopted tRNS parameters in order to further understand the potential source of variability among different tRNS set-ups. Considering that tRNS is a relatively recent technique, more studies are indeed warranted to better understand its effects on cognition [49,50].

In contrast to the explicit timing task, the fact that the foreperiod effect (our index of implicit time processing) was unaffected by HD-tRNS over the SMA suggests that such a region is not part of a "core" implicit timing circuit [9]. However, interpretation of a null result is always challenging in studies of brain stimulation, as multiple alternatives exist for why stimulation does not elicit an effect [69]. One possibility is that tRNS is more effective with higher task demands and engagement of more neuronal resources (e.g., [70]). Our implicit timing task was less demanding than the explicit timing task, as often occurs in studies comparing explicit and implicit timing [71]. In fact, while our explicit timing task stressed discrimination requirements, the implicit timing task was a simple-RT task. Future work should try to better balance the cognitive demands of explicit and implicit timing tasks (see also [72]).

In conclusion, our study provides the first non-invasive brain stimulation evidence on the contribution of the SMA to explicit and implicit timing in the same group of participants. Our approach may serve as starting point for future research aiming to directly compare the role of SMA (or other brain regions) in explicit and implicit timing tasks and to further investigate the absence of HD-tRNS effects on implicit timing.

Data Availability

Data will be made available on request.

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Authors' contributions

Conceptualization: Giovanna Mioni, Mariagrazia Capizzi and Martin Wiener; Data curation: Giovanna Mioni and Antonino Visalli; Formal analysis: Antonino Visalli; Investigation: Giovanna Mioni; Methodology: Giovanna Mioni, Mariagrazia Capizzi, Antonino Visalli and Martin Wiener; Project administration: Giovanna Mioni, Mariagrazia Capizzi, Antonino Visalli and Martin Wiener; Resources: Giovanna Mioni; Software: Giovanna Mioni; Supervision: Giovanna Mioni and Antonino Visalli; Validation: Giovanna Mioni, Mariagrazia Capizzi, Antonino Visalli and Martin Wiener; Visualization: Antonino Visalli; Roles/Writing – original draft: Mariagrazia Capizzi; Writing – review & editing: Giovanna Mioni, Mariagrazia Capizzi, Antonino Visalli and Martin Wiener.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2023.114383.

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