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# Differential sensory cortical involvement in auditory and visual sensorimotor temporal recalibration: Evidence from transcranial direct current stimulation (tDCS)

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## Abstract

Adaptation to delayed sensory feedback following an action produces a subjective time compression between the action and the feedback (temporal recalibration effect, TRE). TRE is important for sensory delay compensation to maintain a relationship between causally related events. It is unclear whether TRE is a sensory modality-specific phenomenon. In 3 experiments employing a sensorimotor synchronization task, we investigated this question using cathodal transcranial direct-current stimulation (tDCS). We found that cathodal tDCS over the visual cortex, and to a lesser extent over the auditory cortex, produced decreased visual TRE. However, both auditory and visual cortex tDCS did not produce any measurable effects on auditory TRE. Our study revealed different nature of TRE in auditory and visual domains. Visual-motor TRE, which is more variable than auditory TRE, is a sensory modality-specific phenomenon, modulated by the auditory cortex. The robustness of auditory-motor TRE, unaffected by tDCS, suggests the dominance of the auditory system in temporal processing, by providing a frame of reference in the realignment of sensorimotor timing signals.

## Introduction

Temporal recalibration refers to the subjective realignment of asynchronous sensory signals to reduce the timing difference between inter-related stimuli, after adaptation to a constant timing difference between the two stimuli. For example, when a delayed auditory stimulus (e.g., 150ms) is repeatedly presented after a visual stimulus, the auditory stimulus is perceived as earlier than the visual stimulus when the delay is subsequently removed (Fujisaki, Shimojo, Kashino, & Nishida, 2004; Vroomen, Keetels, De Gelder, & Bertelson, 2004). Temporal recalibration occurs not only between presentation of sensory stimuli, but also between an action and its sensory consequences. For example, Stetson, Cui, Montague, and Eagleman (2006) found that, when participants observe a repeatedly inserted delay between an action and the sensory consequence of that action, this delay adaptation can shift an observer's point of subjective simultaneity (PSS: the point where two stimuli are perceived as occurring simultaneously) in the direction of the delay, hence producing a subjective compression of time. Therefore, temporal recalibration is important for sensory delay compensation to maintain a causal relationship between events. However, to date, mechanisms underlying temporal recalibration are not fully understood.

A supramodal mechanism, beyond the modality-specific brain areas regulating sensorimotor temporal recalibration, was proposed by Heron, Hanson, and Whitaker (2009). They found that temporal recalibration can be observed in visual, auditory and tactile modalities, and can be transferred between modalities. For example, an auditory stimulus was used in the adaptation period and a visual stimulus was used in the testing period to observe temporal recalibration. Sugano, Keetels, and Vroomen (2010) found consistent results but suggested that temporal recalibration might be an outcome of a shift in the motor component instead of a shift in the sensory component, allowing temporal recalibration transference between modalities. However, some findings are not explained by the supramodal account (Sugano, Keetels, & Vroomen, 2012, 2014; Yarrow, Sverdrup-Stueland, Roseboom, & Arnold, 2013) or the motor component shift account (Sugano et al., 2012, 2015). For instance, using a sensorimotor synchronization task, requiring synchronized finger tapping to a rhythmic sequence of regular stimuli, Sugano et al. (2012) found that temporal recalibration effect (TRE) transfers from visual to auditory modality but not vice versa. One would expect the same transference effect between modalities if there was a supramodal mechanism or shift in the motor component. It is possible that visual timing information is transferred to the auditory system so that visual temporal recalibration can be transferred to auditory modality; however, auditory temporal information may not be transferred to the visual system. This suggests a critical role of the auditory cortex in timing across different stimulus modalities (Guttman, Gilroy, & Blake, 2005; Grahn, Henry, & McAuley, 2011; Kanai, Lloyd, Bueti, & Walsh, 2011; Meyer, Baumann, Marchina, & Jancke, 2007; Sugano et al., 2012). Therefore, the auditory cortex might be a candidate for amodal time regulation (analogous to visual cortex role in auditory spatial perception, Lewald, Meister, Weidemann, & Töpper, 2004; Zimmer, Lewald, Erb, Grodd, & Karnath, 2004; also see ventriloquism effect, Chen & Vroomen, 2013) and its role might extend to temporal recalibration process. However, this hypothesis has not been tested directly using brain stimulation.

Here, we performed three experiments to investigate the critical role of the auditory cortex and visual cortex during temporal recalibration in auditory and visual modalities by using transcranial direct current stimulation (tDCS). tDCS is a noninvasive brain stimulation technique that delivers a small current (typically 1-2mA) through surface electrodes to the scalp, to modulate excitability of neurons underneath the electrodes (Nitsche et al., 2008). We used cathodal tDCS to suppress activity in these sensory cortical areas. Based on previous studies suggesting auditory system dominance in timing processes (Gutman et al., 2005; Kanai et al., 2011; Sugano et al., 2012), we hypothesized that auditory cortex stimulation would significantly impact upon temporal recalibration regardless of stimulus modality, but visual cortex stimulation would affect visual temporal recalibration only.

## Experiment 1

We firstly investigated a possibility of double dissociation in a 2 by 2 factorial design to test whether or not temporal recalibration is a sensory modality-specific phenomenon. This possibility has not been tested before. If temporal recalibration is an entirely sensory specific phenomenon, we would find a cross-over interaction effect: auditory temporal recalibration would only be affected by auditory cortex tDCS, and visual temporal recalibration would only be influenced by visual cortex tDCS. Based on auditory cortex dominance in timing, we hypothesized that auditory cortex stimulation would significantly impact upon temporal recalibration both in auditory and visual TRE.

### Method

#### Participants

Forty-seven student volunteers from the University of Sheffield (20 females, mean age 24.2, sd = 4.2, 8 left handed) participated. They had normal or corrected to normal vision and hearing, and they did not report any history of psychiatric/neurological conditions including seizure disorders. All control variables were reported in Table 1. All participants gave informed consent. The study was approved by the Department of Psychology Research Ethics Committee at the University of Sheffield.

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Table 1 about here

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#### Apparatus and materials

Because timing was of critical importance in this study, we used an open-source Arduino Mega 2560 micro-controller board (ATmega2560) to control experimental events and record data within a few milliseconds timing accuracy (Teikari et al., 2012). Responses were collected using a customized button box (with Sanwa OBSFS 30 Silent arcade buttons) connected to the same Arduino board. The visual stimulus was provided by a small white LED (5mm diameter with a luminance of 4 cd/m$^2$, attached to the center of a customized 19-inch black background monitor. The duration of the LED stimulus was 10ms. The auditory stimulus was a binaurally presented tone burst (10ms duration, 1500 Hz square-wave at a sound pressure level of approximately 74 dB) via Sennheiser HD 202 Stereo headphones. During the experiment, participants listened to constant 64 dB white noise to mask the mechanical noise of their button presses (Sugano et al., 2012).

## Transcranial Direct-Current Stimulation (tDCS)

Direct current was delivered with two saline-soaked surface sponge electrodes (cathode electrode: 5 cm×5 cm; reference electrode: 5 cm×7 cm) using a battery-driven constant current regulator (TCT research, Hong Kong). Current strength was 2 mA. We stimulated the right auditory cortex by placing the cathode electrode over T4 according to the international 10-20 EEG electrode placement system. The right auditory cortex was targeted instead of the left, because the right auditory cortex was reported to be involved in both auditory and visual time discrimination tasks in a previous transcranial magnetic stimulation (TMS) study (Kanai et al., 2011). Consistent with this, the right auditory cortex was involved in higher-order auditory temporal processing in the current time window of investigation (a few hundred milliseconds), whereas the left auditory cortex was associated with a fine-grained analysis of auditory signals in a short-time window (25-50ms) (Clunies-Ross, Brydges, Nguyen, & Fox, 2015). Furthermore, right sided activity was found in various time perception studies using fMRI (Wiener, Turkeltaub, & Coslett, 2010). For visual cortex stimulation, the cathode electrode was placed over Oz. In both stimulation conditions, the reference electrode was placed over the left cheek over the buccinator muscle, to avoid potential confounding effects of cortical stimulation beneath the reference electrode (Nitsche et al., 2008; Yau, Celnik, Hsiao, & Desmond, 2014). To reduce adverse effects of electric current being delivered abruptly, electric current was increased in a ramp-like fashion over 30 seconds until it reached to 2 mA (Nitsche et al., 2003a). The stimulation duration of 9 minutes was chosen, because it would produce up to 1-hour aftereffect (Nitsche et al., 2003b) covering the entire duration of our adaptation/post-SMS task sessions (approximately 25 min). During tDCS, some participants reported a severe burning sensation (n=1), sleepiness (n=3) and trouble concentrating (n=1) using the tDCS Adverse Effects Questionnaire (Brunoni et al., 2011). However, participants did not report these adverse effects lasting beyond the experimental period.

## Procedure

We used a sensorimotor synchronization (SMS) task to measure temporal recalibration effect. In the task, participants are asked to tap in synchrony with a regular sequence of pacing stimuli. Taps typically precede the stimulus onset by 20 to 80ms on average, which is known as the Negative Mean Asynchrony (NMA) (see Repp, 2005; Repp and Su, 2013 for review). The NMA is considered to be participant's point of subjective impression of tap-stimulus synchrony (Aschersleben, 2002). Sugano et al. (2012, 2014, 2015) have shown that sensorimotor synchronization task can measure temporal recalibration effect by comparing the participants' NMAs before and after delay adaptation. They showed that compared to no-delay adaptation condition, participants who were adapted to 150ms delay between their button press and feedback had greater NMAs. In our study, using the same paradigm, we applied tDCS over the areas of interest immediately before the delay adaptation period to investigate the effect of stimulating the auditory and visual cortices.

Task modality (auditory or visual) was a between-subjects factor: approximately half of the participants completed a visual sensorimotor synchronization task (N = 23), the remainder of participants performed an auditory sensorimotor synchronization task (N = 24). All participants attended two tDCS sessions separated by a minimum of 2 days (mean = 138.1 hours, sd = 67.5) and stimulation order was counterbalanced (tDCS over the auditory vs. visual cortex).

In each session, they completed pre-sensorimotor synchronization task just before tDCS and adaptation/post-sensorimotor synchronization task immediately after tDCS. In the pre-sensorimotor synchronization task, they were required to press the button in synchrony with the pacing stimuli.

There was a practice trial followed by 25 main trials. In each trial, pacing stimuli (auditory or visual) were presented 15 times with a constant 750ms inter-stimulus interval. Participants were asked to attend to the first 2 stimuli to get into the rhythm, and then to tap in synchrony with the rest of the stimulus sequence. Immediately after the completion of the pre-sensorimotor synchronization task of 25 trials (no delay adaptation involved), cathodal tDCS over the area of interest began for 9 minutes. After the completion of tDCS, participants completed 25 pairs of delay adaptation and post-sensorimotor synchronization trials. In an adaptation trial, participants voluntarily pressed the button 15 times: they were instructed to keep similar pace to the pre-sensorimotor synchronization task. A feedback stimulus was delivered 150ms after each button press (i.e., delay adaptation). This delay duration was chosen because it has been shown that approximately 150ms delay adaptation produced the highest level of temporal recalibration effect (Heron et al., 2009; Stetson et al., 2006). Immediately after one adaptation trial, one post-sensorimotor synchronization task trial began which was identical to the pre-sensorimotor synchronization task. Participants started each trial at a time of their own choosing by pressing the start button. The entire experimental procedure lasted approximately 60 minutes.

**Results**

In each trial, negative mean asynchronies (NMAs) above and below two standard deviations were considered as outliers and removed from each trial before obtaining average NMAs across trials for each condition (3% of total data including participants' missing button presses were removed). Temporal recalibration effect (TRE) was calculated by subtracting averaged pre-test NMAs from the averaged post-test NMAs. When the Mauchley sphericity test concerning the homogeneity of variance was violated, we adjusted the degrees of freedom in the following analyses by using the Greenhouse-Geisser correction. Handedness (measured by Edinburgh Handedness Inventory; Oldfield, RC., 1971) and musical sophistication scores (measured by Goldsmiths Musical Sophistication Index; Müllensiefen, Gingras, Musil, & Stewart, 2014) were not significantly different between auditory and visual task groups ($ps > .25$).

Temporal recalibration effects (TRE: post-test NMAs minus pre-test NMAs) for each condition were shown in Figure 1. A 2x2 mixed-model ANOVA was conducted on TRE values with task modality (auditory vs. visual tasks) as a between-subjects factor and with stimulation area (tDCS over the auditory cortex vs. visual cortex) as a within-subjects factor. There was a significant interaction effect between task modality and stimulation area [$F (1, 45) = 4.3$, $p = 0.043$, $\eta_p^2 = 0.088$]. Pairwise-comparisons showed that auditory cortex tDCS condition had significantly higher TRE than visual cortex tDCS condition in the visual task [$F (1, 45) = 6.0$, $p = .018$, $\eta_p^2 = 0.118$]. However, TRE did not significantly differ for auditory and visual cortex tDCS in the auditory task condition [$F (1, 45) = 0.26$, $p = .61$]. TRE was not significantly different between the auditory and visual tasks within each of stimulation conditions ($p > .05$). Neither the main effect of the task [$F (1, 45) = 0.16$, $p = .69$] nor the main effect of the stimulation area was significant [$F (1, 45) = 1.8$, $p = .18$].

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Figure 1 about here

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As a control analysis, we conducted another mixed model ANOVA on TRE values by adding session order (AC or VC tDCS first) as a between-subjects factor to examine a potential carryover effect between sessions. Neither the main effect of session order [$F (1, 43) = 0.93$, $p = .339$] nor any interaction effects involving the session order factor was significant. To further investigate the nature of differences in the pre-test NMAs between groups (see Table 2), we examined the effect of stimulation order as a between-group factor (AC or VC tDCS first) within each task group on pre-test NMAs. In the auditory task group, NMAs significantly increased when the task was performed $2^{nd}$ time in the AC tDCS condition (before stimulation) [$F (1, 43) = 5.13$, $p = 0.028$, $\eta_p^2 = 0.107$] but there was no significant stimulation order effect in the VC tDCS condition [$F (1, 43) = 0.12$, $p > .25$]. This finding suggests that participants had increased NMAs if they had VC tDCS in their first session, compared to the participants who did the task for the first time. The same effect did not occur when participants had AC tDCS in their previous session. In the visual task group, this carry-over effect was at a trend level of significance [AC tDCS condition, $F (1, 43) = 3.08$, $p = .086$, $\eta_p^2 = 0.067$].

## Experiment 2

In Experiment 1, we found that, in the visual task, auditory cortex stimulation resulted in higher temporal recalibration effect (TRE) compared to visual cortex stimulation. However, in the auditory task, auditory and visual cortex stimulation did not have differential impacts on TRE. Hence, we did not find the cross-over interaction effect indicating that TRE is a sensory-modality specific phenomenon. The TRE difference in the visual task could be because of increased visual TRE produced by tDCS over the auditory cortex. Alternatively, it would be consequence of decreased visual TRE as a result of tDCS over the visual cortex. In Experiment 2, we tested whether tDCS over the auditory cortex increased visual TRE, by employing auditory cortex tDCS and sham tDCS groups in a between-group design.

### Method

#### Participants, apparatus and materials

A new sample of sixty student volunteers from the University of Sheffield (20 males, mean age 20.02, sd = 1.39, 4 left handed) participated. Apparatus and materials were identical to those in Experiment 1.

#### Procedure

In a between-group design, half of the participants were in the real tDCS condition (N = 30), the remainder half were in the sham tDCS condition (N = 30). All participants performed both auditory and visual tasks in one session before and after tDCS. Task order was counterbalanced across participants, but the same task order before and after tDCS was used for the same participant. For sham tDCS, the current increased in a ramp-like fashion over 30 s and then stopped. This method has been shown to be effective for producing the feeling of the real stimulation to the participants (Gandiga, Hummel, & Cohen, 2006; Yau et al., 2014). Some participants reported that they had severe itching (n=1), tingling (n=1), sleepiness (n=2) mood change (n=1) and trouble concentrating (n=2) during tDCS. These adverse effects did not last beyond the experimental period.

**Results**

Data analysis was the same as in Experiment 1 including outlier removal (2.8% of total data removed). Handedness and musical sophistication scores were not significantly different between real and sham groups (ps > .05).

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Figure 2 about here

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Three participants were excluded from the further analysis (n=2 from real, n = 1 from sham AC tDCS group) due to excessive TRE values (2 SD above group mean). A 2x2 mixed model ANOVA was conducted on TRE values with stimulation group (real vs. sham) as a between-subjects factor and with task modality (auditory vs. visual) as a within-subjects factor. The interaction effect between stimulation condition and task modality was not significant [$F\ (1, 55) = 1.89$, $p = 0.174$, $\eta p2 = 0.033$]. Neither the main effect of group [$F\ (1, 55) = 1.60$, $p = 0.211$, $\eta p2 = 0.028$] nor the main effect of task [$F\ (1, 55) = 0.63$, $p = 0.441$, $\eta p2 = 0.011$] was significant. Nonetheless, as shown in Figure 2, we found a trend level of between-group difference in the visual task, indicating decrease of visual TRE produced by auditory cortex real tDCS [$F\ (1, 55) = 3.06$, $p = 0.086$, $\eta p2 = 0.053$].

Pre-Test NMA Differences Between Groups

As in experiment 1, since there were differences in the pre-test NMAs (see Table 2), we conducted a 2x2x2 mixed model ANOVA on pre-test NMAs with experimental group (Real vs. Sham AC tDCS) and task order (Auditory vs. Visual Task First) as between-subjects factors and with task modality (Auditory vs. Visual Task) as a within-subjects factor. There was a significant interaction effect between task order and task modality [$F\ (1, 53) = 6.04$, $p = .017$, $\eta p2 = 0.102$]. Pairwise comparisons showed that participants had smaller NMAs when they performed the task again with different modality (auditory task first, $F (1, 53) = 4.07$, $p = 0.049$, $\eta p2 = 0.071$; visual task first, $F (1, 53) = 29.50$, $p < 0.001$ $\eta p2 = 0.358$). However, task order effect was not significant within each task modality, all $ps > .05$. This pattern of interaction was supported by a significant main effect of the task modality [$F (1, 53) = 27.96$, $p < .001$, $\eta p2 = 0.345$]; participants had larger NMAs in the auditory task than they had in the visual task. Finally, neither the main effect of task order [$F (1, 53) = 0.034$, $p = .85$] nor its interaction effect with experimental group [$F (1, 53) = 1.22$, $p = .27$] was significant.

**Experiment 3**

In Experiment 2, in a between-group design, we found that auditory TRE was not different between auditory cortex (AC) tDCS real and sham groups, consistent with Experiment 1 employing a within-group design. Furthermore, an inspection of Figure 2 suggested a decrease of visual TRE produced by auditory cortex tDCS. If cathodal tDCS over the AC decreased visual temporal recalibration, the difference between AC and visual cortex (VC) tDCS on visual temporal recalibration we found in experiment 1 would be because VC tDCS decreased visual temporal recalibration more than AC tDCS did. To directly test this prediction, we performed a third experiment comparing the effects of 3 experimental tDCS groups (AC tDCS, VC tDCS, and sham tDCS) on visual temporal recalibration. We used a between-group design in order to avoid a possible effect of repeated tDCS or task order. We investigated these effects only for visual temporal recalibration because in the previous experiments we did not find any tDCS effects on auditory temporal recalibration process.

Participants, apparatus and materials

Seventy-three student volunteers from the University of Sheffield (25 males, mean age 19.63, sd = 2.48, 12 left handed) participated. As with the two previous experiments, all satisfied our inclusion criteria. Apparatus and materials were identical to Experiment 1 and 2.

Procedure

In a between-group design, approximately one third of the participants were in the auditory cortex (AC) real tDCS group (N = 24), the other approximately one third of the participants were in the visual cortex (VC) real tDCS group (N = 23) and the remainder of the participants were in the sham tDCS group (N = 26). Half of the participants in the sham group were in the AC sham group (N = 13) and the remainder half were in the VC sham group (N = 13). All participants completed visual task which was identical to that used in Experiment 1 and 2. The entire experimental procedure lasted approximately 40 minutes including task instructions, practice, tDCS and the main experiment.

## Results

Data analysis and outlier removal (3.3% of total data) procedure was the same as for previous experiments. Four participants were excluded from the further analysis (n=3 from VC, n = 1 from sham tDCS group) due to excessive temporal recalibration effects (TREs 2 SD above group means).

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Figure 3 and Table 2 about here

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Figure 3 shows a significant TRE difference between VC real and sham tDCS groups [$t(43) = -1.856$, $p = .035$, $d = 0.566$, one-tailed]. Therefore, in line with our hypothesis, cathodal VC tDCS had a lowering effect on visual TRE compared to sham tDCS. AC real tDCS group exhibited an intermediate level of TRE that did not differ significantly from either sham tDCS [$t(42) = 1.160$, $p = .126$, one-tailed] or VC tDCS group [$t(47) = -0.591$, $p = .278$, one-tailed].

A one-way ANOVA on pre-test NMAs showed no significant differences between real AC, VC and sham tDCS groups [$F(2,66) = .46$, $p > 0.25$]. Groups also did not significantly differ for their post-stimulation subjective ratings (in terms of pain, attention and fatigue, ps > .25) indicating sham and real tDCS groups had the same perceived tDCS experience. In addition, there was no significant difference between groups in terms of handedness and musical sophistication scores (ps > .05).

**Discussion**

We investigated the contributions of the auditory and visual cortices to both auditory and visual temporal recalibration effect (TRE). Experiment 1 suggested that either visual TRE was affected by auditory cortex tDCS (by increasing TRE) or affected by visual cortex tDCS (by decreasing TRE). Experiment 2 showed a trend that auditory cortex tDCS decreased visual TRE compared with sham stimulation. Across these 2 experiments, auditory cortex tDCS did not change auditory TRE. Experiment 3 revealed that visual cortex tDCS significantly decreased visual TRE compared with sham tDCS, but auditory cortex tDCS produced an intermediate effect that did not differ from either visual cortex or sham tDCS effect. Taken together, we found that cathodal tDCS over the visual cortex, and to a lesser extent over the auditory cortex, produced decreased visual TRE. However, both auditory and visual cortex tDCS did not produce any measurable effects on auditory TRE, indicating the robustness of auditory temporal processing.

This study provides direct evidence for the involvement of the visual cortex in visuo-motor temporal recalibration. We found that cathodal tDCS over the visual cortex decreased visual TRE, instead of increasing it. Cathodal tDCS has a neural suppression effect by decreasing neuronal firing rate (Nitsche et al., 2008). Because temporal recalibration is a compensatory process for reducing a temporal delay between causally linked stimuli (Fujisaki et al., 2004), the decrease of TRE following the neural suppression of the primary visual cortex would mean that this compensatory processing is disrupted, and that the mechanism of visual TRE is sensory-specific to the visual system. This explanation is consistent with the perceptual shift account in TRE (Di Luca, Machulla, and Ernst, 2009; Sugano et al., 2015; Yarrow, Minaei, and Arnold, 2015). One might argue that visual cortex tDCS slowed down visual sensory processing speed, hence creating a further subjective delay between action and feedback during delay adaptation period. Against this possibility is that the slowing down of processing speed would also affect post-test NMAs. In this case, TRE would be increased rather than decreased. Alternatively, it was possible that visual cortex tDCS did not slow down visual sensory processing speed but that it disrupted an adaptive speeding of the detection of the pacing signal, thus, leading to decreased TRE (see Fig 1, Sugano, Keetels & Vroomen, 2015).

Our finding that tDCS over both auditory and visual cortices produced a decreasing effect of visual TRE is consistent with a previous transcranial magnetic stimulation (TMS) study reporting that both the auditory and visual cortices are involved in visual temporal discrimination process (Kanai et al., 2011). In particular, our finding of auditory cortex involvement during visual temporal recalibration, albeit perhaps weak, suggests that visual TRE can be transferred to the auditory system. This may explain why TRE occurred after adaptation to delayed visual feedback in auditory modality, but not the opposite (Sugano et al., 2012). In line with others, we suggest that temporal information is required to be transformed into auditory representation (Gutman et al., 2005; Kanai et al., 2011; Shih, Kuo, Yeh, Tzeng, & Hsieh, 2009; Sugano et al., 2012). If the visual temporal information is being translated into an auditory code, translation might require increased processing load for the visual temporal information than the auditory temporal information. Hence, this process might make visual temporal recalibration more vulnerable to tDCS.

We found that tDCS over the auditory cortex did not produce significant changes in auditory TRE. It has been shown that the auditory system has higher temporal precision and faster processing speed than the visual system (Andreassi & Greco, 1975; Molholm et al., 2002; Stone et al., 2001). Consequently, auditory timing information could be used for a frame of reference for temporal judgements (Di Luca et al., 2009). With tDCS over the auditory cortex, auditory temporal recalibration process would not be affected, because the auditory signal might serve as a reference (i.e., more trusted sensory estimate, see Di Luca et al., 2009 for further discussion). Hence, we suggest that the perceptual latency shift can occur in the motor component during auditory temporal recalibration, whereas in the visual temporal recalibration this shift can occur in the visual sensory component (see Figure 4B).

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Figure 4 about here

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Decrease of TRE by applying cathodal tDCS can have therapeutic implications for patients exhibiting increased TRE. Increased TRE can cause an increase of illusory reversals of cause and effect (Stetson et al., 2006) which diminishes sense of agency (SoA: feeling of authorship over one's action). For example, diminished SoA associated with increased TRE (Timm, Schönwiesner, SanMiguel, & Schröger, 2014) would result in attributing self-generated thoughts and actions to an external force in schizophrenia. Patients with schizophrenia showed a similar increased contraction of subjective time between their voluntary action and its consequence through an intentional binding paradigm (Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003; Maeda et al., 2012; Voss et al., 2010). Given that visual sensory adaptation could be transferred to auditory TRE (Heron et al., 2009; Sugano et al., 2010, 2012), this transference effect would need to be examined in patient studies when examining auditory TRE for future interventional studies.

There are some issues to consider in interpreting our results. First, we found pre-test negative mean asynchrony (NMA) differences between conditions and groups, comparable to those in Sugano et al., (2015), even though handedness and musical sophistication scores were not different between groups in our study. NMAs can be affected by several factors such as musical ability, task modality and practice (see Repp, 2005; Repp and Su, 2012 for review). The issue of pre-test NMA difference is difficult to resolve. Nonetheless, our control analyses showed that our results were not significantly affected. Secondly, a related finding should be noted is that we found participants had increased NMAs if they had visual cortex tDCS in their first session, compared to the participants who did the task for the first time in the auditory task group in Experiment 1, although sessions were separated by a minimum of 2 days. This effect would need to be further investigated, as visual cortex tDCS may produce a long-lasting effect for auditory temporal processing. Finally, we chose the right auditory cortex as our stimulation site, based on right auditory cortex involvement in interval discrimination tasks in both auditory and visual modalities (Kanai et al., 2011), and a meta-analytic studies of fMRI time perception studies indicating right-sided auditory cortex activity across various time perception tasks (Wiener et al., 2009). It is possible that we did not stimulate the correct area (i.e., the left auditory cortex) to observe a disruption effect on auditory TRE. Against this possibility was that we observed a modulatory effect (albeit weak) of the right auditory cortex on visual TRE. This remote, indirect effect has frequently been reported in both tDCS and TMS literature (Lang et al.,2005; Blankenburg et al., 2010). We suggest that auditory TRE might be difficult to disturb because of the higher temporal precision of the auditory system and faster processing of the auditory modality than the visual modality (Andreassi & Greco, 1975; Molholm et al., 2002; Stone et al., 2001).

In conclusion, the present study showed, for the first time, that temporal recalibration process can be affected by brain stimulation techniques such as cathodal tDCS. We found robust evidence for modality-specific contribution of the visual cortex on visual TR, together with the robustness of auditory temporal recalibration process. Future studies would want to focus on cross-modal temporal recalibration transference and its neural basis, as it may have therapeutic implications for patients with abnormal TRE. With relatively large samples across three experiments, this study provided a basis for such future studies.

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## References

Andreassi, J. L., & Greco, J. R. (1975). Effects of bisensory stimulation on reaction time and the evoked cortical potential. Physiological Psychology, 3(2), 189-194.

Aschersleben, G., 2002. Temporal control of movements in sensorimotor synchronization. Brain Cogn. 48 (1), 66–79.

Blankenburg, F., Ruff, C. C., Bestmann, S., Bjoertomt, O., Josephs, O., Deichmann, R., & Driver, J. (2010). Studying the role of human parietal cortex in visuospatial attention with concurrent TMS–fMRI. Cerebral Cortex, 20(11), 2702-2711.

Brunoni, A. R., Amadera, J., Berbel, B., Volz, M. S., Rizzerio, B. G., & Fregni, F. (2011). A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation. International Journal of Neuropsychopharmacology, 14(8), 1133-1145.

Chen, L., & Vroomen, J. (2013). Intersensory binding across space and time: a tutorial review. Attention, Perception, & Psychophysics, 75(5), 790-811.

Clunies-Ross, K. L., Brydges, C. R., Nguyen, A. T., & Fox, A. M. (2015). Hemispheric asymmetries in auditory temporal integration: a study of event-related potentials. Neuropsychologia, 68, 201-208.

Di Luca, M., Machulla, T. K., & Ernst, M. O. (2009). Recalibration of multisensory simultaneity: cross-modal transfer coincides with a change in perceptual latency. Journal of vision, 9(12), 7-7.

Fujisaki, W., Shimojo, S., Kashino, M., & Nishida, S. Y. (2004). Recalibration of audiovisual simultaneity. Nature neuroscience, 7(7), 773-778.

Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS): a tool for double-blind sham-controlled clinical studies in brain stimulation. Clinical Neurophysiology, 117(4), 845-850.

Grahn, J. A., Henry, M. J., & McAuley, J. D. (2011). FMRI investigation of cross-modal interactions in beat perception: audition primes vision, but not vice versa. Neuroimage, 54(2), 1231-1243.

Guttman, S. E., Gilroy, L. A., & Blake, R. (2005). Hearing what the eyes see auditory encoding of visual temporal sequences. Psychological Science, 16(3), 228-235.

Haggard, P., Martin, F., Taylor-Clarke, M., Jeannerod, M., & Franck, N. (2003). Awareness of action in schizophrenia. Neuroreport, 14(7), 1081-1085.

Heron, J., Hanson, J. V., & Whitaker, D. (2009). Effect before cause: supramodal recalibration of sensorimotor timing. PLoS One, 4(11), e7681-e7681.

Kanai, R., Lloyd, H., Bueti, D., & Walsh, V. (2011). Modality-independent role of the primary auditory cortex in time estimation. Experimental brain research,209(3), 465-471.

Lang, N., Siebner, H. R., Ward, N. S., Lee, L., Nitsche, M. A., Paulus, W., ... & Frackowiak, R. S. (2005). How does transcranial DC stimulation of the primary motor cortex alter regional neuronal activity in the human brain? European Journal of Neuroscience, 22(2), 495-504.

Lewald, J., Meister, I. G., Weidemann, J., & Töpper, R. (2004). Involvement of the superior temporal cortex and the occipital cortex in spatial hearing: evidence from repetitive transcranial magnetic stimulation. Journal of cognitive neuroscience, 16(5), 828-838.

Maeda, T., Kato, M., Muramatsu, T., Iwashita, S., Mimura, M., & Kashima, H. (2012). Aberrant sense of agency in patients with schizophrenia: Forward and backward over-attribution of temporal causality during intentional action. Psychiatry research, 198(1), 1-6.

Meyer, M., Baumann, S., Marchina, S., & Jancke, L. (2007). Hemodynamic responses in human multisensory and auditory association cortex to purely visual stimulation. BMC neuroscience, 8(1), 14.

Molholm, S., Ritter, W., Murray, M. M., Javitt, D. C., Schroeder, C. E., & Foxe, J. J. (2002). Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study. Cognitive brain research, 14(1), 115-128.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: an index for assessing musical sophistication in the general population. PloS one, 9(2), e89642.

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., ... & Pascual-Leone, A. (2008). Transcranial direct current stimulation: state of the art 2008. Brain stimulation, 1(3), 206-223.

Nitsche, M. A., Liebetanz, D., Antal, A., Lang, N., Tergau, F., & Paulus, W. (2003a). Modulation of cortical excitability by weak direct current stimulation–technical, safety and functional aspects. Suppl Clin Neurophysiol, 56(3), 255-276.

Nitsche, M. A., Nitsche, M. S., Klein, C. C., Tergau, F., Rothwell, J. C., & Paulus, W. (2003b). Level of action of cathodal DC polarisation induced inhibition of the human motor cortex. Clinical Neurophysiology, 114(4), 600-604.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia, 9(1), 97-113.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. Psychonomic bulletin & review, 12(6), 969-992.

Repp, B.H., Su, Y.H., 2013. Sensorimotor synchronization: a review of recent research (2006–2012). Psychon. Bull. Rev. 20 (3), 403–452.

Shih, L. Y., Kuo, W. J., Yeh, T. C., Tzeng, O. J., & Hsieh, J. C. (2009). Common neural mechanisms for explicit timing in the sub-second range. Neuroreport, 20(10), 897-901.

Stetson, C., Cui, X., Montague, P. R., & Eagleman, D. M. (2006). Motor-sensory recalibration leads to an illusory reversal of action and sensation.Neuron, 51(5), 651-659.

Stone, J. V., Hunkin, N. M., Porrill, J., Wood, R., Keeler, V., Beanland, M., ... & Porter, N. R. (2001). When is now? Perception of simultaneity. Proceedings of the Royal Society of London B: Biological Sciences, 268(1462), 31-38.

Sugano, Y., Keetels, M., & Vroomen, J. (2010). Adaptation to motor-visual and motor-auditory temporal lags transfer across modalities. Experimental brain research, 201(3), 393-399.

Sugano, Y., Keetels, M., & Vroomen, J. (2012). The build-up and transfer of sensorimotor temporal recalibration measured via a synchronization task. Frontiers in psychology, 3.

Sugano, Y., Keetels, M., & Vroomen, J. (2014). Concurrent sensorimotor temporal recalibration to different lags for the left and right hand. Frontiers in psychology, 5.

Sugano, Y., Keetels, M., & Vroomen, J. (2015). Auditory dominance in motor-sensory temporal recalibration. Experimental brain research, 1-14.

Teikari, P., Najjar, R. P., Malkki, H., Knoblauch, K., Dumortier, D., Gronfier, C., & Cooper, H. M. (2012). An inexpensive Arduino-based LED stimulator system for vision research. Journal of neuroscience methods, 211(2), 227-236.

Timm, J., Schönwiesner, M., SanMiguel, I., & Schröger, E. (2014). Sensation of agency and perception of temporal order. Consciousness and cognition, 23, 42-52.

Vroomen, J., Keetels, M., De Gelder, B., & Bertelson, P. (2004). Recalibration of temporal order perception by exposure to audio-visual asynchrony. Cognitive brain research, 22(1), 32-35.

Voss, M., Moore, J., Hauser, M., Gallinat, J., Heinz, A., & Haggard, P. (2010). Altered awareness of action in schizophrenia: a specific deficit in predicting action consequences. Brain, 133(10), 3104-3112.

Wiener, M., Turkeltaub, P., & Coslett, H. B. (2010). The image of time: a voxel-wise meta-analysis. Neuroimage, 49(2), 1728-1740.

Yarrow, K., Sverdrup-Stueland, I., Roseboom, W., & Arnold, D. H. (2013). Sensorimotor temporal recalibration within and across limbs. Journal of Experimental Psychology: Human Perception and Performance, 39(6), 1678.

Yarrow, K., Minaei, S., & Arnold, D. H. (2015). A model-based comparison of three theories of audiovisual temporal recalibration. Cognitive psychology, 83, 54-76.

Yau, J. M., Celnik, P., Hsiao, S. S., & Desmond, J. E. (2014). Feeling Better Separate Pathways for Targeted Enhancement of Spatial and Temporal Touch. Psychological science, 0956797613511467.

Zimmer, U., Lewald, J., Erb, M., Grodd, W., & Karnath, H. O. (2004). Is there a role of visual cortex in spatial hearing? European Journal of Neuroscience, 20(11), 3148-3156.

## Figure and table captions

**Figure 1.** Temporal recalibration effects in auditory cortex (AC) and visual cortex (VC) tDCS conditions in auditory and visual task groups. Temporal recalibration effect is calculated by subtracting pre-test negative mean asynchronies from post-test negative mean asynchronies. Errors bars represent SEMs. Values converted into positive for illustration purposes. *p = 0.018.

**Figure 2**. Temporal recalibration effects according to the modality of the task in each stimulation group (auditory cortex real tDCS group vs sham tDCS group). Temporal recalibration effect is calculated by subtracting pre-test negative mean asynchronies from post-test negative mean asynchronies. Error bars represent SEM. Values converted into positive for illustration purposes.

**Figure 3**. Temporal recalibration effects for the Auditory Cortex (AC), Sham and Visual Cortex (VC) tDCS groups. Temporal recalibration effect is calculated by subtracting pre-test negative mean asynchronies from post-test negative mean asynchronies. Errors bars represent SEMs. Values converted into positive for illustration purposes. *p = 0.035 (one-tailed).

**Table 1.** Mean control variables age, gender, handedness and musical sophistication for the sub-groups of all three experiments.

**Table 2**. Means and standard deviations for Negative Mean Asynchronies (NMAs) and Temporal Recalibration Effects (TREs) for three experiments.

Note: NMAs are presented in millisecond. Negative values indicate tap comes before the stimulus time. Temporal recalibration effect (TRE) calculated as subtracting pre-test performance from post-test performance. Standard deviations are presented in the parenthesis. Variability of the current results are consistent with previous studies using SMS task to measure temporal recalibration (Sugano et al., 2012; 2014; 2015).

**Figure 4.** Schematic representation of temporal recalibration in a sensorimotor synchronization paradigm and differential modality effects of delay adaptation. Time is not to scale. **(A)** A pacing stimulus (either auditory or visual stimulus) was presented 15 times with a constant 750ms inter-stimulus interval. Tapping responses precede the stimulus onset by 20 to 80 milliseconds on average before temporal recalibration (pre TR tapping). This negative mean asynchrony (NMA) may represent participants' subjective tap-stimulus synchrony. After a delay adaptation phase (illustrated in Figure 4B), participants tap even earlier (post TR tapping) than pre TR tapping, thereby establishing a new subjective tap-stimulus asynchrony. Temporal recalibration effect (TRE) was obtained by subtracting averaged pre TR NMA from averaged post TR NMA values. Note that the perceptual element of the pacing stimulus was assumed to be constant (not shifted in post TR) in diagram A. **(B)** Potential mechanisms of subjective time compression following adaptation to a repeated button press and a delayed feedback. In our study, participants voluntarily pressed the button 15 times and a delayed feedback (150ms) was delivered after each button press. TR produces a subjective time compression between the action and the feedback. Our results suggest that motor-auditory delay adaptation (M-A) causes a slowing down of the motor component (dashed arrow pointing right). This is supported by the robustness of auditory TRE against the effect of tDCS. By contrast, motor-visual delay adaptation (M-V) produces speeding-up of visual processing (dashed arrow pointing left). This is supported by the decreasing effect of visual cortex tDCS on visual TRE.

**Figure 1, 2, 3 and 4 are presented in separate files**

**Table 1**

| | Task Modality | Stimulation Area/Type | Age | Gender (number of males) | Handedness | Musical Sophistication |
|---|---|---|---|---|---|---|
| **Experiment 1** | Auditory | AC Real | 25.2 (4.7) | 11 | L: 4.9 (5.2), R: 15.1 (5.2) | 82.8 (16.0) |
| | | VC Real | 25.2 (4.7) | 11 | L: 4.9 (5.2), R: 15.1 (5.2) | 82.8 (16.0) |
| | Visual | AC Real | 23.3 (3.5) | 16 | L: 4.0 (6.5), R: 16.0 (6.5) | 79.5 (19.8) |
| | | VC Real | 23.3 (3.5) | 16 | L: 4.0 (6.5), R: 16.0 (6.5) | 79.5 (19.8) |
| **Experiment 2** | Auditory | AC Real | 20.1 (1.7) | 10 | L: 3.9 (5.2), R: 15.7 (5.3) | 60.6 (15.2) |
| | | AC Sham | 19.9(1.1) | 9 | L: 2.1 (3.2), R: 17.9 (3.2) | 62.0 (11.0) |
| | Visual | AC Real | 20.1 (1.7) | 10 | L: 3.9 (5.2), R: 15.7 (5.3) | 60.6 (15.2) |
| | | AC Sham | 19.9(1.1) | 9 | L: 2.1 (3.2), R: 17.9 (3.2) | 62.0 (11.0) |
| **Experiment 3** | Visual | AC Real | 20.9 (5.8) | 10 | L: 2.9 (4.3), R: 13.7 (5.9) | 65.8 (17.7) |
| | | VC Real | 19.7 (3.1) | 7 | L: 5.0 (5.6), R: 11.6 (5.5) | 61.8 (11.5) |
| | Visual | Sham | 19.3 (1.3) | 6 | L: 3.8 (4.3), R: 14.3 (4.5) | 61.2 (14.6) |

**Table 2**

| | Task Modality | Stimulation Area/Type | Pre-test | Post-test | TRE |
|---|---|---|---|---|---|
| **Experiment 1** | Auditory | AC Real | - 101.5 (45.8) | - 131.4 (45.8) | -29.8 (29.9) |
| | | VC Real | - 89.3 (55.7) | - 123.1 (52.2) | -33.8 (29.4) |
| | Visual | AC Real | - 90.2 (34.7) | - 135.5 (49.4) | -45.3 (49.4) |
| | | VC Real | - 104.1 (51.5) | - 130.6 (47.4) | -26.5 (45.0) |
| **Experiment 2** | Auditory | AC Real | - 111.8 (60.4) | - 131.6 (55.2) | -19.7 (39.4) |
| | | AC Sham | - 125.1 (47.3) | - 147.1 (37.2) | -22.0 (32.9) |
| | Visual | AC Real | - 90.1 (48.1) | - 106.4 (45.0) | -16.2 (37.4) |
| | | AC Sham | - 74.0 (50.7) | - 108.7 (46.0) | -34.7 (42.1) |
| **Experiment 3** | | AC Real | - 73.4 (56.3) | - 107.1 (46.4) | -33.7 (42.9) |
| | | VC Real | - 87.6 (55.9) | - 108.3 (50.7) | -20.6 (28.8) |
| | | Sham | - 73.6 (52.6) | - 114.5 (50.7) | -40.8 (41.1) |