Title: Transcranial magnetic stimulation of the occipital cortex interferes with foot movements in blind individuals

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Abstract

Research in blind individuals has shown that after visual loss, the occipital cortex can be reorganized and repurposed for nonvisual perception and cognitive functions. However, no studies have directly examined the involvement of the visual cortex in motor function. Here, we show that a rhythmic foot movement performed by blind individuals can be disrupted by transcranial magnetic stimulation (TMS) to their primary and secondary visual cortex (V1/V2). This disruptive effect of TMS was absent for sighted participants. Our result suggests that the visual cortex of blind individuals is involved in sensorimotor control. This is the first experimental evidence that functional repurposing of the human visual cortex is not be restricted to perception and cognitive functions, but also extends to motor function.

Introduction

Sensory loss can lead to dramatic plasticity of the cerebral cortex (Merabet et al., 2005, Merabet and Pascual-Leone, 2010). There is accumulating evidence for cross-modal plasticity after visual loss, where the visual cortex is reorganized to participate in the remaining sensory modalities. For example, the visual cortex of blind individuals responds to auditory (Kujala et al., 1995, Weeks et al., 2000, Amadeo et al., 2019, Vetter et al., 2020) and tactile stimuli (Sadato et al., 1996, Cohen et al., 1997, Burton et al., 2002, Pietrini et al., 2004, Ptito et al., 2008). This cross-modal plasticity has been regarded as the neural underpinnings driving blind individuals' superior ability over sighted individuals in nonvisual perception like sound localization and tactile spatial discrimination (Lessard et al., 1998, Roder et al., 1999, Goldreich and Kanics, 2003, Voss et al., 2004). Furthermore, researchers have suggested that the visual cortex can also be reorganized to contribute to higher cognitive processes like verbal memory, language processing, and mathematical processing (Amedi et al., 2003, Amedi et al., 2004, Bedny et al., 2011, Kanjlia et al., 2016). Thus, the visual cortex of blind individuals takes a more prominent role in nonvisual perception and cognitive functions than the visual cortex of sighted individuals.

Despite this understanding, surprisingly few studies have examined whether the visual cortex can be reorganized to contribute to sensorimotor control. Previous studies have reported that the primary visual cortex (V1) of blind individuals can be recruited for cognitive tasks involving motor output like braille reading tasks (Sadato et al., 1996, Cohen et al., 1997, Burton et al., 2002). However, the recruitment of V1 has been attributed to their nonvisual perception or cognitive function, but not motor function. To

our knowledge, only one study has suggested that the visual cortex may be reorganized to participate in sensorimotor control involving the spared sensory modalities, with blind opossums being superior to sighted ones in somatosensory-based motor control during ladder-rung walking (Englund et al., 2020). The direct evidence in humans is, however, still lacking.

To directly test the possibility that the visual cortex can be reorganized for sensorimotor control, we applied transcranial magnetic stimulation (TMS) to the occipital cortex, including the primary and secondary visual cortex (V1/V2), of blind participants during a rhythmic foot movement. We found that TMS of the occipital cortex increases the variability of this foot movement in the blind participants but not in sighted controls. Our results suggest that the visual cortex of blind individuals is reorganized to contribute to sensorimotor control.

Results

Twelve acquired blind participants, including six athletes (current or former members of the Japanese national blind football team; see Methods), and twelve age-matched sighted participants participated in the experiment (see Table 1 for participant characteristics). Blindfolded participants in both groups made rhythmic movements of alternating dorsiflexion and plantar flexion of the feet (Fig. 1A) without any sound cue. We selected this rhythmic and alternating lower limb movement because it can be easily performed without vision. The participants were instructed to keep their movement frequency (1 Hz) as constant as possible.

During the movement, 20 single TMS pulses were applied to one of 14 stimulation sites over the occipital cortex (Fig. 1B) with 2–4 s interstimulus intervals (see Methods for details). The intensity of TMS used in the experiment was comparable between the blind (mean ± standard deviation across participants; 77.083% ± 11.968% of the maximum stimulator output) and sighted (84.583% ± 9.643%) groups (unpaired t-test: $t_{22} = 1.691$, $p = 0.105$ without correction). In addition, no-stimulation trials were conducted in which the participants performed the same movements without TMS. We evaluated the effects of TMS on the rhythmic foot movement by quantifying the variability of the movement frequency with the standard deviation (SD) of the cycle duration (Fig. 1A, see Methods for details). We did not observe any immediate motor effects of TMS, such as muscle twitching or movement stops. We also did not find any TMS effect specific to movement phases of the cycle. Our main target area in this study was the early visual cortex. Thus,

the results we show in the main text are limited to stimulation site #11 (see Fig. 1B), which corresponds to the putative V1/V2 (pV1/V2). Supplementary Fig. S1 reports the average SD over all stimulation sites, covering broader visual areas.

We first confirmed that both groups of participants successfully performed the instructed movement. The average movement frequency frequencies over all trials in the stimulation and no-stimulation conditions were 0.942 ± 0.168 Hz and 0.968 ± 0.163 Hz for the blind and sighted groups, respectively. Importantly, no significant difference was found between the groups (unpaired t-test: $t_{22} = 0.381$, $p = 0.707$ without correction).

We did, however, find distinct group differences in the effect of TMS on movement performance. TMS to pV1/V2 interfered with the foot movements in the blind group (blue bars in Fig. 2) but not in the sighted group (red bars in Fig. 2). We performed a two-way mixed-design analysis of variance (ANOVA) on the SD with a within-subject factor of stimulation condition (no-stimulation vs. stimulation to pV1/V2) and a between-subject factor of group (blind vs. sighted). We found neither a significant main effect of stimulation condition ($F_{1,22} = 2.195$, $p = 0.153$, $\eta_p^2 = 0.088$) nor a significant main effect of group ($F_{1,22} = 2.133$, $p = 0.158$, $\eta_p^2 = 0.091$). However, we observed a significant interaction ($F_{1,22} = 4.318$, $p = 4.959 \times 10^{-3}$, $\eta_p^2 = 0.164$). Given the significant interaction, we first examined the effect of stimulation condition within each group. We found that TMS to pV1/V2 increased the SD in the blind group compared with the no-stimulation condition (paired t-test: $t_{11} = 2.643$, $p = 0.046$ with correction) but not in the sighted group (paired t-test: $t_{11} = 0.415$, $p = 0.686$ without correction) (Fig. 2 and Table 2).

In the blind group, the increase in SD for the TMS was not correlated with their age ($r = -0.124$, $p = 0.700$), the age at onset of visual loss ($r = -0.040$, $p = 0.902$), or the duration of visual loss ($r = 0.105$, $p = 0.746$). Moreover, this increase in SD did not differ between the athlete blind (BL^A in Table 1 and 2, blue solid lines in Fig. 2) and nonathlete blind subgroups (BL^{NA}, blue dashed lines; unpaired t-test: $t_{10} = 0.030$, $p = 0.977$ without correction).

Next, we evaluated the effect of group within each stimulation condition given the above significant interaction. We found no significant difference between the groups in the stimulation-to-pV1/V2 condition (unpaired t-test: $t_{22} = 1.068$, $p = 0.297$ without correction; Fig. 2). In contrast, we observed a trend in the no-stimulation condition where the SD was smaller in the blind group than the sighted group (unpaired t-test: $t_{22} = 1.803$,

$p = 0.085$ without correction; Fig. 2). The lower mean of SD in the blind group was mainly due to the athlete blind subgroup whose mean (solid blue lines in Fig. 2) was prominently lower in the no-stimulation condition than the sighted group (red lines; see also $SD_{no\text{-}stim}$ in Table 2). The SD in the nonathlete blind subgroup (blue dashed lines) was comparable to the sighted group.

Finally, when we conducted the same ANOVA on the average SD over all the stimulation sites (Fig. S1), we found no significant main effect of stimulation condition ($F_{1,22} = 2.455$, $p = 0.131$, $\eta_p^2 = 0.100$) or group ($F_{1,22} = 2.773$, $p = 0.112$, $\eta_p^2 = 0.112$), and no significant interaction ($F_{1,22} = 2.397$, $p = 0.136$, $\eta_p^2 = 0.098$; Fig. S1).

Discussion

We showed that TMS to the pV1/V2 disrupts a foot movement task in blind individuals but not in sighted individuals. Our results provide the first neurobehavioral evidence that the visual cortex of blind individuals contributes to sensorimotor control. Numerous studies have reported that the visual cortex of blind individuals is reorganized to participate in nonvisual perception and cognitive functions (Merabet and Pascual-Leone, 2010, Fine and Park, 2018, Castaldi et al., 2020). Our finding extends the knowledge about the reorganization of the visual cortex in blind individuals. Specifically, the visual cortex can be reorganized not only for perceptual and cognitive functions, but also for motor function.

We first discuss possible confounders for our results. The disruptive TMS effect (i.e., increase in the SD) may have been observed only in the blind group because half of them were experts in the sensorimotor control of foot movements (i.e., current or former members of the Japanese national blind football team (BL^A)). It is true that the baseline performance in the BL^A was better than the nonathlete blind subgroup (BL^{NA}) or the sighted group ($SD_{no\text{-}stim}$ in Table 2). However, note that the disruptive TMS effect (ΔSD in Table 2) observed in the BL^A was also observed in the BL^{NA} group although the BL^{NA} group showed a similar baseline performance to the sighted group ($SD_{no\text{-}stim}$ in Table 2). Therefore, we claim that the disruptive effect of TMS observed in the blind participants cannot be attributed to the athletes or their superior baseline performance.

Another concern is that the disruptive TMS effect in the blind group may be mainly caused by sensory side effects of TMS, such as tactile (pain) sensations or a clicking

sound (Duecker and Sack, 2015). However, this is unlikely. We carefully calibrated the TMS intensity for each participant so that TMS did not induce pain (see Methods). In addition, no participant reported any nociceptive feelings, including pain or noisy sounds, during the experiment. Notably, the TMS intensity used in the experiment did not differ between the blind and sighted groups (see Results and Table 1). Therefore, the subjective and objective intensity of the sensory side effects is likely similar between the groups. We thus argue that the difference of the TMS effect on motor performance between the blind and sighted groups can be attributed to differences in the neural processing of their visual cortex during the movement task rather than from sensory side effects of TMS.

Our results suggest that the engagement of the visual cortex in sensorimotor control does not depend on the age at onset of blindness, a finding similar to previous reports on the reorganization for perception and cognitive functions (Burton, 2003, Voss et al., 2006, Bedny et al., 2012, Holig et al., 2014). Our sample of acquired blind participants covered a broad range of ages at onset of blindness: five early-blind (age < 6 years), three intermediate-blind (6 ≤ age ≤ 16 years), and four late-blind participants (age > 16 years) (Voss, 2013, Fine and Park, 2018). Except for one late-blind participant (# 9), all blind participants showed an increase in the SD when TMS was applied to pV1/V2 (Fig. 2). Furthermore, we did not find a significant correlation between the increase in SD and the age at onset of blindness. Thus, the amount of visual experience before the participants lost their vision appears not to affect the degree of visual cortex engagement.

However, some visual experience may be necessary to engage the visual cortex in sensorimotor control. For example, none of the four congenitally blind participants in our supplementary experiment showed any clear increase in the SD when TMS was applied to pV1/V2 (Fig. S2, Table S1, and S2). Although we should be cautious due to the limited sample size, this would suggest the necessity of at least some visual experience for the neural reorganization.

We can speculate a possible mechanism for the reorganization of the visual cortex for sensorimotor control based on our main findings and the preliminary results from the congenitally blind participants. Visually-guided movements appear early in human development at around 6-8 months of age (Woodward, 1998, Braddick, 1996, Kanakogi and Itakura, 2011). This suggests the neural connections between the visual cortex and sensorimotor regions, which are essential for visually-guided motor control (Gallivan et al., 2019), are formed at a very early stage of development. However, work in mice

suggests that normal visuomotor experiences are necessary for the typical development of this connection (Leinweber et al., 2017). This neural connection may therefore be established to some extent through visuomotor experiences before vision loss in both early- and late-blind individuals, experiences which may not occur in congenitally blind individuals. Then, after visual loss, the existing neural connections are enhanced and reorganized (Merabet et al., 2005, Merabet and Pascual-Leone, 2010) for sensorimotor control of nonvisually-guided movements such as the motor task used in the present study. Further studies are required to investigate this possible reorganization mechanism by examining a larger number of congenitally, early-acquired, and late-acquired blind participants.

Although the current study cannot identify the exact functional roles of the visual cortex of the blind participants in their motor production, we can hypothesize possible roles based on a computational understanding of sensorimotor control (Scott, 2004). First, the visual cortex almost certainly does not contribute to the generation of motor commands, as we observed that TMS did not induce immediate motor effects such as muscle twitching or movement stops. Instead, our observation of the increased movement variability may indicate that TMS affected higher-order aspects of sensorimotor control (e.g. temporal processing) or feedback control processing. Specifically, we speculate that TMS affected the online estimation of the body state (i.e., position, velocity, or movement phase of the foot), which is transformed into motor commands through motor regions (Todorov and Jordan, 2002, Scott, 2004, Diedrichsen et al., 2010, Takei et al., 2021). This state estimation is thought to be achieved by combining sensory feedback and sensory prediction–predicting the sensory consequences of motor commands (Wolpert and Flanagan, 2001, Shadmehr et al., 2010, Ikegami and Ganesh, 2017). Many studies on cross-modal plasticity have suggested the visual cortex in blind individuals processes nonvisual sensory information (Merabet et al., 2005, Merabet and Pascual-Leone, 2010). Therefore, the visual cortex can receive the nonvisual (likely proprioceptive) sensory feedback of the foot state. In addition, recent studies in both sighted mice and humans have provided growing evidence supporting the role of the visual cortex in predicting the visual consequences of movements (e.g., optical flow) through the connection between the visual cortex and motor regions (Keller et al., 2012, Saleem et al., 2013, Leinweber et al., 2017, Buaron et al., 2020). Therefore, if the connection is reorganized to predict the nonvisual consequences of movements, the visual cortex in blind individuals can contribute to the state estimation by combining a nonvisual feedback signal and a sensory prediction.

We would like to note two methodological limitations of our study. First, we determined stimulation sites (see Methods for additional information) without using a navigation system guided by magnetic resonance imaging (Amedi et al., 2004). Thus, some between-participant differences may exist in the anatomical locations of stimulation sites. However, we focused on the V1/V2, and the corresponding stimulation site (#11) was determined based on the well-established external anatomical landmark (2.5 cm above inion; Beckers and Zeki, 1995, Cowey and Walsh, 2000, Laycock et al., 2007, Salminen-Vaparanta et al., 2012). Therefore, we are confident that we stimulated V1/V2 when TMS was applied to stimulation site #11.

Second, we cannot deny the concern regarding implicit side effects of TMS. As already mentioned, none of the participants explicitly claimed nociceptive feelings during the experiment. The possibility remains, however, that TMS-induced tactile sensations or TMS clicking sounds implicitly affected the movement performance only in the (acquired) blind participants. Further studies are required on the implicit attention of blind individuals to TMS-induced nonvisual sensations to address this concern.

In conclusion, our study is the first to provide neurobehavioral evidence that the visual cortex of blind individuals contributes to sensorimotor control. Our findings indicate that the human brain's plasticity after sensory loss is more flexible than previously thought–functional repurposing of the lower sensory cortices is not be restricted to perception and cognitive functions but also extends to motor function. This plasticity may increase the neural resources available for sensorimotor control in blind individuals and help them navigate or interact with the ever-changing and diverse environment around us without vision.

Methods

Participants

Twelve acquired blind (i.e., lost vision after birth (blind group: BL in Table 1)) and twelve age-matched sighted (sighed group: SI) individuals with normal or corrected-to-normal vision participated in the experiment. All participants were healthy male volunteers without a history of cognitive impairment or psychiatric disorders. They all presented no contraindications to TMS as assessed using a screening questionnaire in compliance with the guidelines for noninvasive magnetic brain stimulation in research applications. The blind group consisted of two subgroups: athlete (BL^{A} in Table 1) and nonathlete (BL^{NA}

in Table 1). The six blind participants in the BL^{A} subgroup were current or former members of the Japanese national blind football team. The remaining six in the BL^{NA} subgroup were blind individuals from the general population. All sighted participants were from the general population. We selected the sample size (n = 12 per group) based on previous works that examined the effect of TMS on motor tasks (Foltys et al., 2001, Orban de Xivry et al., 2011a, Orban de Xivry et al., 2011b, Mawase et al., 2017). The experiment was approved by the ethics committee of the National Institute of Information and Communications Technology and was conducted according to the Declaration of Helsinki. All participants provided written informed consent prior to participating in the experiment and were naïve to the purpose of the study.

Apparatus

All participants wore both eye patches and an eye mask to eliminate any possible visual stimuli ~30 min before the experiment began until the end. They were also instructed to close their eyes through the experiment. They sat in a comfortable reclining chair with their heads on a chinrest and legs extended on a leg rest. The height and location of the chinrest and the leg rest were adjusted for each participant so that they could comfortably make the rhythmic movements of alternating dorsiflexion and plantar flexion of their feet. The elevation angles of the first metatarsals of both feet from the horizontal plane were recorded using an electromagnetic position sensor (Micro Sensor 1.8 Extra Flex, Polhemus Liberty, Burlington, VT). The obtained data were digitized with a temporal sampling ratio of 240 Hz and then low-pass filtered with a cutoff frequency of 5 Hz.

Electromyographic (EMG) activity was recorded at 2,000 Hz utilizing surface electrodes from the medial and lateral heads of the gastrocnemius and tibialis anterior of both legs using wireless EMG sensors (Wave Plus Wireless EMG, Cometa, Bareggio, Italy). This EMG recording was prepared to capture possible muscle twitches with TMS. However, as we did not observe any twitches, EMG data are not reported in this study.

TMS stimulation was applied using a 70-mm figure-eight coil and a Magstim Rapid Transcranial Magnetic Stimulator (Magstim Company, Spring Gardens, UK). The maximum stimulator output was 2.1 T. TMS pulse delivery was controlled by an in-house program running on MATLAB, version R2013b (The MathWorks, Natick, MA).

TMS protocol

The stimulation sites for each participant were identified using an elastic swimming cap

with 14 (2 × 7) markers (Fig. 1B). The marker positions were determined by a cap worn by a male individual with an average head size for Japanese men (head circumference: ~57 cm; Kouchi and Mochimaru, 2008) who did not participate in the experiment. The markers were placed at inion, 2.5 cm (stimulation site #11), and 5 cm (stimulation site #4) dorsal from the inion on the median line (nasion-to-inion line through the vertex), and 2, 4, and 6 cm right and left away from the median line at the same level as stimulation sites #4 and #11. Each participant wore the swimming cap on the head with 1) the inion mark placed at the participant's inion, 2) stimulation sites #4 and #11 aligned on the participant's median line, and 3) stimulation site #11 placed 2.5 cm dorsal from the inion to target V1/V2 (Fig. 1A) (Beckers and Zeki, 1995, Cowey and Walsh, 2000, Laycock et al., 2007, Salminen-Vaparanta et al., 2012).

Subsequently, the stimulation intensity for each participant was determined using the highest value that did not induce scalp pain in the individuals (Table 1). Single TMS pulses were applied to each stimulation site in order from sites #1 to #14. For stimulation site #1, stimulation was initially applied with 100% intensity of the stimulator output, and the intensity was decreased gradually by 5% until the participant reported no pain. Consequently, stimulation at each stimulation site was started with the highest intensity of stimulation that did not induce pain at the previous stimulation site. For each participant, the intensity of stimulation determined at stimulation site #14 was used as the stimulation intensity for the experiment.

Task procedure

The experiment was performed with the following task procedure. The participants were blindfolded and while sitting on the chair, made rhythmic alternative movements of dorsiflexion and plantar flexion of the feet without any sound cue. To keep the movement frequency as constant as possible, the participants practiced the movements with a sound frequency of 1 Hz for ~2 min twice: once before the determination process of the stimulation intensity and once before starting the experiment. They were instructed to maintain the consistent movement frequency throughout the experiment. No instructions were provided regarding the motion range of the foot movement.

In each experimental trial, the rhythmic movement was performed in each of the following three conditions. During the stimulation condition, 20 single TMS pulses were applied to one of the 14 stimulation sites at interstimulus intervals of 2–4 s (drawn from a uniform random distribution). The TMS coil was held tangentially to the scalp. The trial

was started 3 s before the first stimulation and ended 3 s after the last stimulation. Each trial duration was 56.34–70.26 s. During the sham condition, a fake coil was placed over stimulation site #11, while another coil delivered 20 single TMS pulses in the air near the fake coil. Thus, the participant could feel the clicking sound coming from the fake coil on the scalp. The duration and timing of the TMS pulses were determined according to the protocol used in the stimulation condition. During the no-stimulation condition, no coil was placed on the scalp, and the TMS pulses were not generated. The trial duration was set at 50 s.

The participants completed two blocks of 15 trials, including 14 stimulation trials (one for each of the 14 stimulation sites) and one sham trial. The trial order was pseudorandomized for each block. Each of the two no-stimulation trials was performed before the first block and after the second block. Thus, the participants completed a total of 32 experimental trials.

Data analysis

The effects of TMS on movement were examined by evaluating the movement frequency. For each foot in each trial, the duration of each movement cycle was determined, defined as the time between the adjacent dorsiflexion peaks (Fig. 1A and see details in the next paragraph), and the SD of the durations was calculated from all the movement cycles. Then, the SD for each stimulation site was obtained by averaging the four SD values for left and right feet in the two stimulation trials (first and second blocks). Similarly, the SD for the no-stimulation trials was calculated as control. For stimulation site #14 of participant #23 (Table 1), data from only the second block were utilized to calculate the SD because of the lack of the first block data due to a recording error. For stimulation site #5 of participant #20, the second block data of the left foot were excluded as the foot posture changed significantly during the trial. Notably, the data from the sham trials were not analyzed since almost all the participants (22/24) noticed the lack of stimulation and/or felt something going wrong during the trials. Hence, the data were likely biased by this surprising effect. The primary interest of our analysis was in the data obtained from stimulation site #11, which was putative V1/V2 (pV1/V2, see TMS protocol). Our analysis in the main text focused on stimulation site #11. The other stimulation sites may cover broad visual areas, including early (V1/V2) and higher-order (V3, V4, and V5) visual areas, according to the literature (Cowey and Walsh, 2000, Pascual-Leone and Walsh, 2001, Salminen-Vaparanta et al., 2012, Amemiya et al., 2017). To observe the overall trend of the TMS effect on the early and higher-order visual cortices, the average

SD of all the stimulation sites was analyzed, which is reported in supplementary Fig. S1.

The dorsiflexion peaks (Fig. 1A) for each foot of each trial were identified as follows. First, the time average of the elevation angle was calculated and subtracted from the entire time series to obtain the time series of a relative angle (θ in Fig. 1A). Then, the crossing times where θ changed from negative to positive were identified. Finally, the point of maximum value between each of the two consecutive crossing times was identified and defined as a peak. The identification code is available online (See Data availability).

Statistical analysis

Statistical analyses were conducted as follows. The effects of TMS on stimulation site # 11 (pV1/V2) were examined using a two-way mixed-design ANOVA on the SD with a within-subject factor of stimulation condition (no-stimulation vs. stimulation to pV1/V2) and a between-subject factor of group (blind vs. sighted). As a significant interaction was found, the effect of stimulus condition was examined within each group by a paired t-test, whereas the effect of group was examined within each stimulus condition by an unpaired t-test. The same ANOVA was conducted for the average SD of all the stimulation sites (Fig. S1). Since the blind group showed a significant increase in SD, correlation analyses were performed to examine the relationship of SD increase (ΔSD in Table 2; SD in stimulation condition minus SD in no-stimulation condition) with age, age at onset of visual loss, and duration of visual loss. We reported Pearson's correlation coefficients and statistical *p*-values for the test of no correlation. In addition, to evaluate the relationship between SD increase and the participants' sports experience, the athlete (BL^{A} in Table 1) and nonathlete (BL^{NA}) blind subgroups were compared using an unpaired *t*-test. The analyses were conducted in MATLAB version R2018b (The MathWorks, Natick, MA). The significance level was set at 0.05 in all the analyses. All t-tests were two-tailed, and the Bonferroni correction was used for multiple comparisons. All data have been presented as mean ± standard deviation for all the participants.

Data availability

Data and codes to reproduce Figs. 2, S1, and S2 and the related analyses are available from https://github.com/ikegami244/Blind-TMS. The code to identify the peaks is also available from the same repository.

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557 **Tables**

558 **Table 1. Characteristics of the participants**

Participant #	Group	Age (y)	Onset of blindness (y)	Cause of blindness	Light sensitivity at present	TMS intensity (%)
1	BL^{A}	26	2	retinoblastoma	none	80
2	BL^{A}	27	14	retinal choroidal degeneration	yes	75
3	BL^{A}	39	20	morning glory anomaly	none	85
4	BL^{A}	28	23	uveitis	yes	90
5	BL^{A}	20	1	retinoblastoma	none	75
6	BL^{A}	40	25	retinitis pigmentosa	yes	85
7	BL^{NA}	25	14	chorioretinal atrophy	yes	70
8	BL^{NA}	25	5	glaucoma	none	65
9	BL^{NA}	42	17	uveitis + glaucoma	occasional	70
10	BL^{NA}	19	2	behcet's disease	none	100
11	BL^{NA}	20	3	retinal cell death	none	75
12	BL^{NA}	19	15	glaucoma	none	55
13	SI	22	-	-	-	85
14	SI	22	-	-	-	85
15	SI	23	-	-	-	95
16	SI	22	-	-	-	90
17	SI	34	-	-	-	70
18	SI	35	-	-	-	85
19	SI	40	-	-	-	80
20	SI	26	-	-	-	75
21	SI	23	-	-	-	70
22	SI	27	-	-	-	100
23	SI	20	-	-	-	95
24	SI	39	-	-	-	85

559 *BL, blind; SI, sighted; y, year. Superscripts A and NA indicate athlete and nonathlete blind*
560 *participants, respectively.*

Table 2. SD values in non-stimulation condition (no-stim) and stimulation-to-pV1/V2 condition (stimulation site #11) and the increase in SD for each group

	$SD_{no\text{-}stim}$	$SD_{pV1/V2}$	ΔSD
BL (n=12)	**0.072 ± 0.045**	**0.085 ± 0.043**	**0.013 ± 0.017**
BL^{A} (n=6)	0.049 ± 0.013	0.063 ± 0.026	0.013 ± 0.019
BL^{NA} (n=6)	0.095 ± 0.055	0.108 ± 0.045	0.013 ± 0.018
SI (n=12)	**0.106 ± 0.048**	**0.104 ± 0.043**	**-0.002 ± 0.019**

BL, blind; SI, sighted; y, year. Superscripts A and NA indicate athlete and nonathlete blind participants, respectively. $\Delta SD = SD_{pV1/V2} - SD_{no\text{-}stim}$. *All data are reported as mean ± standard deviation across participants. The units are seconds.*

Figures

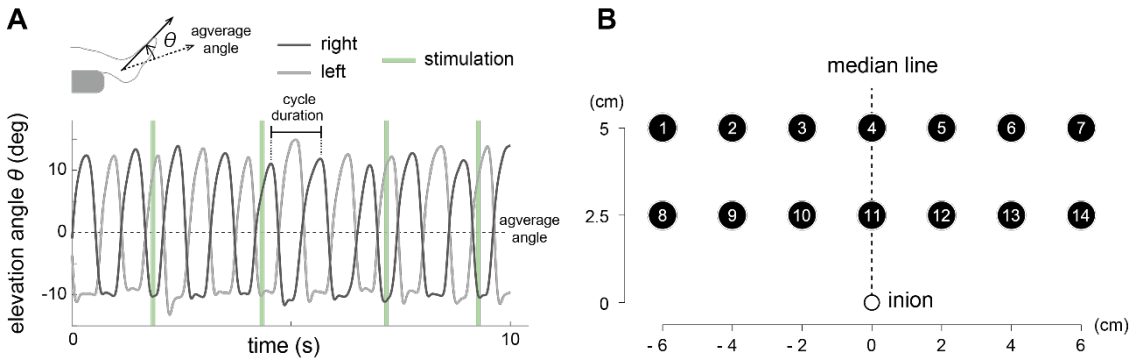

Fig. 1. The experiment and stimulation sites: A) The rhythmic foot movement of a representative participant for a 10-s period is shown by the elevation angle, θ of right foot (dark gray line) and left foot (light gray line). For each foot in each trial, θ is defined as the angle relative to the average angle of the trial (θ = 0, dashed line). Each light-green vertical line indicates the timing of a single transcranial magnetic stimulation (TMS) pulse delivered at random. The cycle duration was defined as the time between the adjacent dorsiflexion peaks. The SD of the cycle durations was calculated for each foot in each trial (see Methods). B) Fourteen stimulation sites arranged in a 2 × 7 grid were identified for each participant using the inion and the median line as reference points (see Methods). Stimulation site #11 corresponds to putative primary and secondary visual cortex (pV1/V2).

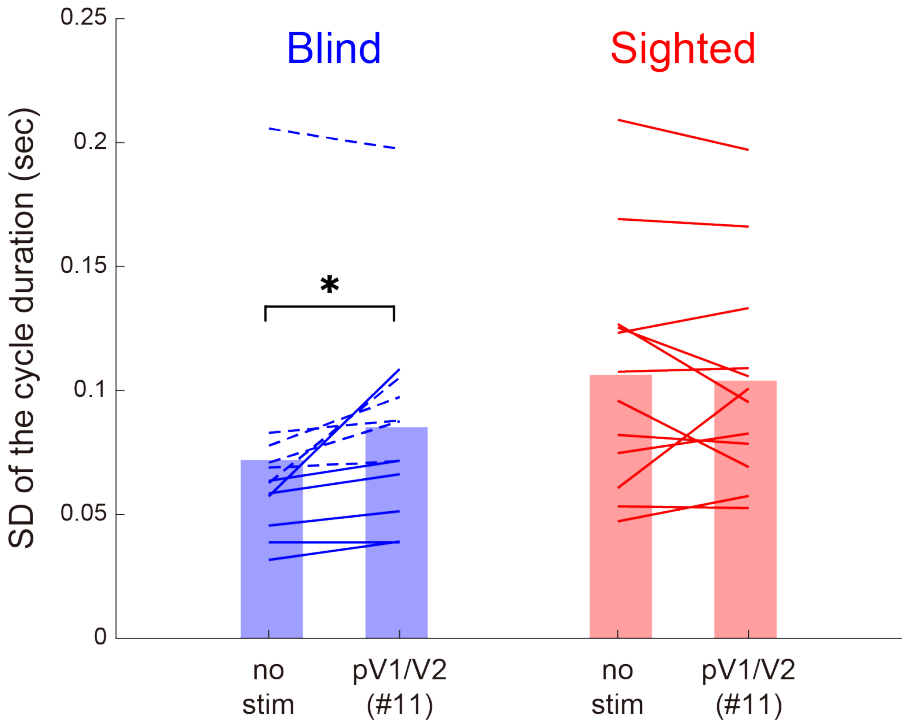

Fig. 2. SD of the cycle duration for blind (blue) and sighted (red) participants. The SD was compared between the no-stimulation condition (no-stim) and the stimulation condition in which TMS was applied over pV1/V2 (stimulation site #11). Each line represents data from an individual participant. For the blind participants, solid blue lines and dashed lines indicate subgroups of athletes (BL^{A}) and nonathletes (BL^{NA}), respectively. Bars indicate the mean. The asterisk indicates $p < 0.05$.

SUPPLEMENTARY INFORMATION

Supplementary figures

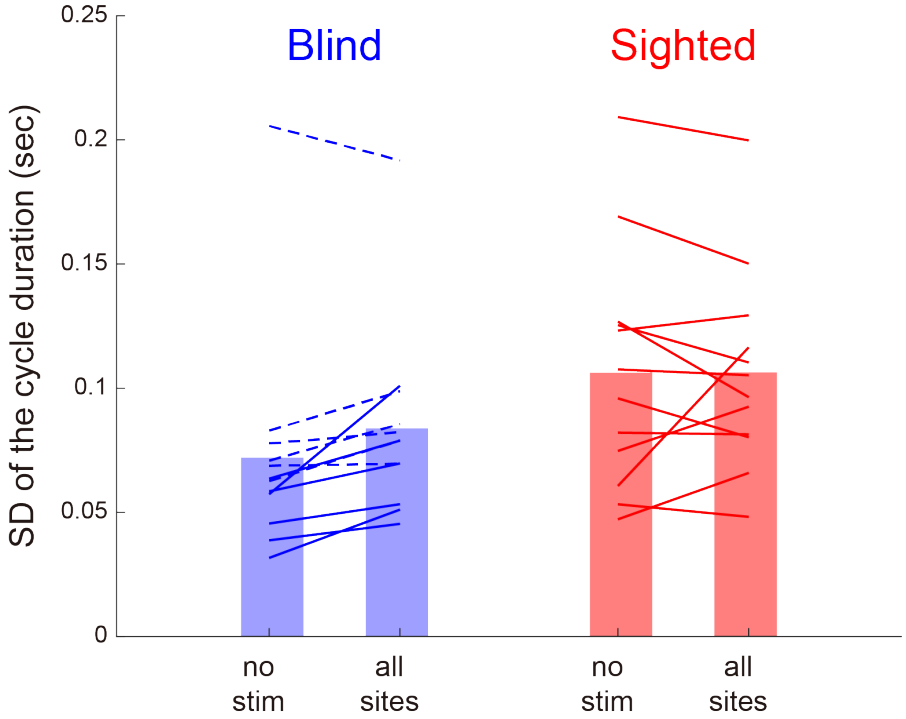

Fig. S1. SD of the cycle duration for blind (blue) and sighted (red) groups. The average SD over all stimulation sites was compared with the SD in the no-stimulation condition (no-stim). Each line represents data from an individual participant. For the blind group, solid blue lines and dashed lines indicate the subgroups of athletes (B^{LA}) and nonathletes (BL^{NA}), respectively. Bars indicate the mean.

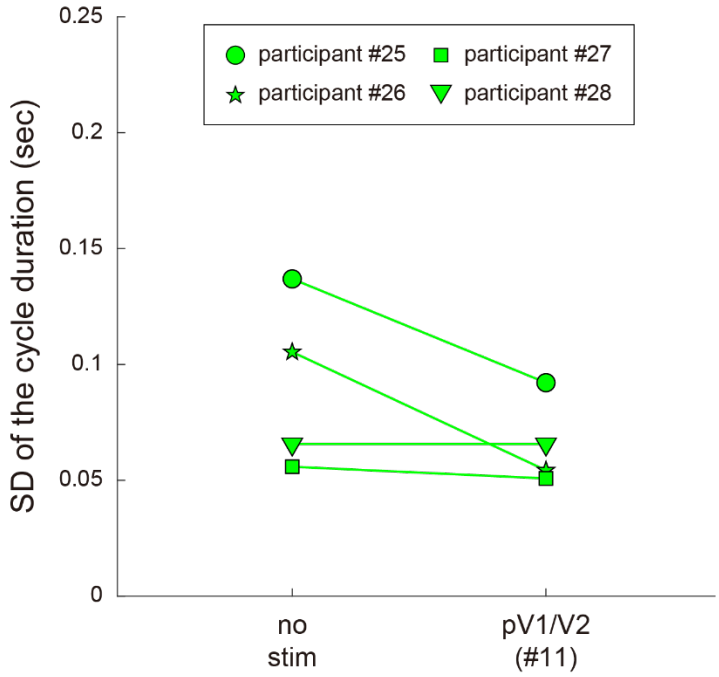

Fig. S2. SD of the cycle duration for congenitally blind participants for the no-stimulation condition (no stim) and the stimulation condition in which TMS was applied over pV1/V2 (stimulation site #11). Four congenitally blind participants, who had never experienced vision (CBL), participated in this supplementary experiment (see Supplementary Table S1). Each line represents data from an individual participant. In contrast to the result from the acquired blind participants (Fig. 2), TMS of pV1/V2 did not induce an evident increase in SD of the cycle duration relative to the no-stimulation condition in all of the participants.

Supplementary tables

Table S1. Characteristics of the congenitally blind participants

Participant #	Group	Age (y)	Onset of blindness (y)	Cause of blindness	Light sensitivity at present	TMS intensity (%)
25	CBL	29	birth	unknown	none	80
26	CBL	40	birth	cataract	none	95
27	CBL	36	birth	anophthalmia + persistent fetal vasculature	none	60
28	CBL	32	birth	amaurosis	yes	75

CBL, congenitally blind; y, year.

Table S2. SD values in non-stimulation trial (no-stim) and stimulation trial for pV1/V2 (stimulation site #11) and the increase for congenitally blind participants

	$SD_{no\text{-}stim}$	$SD_{pV1/V2}$	Δ SD
Participant #25	0.137	0.092	-0.045
Participant #26	0.105	0.054	-0.051
Participant #27	0.056	0.051	-0.005
Participant #28	0.066	0.066	0.000

$\Delta SD = SD_{pV1/V2} - SD_{no\text{-}stim}$. The units are seconds.