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Somatosensory stimulation on the wrist enhances the subsequent hand-choice by biasing toward the stimulated hand

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Hand choice is an unconscious decision frequently made in daily life. The electroencephalogram before target presentation correlates with hand choice for the target where hand choice probability reaches equilibrium. However, whether neurophysiological interventions before target presentation influence hand choice remains unknown. Therefore, this study determined whether instantaneous somatosensory electrical stimulation administered to the unilateral wrist at 0, 300, or 600 ms before the target presentation facilitates or inhibits stimulated hand choice for targets around the hand selection equilibrium point. A single electrical stimulation comprised five trains of 1 ms electrical pulses, with a 20 ms inter-pulse interval. The stimulus intensity was set at 80% of the motor threshold. This study included 14 right-handed healthy adults (five females and nine males; mean age, 25.1 ± 4.64 years). Unilateral wrist stimulation significantly increased the probability of choosing the stimulated hand and led to a faster reaction time than bilateral wrist stimulation and no-stimulation conditions. The results suggest that prior somatosensory stimulation significantly affects the hand-choice process, effectively promoting the selection of the stimulated hand. These findings highlight the potential application of this stimulation method in stroke rehabilitation to facilitate the use of the paretic hand.

During daily activities, individuals unconsciously select the left or right hand to reach for an object. The choice of hand is mainly influenced by target-related information, including the location of the target (which hand can reach it with less effort) and shape and orientation of the target (which hand can grasp it more securely)[1–3]. However, the selection rate for each hand reaches equilibrium when the target-related factors are similar for the left and right hands[1]. The point of subjective equality (PSE) can be estimated as the virtual point in space where participants have an equal probability of using either hand to reach a target. PSE varies among individuals and tends to shift slightly to the left in right-handed individuals[3,4]. Reaction time (RT) becomes prolonged around the PSE compared with that outside the PSE, suggesting the presence of competition[3,5]. Oliveira et al. applied single-pulse transcranial magnetic stimulation (TMS) to introduce perturbation to the left posterior parietal cortex (PPC) after the target presentation and before the onset of reaching, the interval when competition is likely to occur[3]. Single-pulse TMS introduces random activity that disrupts neural activity, which is maintained between 50 and 200 ms in cortical neural activity[6,7]. A significant reduction in right-hand selection rates and prolongation in RTs were observed for targets positioned around the PSE than for those that were not, impeding competition resolution. This indicates the potential for intervening in the hand-selection process around the PSE. Interventions at the beginning of competition can aid in competition resolution and make one hand more favorable over the other[3]. Consequently, the intervened hand may be selected more quickly and with a higher selection probability.

Several studies have provided evidence in the field of perceptual decision-making showing that the state of the brain before the presentation of a target stimulus (before the competition starts) correlates with subsequent judgment around the PSE[8,9]. In a study by Bode et al., participants were required to select between two options: whether the image presented was of a piano or a chair[9]. The authors added noise to the images, and in one-quarter of the images, there was only noise with no discernable information to determine whether the image was of a piano or a chair. Electroencephalogram (EEG) features recorded before the presentation of the images

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without discriminative information can help to predict the selection outcomes[9]. Hamel-Thibault et al. compared EEG in the motor cortex during target presentation in a task where participants had to select the left or right hand to reach a target. The authors found that the hand contralateral to the motor cortex with a more negative instantaneous delta phase was more likely to be selected. The negative phase of the delta wave signals an increase in neural excitability, suggesting that hand selection can be predicted based on the excitability of the motor cortex by the time of the target presentation[10]. The authors also identified a correlation between the RT and delta phase in the motor area. These findings suggest that the neural state before target presentation influences subsequent hand selection; however, intervention studies are required to demonstrate the causal relationship. Hirayama et al. investigated the effects of a 10-min transcranial direct current electrical stimulation (tDCS) on hand selection and focused on stimulating the left and the right PPCs. Cathodal stimulation of the left PPC (inhibitory effect) and anodal stimulation of the right PPC (facilitatory effect), applied simultaneously, increased the probability of left-hand selection around the PSE[11]. This suggests that neuronal modulation of PPCs can bias the probability of hand selection. However, whether the neural state before the hand choice, as shown by Bode et al.[9], or that during the hand choice has an effect remains to be determined. To clarify this point, instantaneous intervention capable of altering neural excitability is necessary.

Peripheral nerve stimulation induces neural responses[3]. The electrical stimulation of the median or ulnar nerve at the wrist triggers responses in the primary somatosensory cortex (S1) and premotor cortex (PMC), with a short latency of approximately 30 ms. This triggers responses in the PPC after approximately 100 ms[12–15]. The latency from the presentation of visual information to the eyes and the primary visual cortex (V1) is approximately 100 ms, whereas that to the frontal and parietal regions is 150–200 ms[16–18]. Therefore, when somatosensory electrical stimulation is applied to the wrist simultaneously with visual information, the somatosensory information is estimated to reach the parietal and motor cortices before the visual information[3,10,11].

Therefore, this study determines whether short-term somatosensory electrical stimulation applied to the unilateral wrist at the time of or immediately before target presentation influences the probability of selecting the stimulated hand for targets around the PSE, where the selection rate is in equilibrium, and whether short-term somatosensory electrical stimulation shortens or prolongs the RT during hand selection. The results of this study will provide insights into the causal relationship between neurophysiological interventions prior to target presentation and hand selection. Practically, this work will facilitate biasing hand selection without conscious or deliberate effort by the individual through a simple and inexpensive method with the potential application in the rehabilitation of upper limb hemiparesis. Patients with hemiparetic stroke recover some ability to use their paretic hands through rehabilitation. However, in cases where both hands can be used, compensating with the non-paretic hand and not effectively using the paretic hand remain challenging, resulting in the functional decline in the paretic hand[19–21]. In such patients, PSE largely shifts to the paretic side[22]. The present technique will help to shift PSE to the non-paretic side in patients after stroke. This study will help to advance stroke rehabilitation to overcome the nonuse of the paretic hand by facilitating paretic hand choice.

Results

Participants were asked to reach given targets using either the left or right hand as quickly and accurately as possible. The targets were presented at nine random positions on the semicircle (Fig. 1A). The PSE was estimated using logistic regression, representing the point at which participants were equally likely to use either hand to reach the targets (Fig. 1B). Unilateral stimulus (right and left wrist), bilateral stimulus (as the control condition), and no-stimulus conditions were randomly assigned 18 times for each target position (Fig. 2). The stimulus intensity was set at 80% of the motor threshold, and the stimulus comprised five trains of 1-ms electrical pulses, with a 20-ms inter-pulse interval. The target was presented at 0, 300, or 600 ms after the somatosensory electrical stimulation (Fig. 3).

The participants' success rate was $90.2 \pm 6.3\%$ in the unimanual reach trial. The effect of the stimulation conditions on the PSE was investigated using a one-way repeated-measures analysis of variance (ANOVA, four stimulation conditions) (Fig. 4). A significant main effect was observed in the stimulation condition ($F_{(3, 39)} = 15.8$, $P < 0.01$, partial $\eta^2 = 0.55$). Multiple comparisons between each pair of stimulation conditions showed that the PSE in the left stimulation condition (PSE = $4.40° \pm 10.5°$) was significantly larger than that in the other stimulation conditions (adj $P < 0.05$). Conversely, the PSE in the right stimulation condition (PSE = $- 2.04° \pm 9.97°$) was significantly smaller than that in the other stimulation conditions (adj $P < 0.05$). There was no significant difference between the PSE in the bilateral stimulation condition (PSE = $- 0.84° \pm 10.6°$) and that in the no-stimulation condition (PSE = $1.75° \pm 11.3°$; adj $P = 0.16$). These findings indicate that the probability of hand choice increased with stimulation. To examine the effect of the timing of the stimuli (0, 300, and 600 ms) before the target presentation on hand selection, 95% confidence intervals of the PSE for each stimulus timing were calculated using bootstrapping with 10,000 resampling of the data to compensate for the limited data (Fig. 5). These findings suggest that the closer the stimulus timing was to the target presentation, the higher the probability of choosing the stimulated hand.

To determine whether somatosensory electrical stimulation facilitated or inhibited competition resolution for hand choice, for each participant, median RTs were computed for two targets near the PSE, where hand selection was in equilibrium (RT center position), and for the two extreme targets ($\pm 75°$), where hand selection matched the target position (RT extreme position).

RT was defined as the duration between target presentation and the release of the selected hand from the pressure sensor. Two-way repeated-measures ANOVA (four stimulation conditions × two target positions) was conducted to examine the influence of the simulation and target position on RTs. The interaction between the stimulation condition and the target position ($F_{(2.1, 25.0)} = 1.7$, $P = 0.19$) and the main effect of the target position ($F_{(1, 12)} = 0.37$, $P = 0.55$) were not significant. The main effect of the stimulation condition ($F_{(2.1, 24.3)} = 10.9$, $P < 0.01$, partial $\eta^2 = 0.47$) was significant. The simple main effect of the stimulation condition
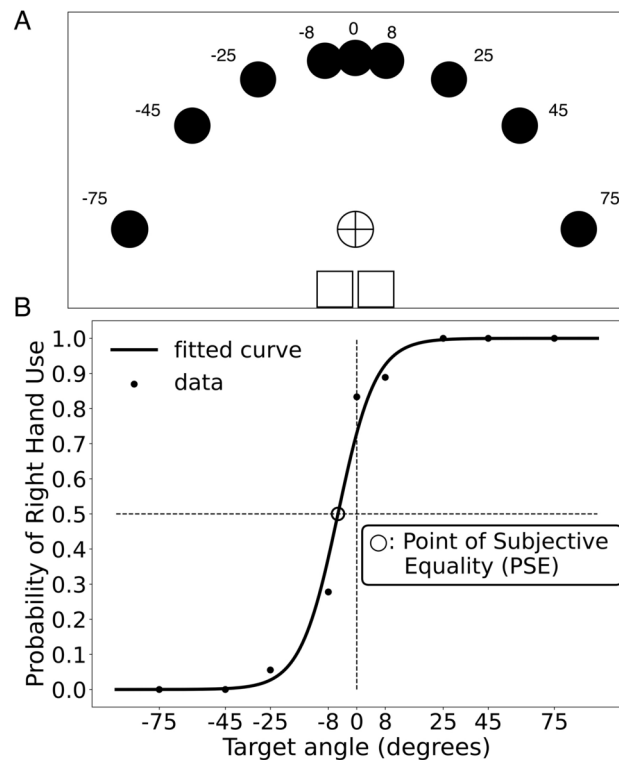
Fig. 1. Stimuli and point of subjective equality (PSE) of a representative participant. (**A**) Starting position (bottom two squares), fixation point (central "+" mark), and the nine possible targets. The targets were set at angles of 0°, 8°, 25°, 45°, and 75° to either side of the midline of the mirror. (**B**) The probability of choosing the right hand for each target is fitted to a logistic function for each participant. The horizontal axis indicates the target angle, with 0 denoting the midline or physical center (a positive degree indicates rightward rotation and a negative degree denotes leftward rotation relative to the midline). The vertical axis indicates the rate of right-hand selection. The PSE, indicating the estimated location at which participants were equally likely to use the right and left hands, was determined.
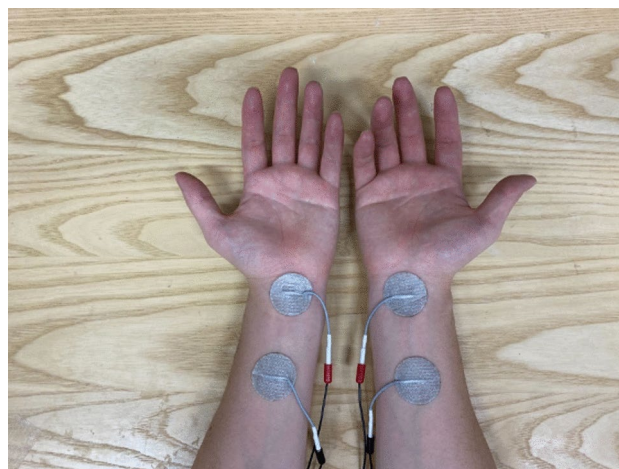

Fig. 2. Somatosensory electrical stimulation settings. Anodal electrodes with a 3-cm diameter are attached to the ventral distal end of the forearm on each side, while the cathodal electrodes are positioned 3 cm proximal from the anodal electrodes. The stimulation intensity is 80% of the motor threshold, and the stimulus duration 85 ms. The stimulus conditions are the unilateral stimulus conditions (left and right) and bilateral and no-stimulus conditions. Each stimulus condition is set 18 times for each target position and assigned in random order.
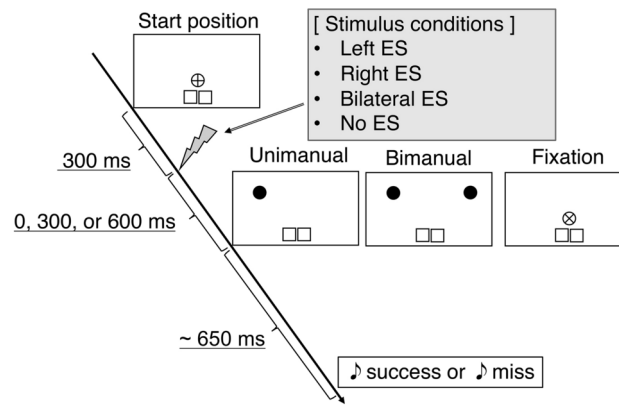
Fig. 3. Task protocol. Each trial commenced with each participant pressing two pressure sensors at the starting position with the left and right hands, respectively. After 300 ms, a somatosensory electrical stimulus is administered based on the stimulus conditions. Subsequently, one of three types of tasks is presented randomly at time intervals of 0, 300, and 600 ms after the somatosensory electrical stimulus. In "unimanual reach trials," the participants reach for the target with one hand. In "bimanual reach trials," two target circles are presented, and the participant reaches out to them with both hands simultaneously. In "fixation catch trials," the "+" at the center of the fixation circle is changed to "×," prompting participants to move both hands to the fixation circle. When one of the sensors on the index finger enters the target circle within 650 ms, the target disappears, and a sound indicating success is played. Otherwise, if the target does not enter the center circle, the target remains visible, and a sound-signaling failure is played.
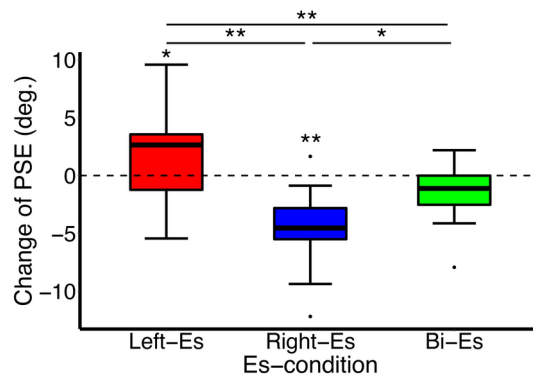

Fig. 4. Change in the point of subjective equality (PSE) for each stimulation condition from the no-stimulus condition. The red (Left-Es), blue (Right-Es), and green boxes (Bi-Es) represent the left, right, and bilateral stimulus conditions, respectively. The vertical axis indicates the PSE; 0° represents the PSE of the no-stimulus condition. Larger angles indicate increased left-hand choice, while smaller angles depict increased right-hand choice. The horizontal axis indicates the stimulation condition (Es-condition). $**P < 0.01$, $*P < 0.05$.

of the center RT (F (2.4, 29.5) = 9.69, $P < 0.01$, *partial* $\eta^2 = 0.45$) was significant (Fig. 6A). The multiple comparisons between each pair of stimulation conditions showed that the RT of the left stimulation condition (416.1 ± 17.8 ms) was significantly smaller than that of the no-stimulation condition (431.5 ± 14.8 ms) and bilateral stimulation condition (437.5 ± 19.0 ms) (*adj* $P < 0.05$). The RT of the right stimulation condition (422.2 ± 16.9 ms) was significantly smaller than that of the bilateral stimulation condition (*adj* $P < 0.05$) and showed a trend toward being smaller than that of the no-stimulation condition (*adj* $P = 0.07$). However, the RT of the bilateral stimulation condition was not significantly different from that of the no-stimulation condition (*adj* $P = 0.25$). In addition, RT was not significantly different between the left and right stimulation conditions (*adj* $P = 0.34$). No significant simple main effect was observed for the RT of the extreme target (F (1.7, 21.5) = 2.4, $P = 0.11$, *partial* $\eta^2 = 0.17$) (Fig. 6B).

A post-experimental questionnaire using a five-point Likert scale was provided to 11 participants to ask about their perceptions of electrical stimuli during tasks. Regarding the degree to which the participants were aware of the stimuli during the task, 6 (54.5%) of the 11 respondents answered "somewhat aware," 3 (27.3%) answered "neutral," and 2 (18.2%) answered "not very aware." Regarding whether stimulation affected hand choice, 5 of the 11 respondents (45.5%) answered "somewhat affected," 4 (36.4%) answered "not much affected," and 2 (18.2%) answered "not affected at all." Regarding whether the stimulated hand was easier to select, 3
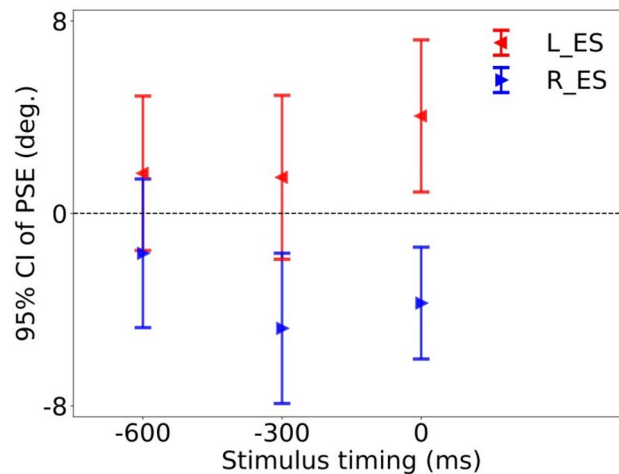
Fig. 5. Point of subjective equality (PSE) and 95% confidence interval for each stimulus timing in the left and right stimulation conditions. The red left-oriented triangles indicate the left stimulus condition, while the blue right-oriented triangles represent the right stimulus condition. The vertical axis indicates the 95% confidence interval of the PSE for each condition, with 0° representing the angle of the body center. A larger value indicates an increase in left-hand choice and a smaller value depicts an increase in right-hand choice. The horizontal axis indicates stimulation timing based on the target presentation time.
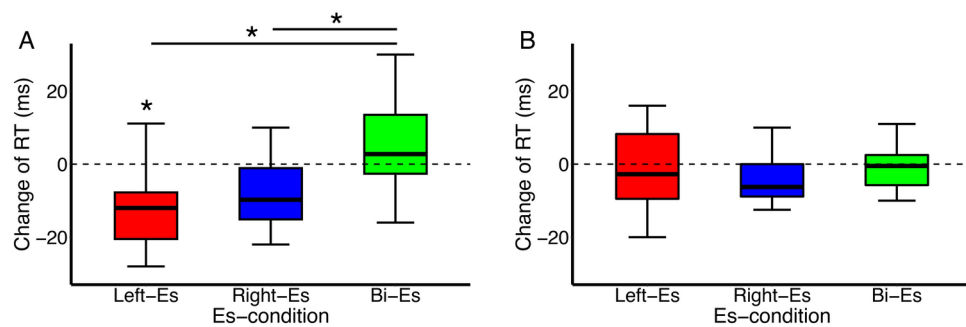

Fig. 6. Changes in the reaction time (RT) of the center target (**A**) and extreme target (**B**) relative to the no-stimulus condition in each stimulation condition. The red (Left-Es), blue (Right-Es), and green boxes (Bi-Es) represent the left, right, and bilateral stimulus conditions, respectively. The vertical axis represents the change in the RT (ms), while the horizontal axis indicates stimulus conditions (Es-condition). The horizontal line inside each box represents the median. The boxes extend to the lower and upper quartiles, whereas the whiskers extend to the extreme values other than outliers. *$P < 0.05$.

(27.3%) of the 11 respondents answered "somewhat easier to select," 4 (36.4%) answered "neutral," and 4 (36.4%) answered "somewhat difficult to select."

Discussion

Somatosensory electrical stimulation of the left or right unilateral wrist at or immediately before the target presentation increased the probability of choosing the stimulated hand. When the target was positioned around the PSE, the RTs were significantly shorter in the left and right wrist stimulation conditions than in the bilateral wrist stimulation condition. Also, the RTs were significantly shorter in the left wrist condition and showed a trend toward being shorter in the right wrist condition than in the no-stimulation condition. Somatosensory electrical stimulation was administered in this study at times of 0, 300, or 600 ms before the target presentation. Electrical stimulation to the wrist may influence the neural processes involved in hand selection earlier than the visual processing of the target information, considering the latency of the visual-evoked potentials. Forss et al. used magnetoencephalography to measure somatosensory-evoked potentials (SEPs) resulting from electrical stimulation of the median nerve at the wrist, at a motor threshold intensity[13]. The authors found that an early component of the SEP appeared in the primary somatosensory cortex and PPC, with a latency of 20–30 ms and 100 ms, respectively. Similarly, Fujii et al. used EEG to investigate the effect of electrical stimulation of the median nerve at the wrist and observed SEPs in the contralateral parietal and frontal EEG channels of P3,4 and F3,4, with a latency of approximately 30 ms[12]. In contrast, the visually presented target information is processed through a different pathway via the V1 to the PPC and PMC. Visual information usually requires approximately

100 ms to reach the V1[16]. Evoked potentials are observed around the frontal and parietal regions with a latency of 150–200 ms following the onset of the visual stimulus (N155/N180)[17,18]. The stimuli in this study produced an SEP peaking at approximately 30 ms in the C4 region, expecting that the stimuli reached the parietal and/or frontal regions before the target information did even when the target was presented just after the electrical stimulation.

Previous studies have suggested that hand choice exhibits stochastic behavior owing to competing neural activities arising from similar reaching costs. There are two theories of neural competition: one assumes that competition occurs in the PMC[5,10] and the other in the PPC[3,23]. The somatosensory stimulation in this study is believed to have likely reached either or both the frontal and parietal regions, which may have influenced neural competition in either the PMC, PPC, or both regions. Neural competition in the PMC has been investigated by Hamel-Thibault et al.[10] who examined the delta wave in the EEG during target presentation in a task that required participants to choose between their left or right hand to reach the target. The authors reported that the negative delta phase signifying excitability of the motor cortex correlated with the choice of the contralateral hand. Our electrical stimulation might have also increased the excitability of the contralateral motor cortex, resulting in the choice of the stimulated hand.

Fitzpatrick et al.[23] used functional magnetic resonance imaging (fMRI) to measure brain activity during a hand-choice task and reported increased activity in the contralateral PPC of the selected hand in the choice condition, where the participants selected the hand after the target presentation and reached the target, compared with the instructed condition, where participants reached the target with a pre-instructed hand. Oliveira et al. provided a single-pulse TMS 100 ms after target presentation[3] to PPC during hand selection and reported that TMS of the left PPC significantly reduced the probability of choosing the right hand. Based on the findings of previous studies, it is possible that the somatosensory stimulation in this study influenced neural competition in either the PMC, PPC, or both, thereby facilitating the selection of the stimulated hand. However, it is unclear whether the PMC or PPC is primarily affected by somatosensory stimulation since it may have reached both areas; therefore, further studies are warranted.

In this study, the RTs for targets near the center tended to be longer than those for targets at the edges under all stimulus conditions. These results are consistent with those of Oliveira et al., who demonstrated that the RTs to targets located near the center, where hand choice is in equilibrium, are prolonged compared with those for targets at the edges[3]. These results suggest that the selection competition is larger for hand selection on targets near the center than that for those at the edges. RT is often used to indicate difficulty in decision-making. Previous studies have reported that the more equilibrium of the determinants between alternatives, the longer the RT in tasks involving the choice of one option from multiple alternatives[24–26]. In this study, the RTs around the PSE were significantly shorter in the left and right wrist stimulation conditions than in the bilateral wrist stimulation condition. Also, the RTs were significantly shorter in the left wrist condition and showed a trend toward being shorter in the right wrist condition than in the no-stimulation condition. However, no significant differences in RTs were observed among the four stimulus conditions for extreme targets. Therefore, stimulation of the unilateral wrist facilitated decision-making only when conflicts among alternatives were large and not when conflicts were small because determinants or costs were sufficiently different.

The phenomenon of prolonged RTs in situations in which the choice is in equilibrium has been explained using decision-making models. The drift–diffusion model of perceptual decision-making describes the neural activity related to each alternative and explains that the alternative, whose neural activity reaches the choice threshold, is selected first[26]. The rate of increase in this neural activity is slower than in the competitive state, thus prolonging the time required to reach the threshold and increasing RT. In movement-related action selection, neural activities occur for each of the alternatives and compete with each other[27,28]; this was demonstrated using the affordance competition model[5]. According to these decision-making models, the factors influencing choice and RT include the base state of neural activity before the presentation of the target stimulus and the rate at which neural activity increases. Oliveira et al. stated that interrupting this process by intervening in hand selection with single-pulse TMS to the PPC after target presentation leads to longer RTs[3]. However, the electrical stimulation in this study applied before or at the target presentation shortened the RT, suggesting that neural activity reached the threshold of choice earlier, possibly owing to the bias in the base state before the target stimulus presentation or the impact on the rate of increase after target stimulus presentation, or both.

Spatial attention is often quantified using RT or the percentage of correct responses[29,30]. In the present study, RT for extreme targets was not changed by electrical stimulation; therefore, it is unlikely that the stimuli directly affected the spatial attention that is quantifiable by RT, although we must consider the possibility that spatial attention might have an effect, specifically around the central target, which cannot be assessed with RT.

In this study, electrical sensory stimulation from the wrist just before target presentation influenced hand choice. This suggests that sensory information from the periphery can impact decision-making. However, in real-world applications, it is unknown when a target appears; therefore, a potential solution may involve consistent bias in the neural activity that affects hand choice, regardless of the timing of the target presentation. Previous studies have reported that repetitive somatosensory electrical stimulation on the wrist, lasting for 1.5–2 h, resulted in a sustained increase in neuronal activity in the sensorimotor area[31–33]. Wu et al. performed electrical stimulation with a motor subthreshold intensity of the median nerve at the wrist for 2 h in healthy participants and examined the sensory-motor area activity using fMRI[33]. The authors reported a significant increase in primary sensory and motor area activity for up to 60 min after median nerve stimulation compared with no stimulation. However, whether the repetitive wrist stimulation affects the PPC or PMC remains to be investigated.

Non-invasive brain stimulation could be another option that consistently biases the state of neural activity related to hand selection. Previous studies using tDCS on the PPC or primary motor area have revealed a residual effect on hand selection[11,34]. Hirayama et al. used tDCS to continuously change the PPC activity during a hand-

selection task[11]. The results showed a significant increase in left-hand selection after stimulation compared with pre-stimulation when placing the cathodal electrode on the left PPC and the anodal electrode on the right. In addition, Javadi et al. performed a perceptual decision-making task where participants were asked to look at a rectangular figure and respond with their left hand when the vertical side was longer and with their right hand when the horizontal side was longer[34]. During the task, tDCS was applied simultaneously to the left and right primary motor areas with anodal and cathodal stimulations, respectively, to promote neural activity in the left motor area and inhibit it in the right motor areas and vice versa. The authors reported that when the stimulus was a square, the hand contralateral to the primary motor area, whose activity was facilitated, was more likely to be selected. Hirayama et al. and Javadi et al. did not clarify the effective timepoint of the hand-selection process; however, the effect may potentially be attributed to changes in the base brain state, which was the focus of this study[11,34].

In the present study, the specific brain regions where neural activity was altered in response to the stimulus and influenced hand selection were unclear. Future studies should examine the relationship among somatosensory stimulation, changes in neural activity, and hand selection using neurophysiological techniques, such as EEG, or neuroimaging techniques, such as fMRI.

The present findings hold potential applications in rehabilitation, as they may contribute to promoting the use of the hemiparetic hand in patients with stroke who experience reduced quality of life. Patients with stroke may regain the ability to use their paretic hands through rehabilitation; however, they often rely on their non-paretic hands for daily activities, resulting in "learned non-use," indicating significantly reduced use of the paretic hand[19,22]. Han et al. compared the area reached by the paretic hand in a reaching task under two conditions: forced use of the paretic hand and free choice between the paretic and non-paretic hands[22]. The authors reported that the area used by the paretic hand significantly reduced in the free-choice condition compared with that in the forced-choice condition. This suggests that even if patients can use their paretic hands, they spontaneously choose the non-paretic hand and cannot effectively use the paretic hand when having the option to choose between the two hands. Thus, when the paretic hand that can be used, the present stimuli may trigger the selection of the paretic hand, thereby facilitating its use. The present stimuli could be applied in rehabilitation to prevent functional decline caused by the non-use of the paretic hand by increasing its frequency of use. Future studies should examine the effectiveness of the proposed method in promoting the use of the paretic hands of patients after a stroke.

Conclusions

Unilateral wrist somatosensory stimulation before target presentation significantly increased the probability of choosing the stimulated hand and decreased RT. These results emphasize the possibility of using this stimulation technique in stroke recovery to encourage the use of the paretic hand.

Materials and methods

Participants

A total of 14 right-handed healthy participants (five females, nine males; mean age, 25.1 ± 4.64 years) were recruited in this study. All participants provided written informed consent and were remunerated for their participation. The required sample size was calculated using G*Power v3.1, with a power of 0.9, an alpha level of 0.05, and a large effect size of 0.4. The large effect size was assumed due to its potential clinical application in stroke rehabilitation in the future[35,36]. Following the power analysis, a sample size of 13 was required for a one-way repeated-measures ANOVA with four measurements. The inclusion criteria were as follows: (1) no history of nerve or orthopedic injuries to the upper extremity and (2) no history of chronic or acute neurological, psychiatric, or medical illnesses. The study was approved by the Waseda University Ethics Committee (Tokyo, Japan, approved number 2020–214) and performed in accordance with the principles of the Declaration of Helsinki.

Experimental design

Experimental setup

The participants were comfortably seated on chairs, with their hands resting on the tabletop surface (Fig. 7A). A horizontal display was placed above the table, and the mirror was placed midway between the display and the table surface. The height of the mirror was set in a way that allowed the participants to see their reflection and not the display or their hands. The stimulus was presented on the display, and its reflection in the mirror gave the impression that it was on the table. To track the motion, two three-dimensional magnetic motion tracking sensors (Fastrak, Polhemus, Colchester, VT) were attached to each index finger of the left and right hands, and the fingertip positions were measured at a sampling rate of 60 Hz. The magnetic transmitter was attached to the center of the back of the board. In addition, the current position of both hands was indicated through feedback in the form of two black dots. The participants were instructed to position their fingertip on the pressure sensors of 4 cm in length and width (FSR X 406, Interlink Electronics, CA, USA) placed on the starting position of the table. This setup allowed the sensors to detect when the hands of the participants were located on or released from the start position. The data from each pressure sensor were converted from analog to digital data using Arduino (Arduino Uno, Somerville, MA, USA) and input to the PC. A circle with a "+" symbol was displayed 2.5 cm away from the center to inform the participants of the target visual fixation position (Fig. 7B). Triggers to control the electrical stimulation were released from the PC to the electrical stimulator (SEN 7203, Nihon Koden Corporation, Tokyo, Japan) via a National Instrument (USB-6009, National instruments, TX, USA).
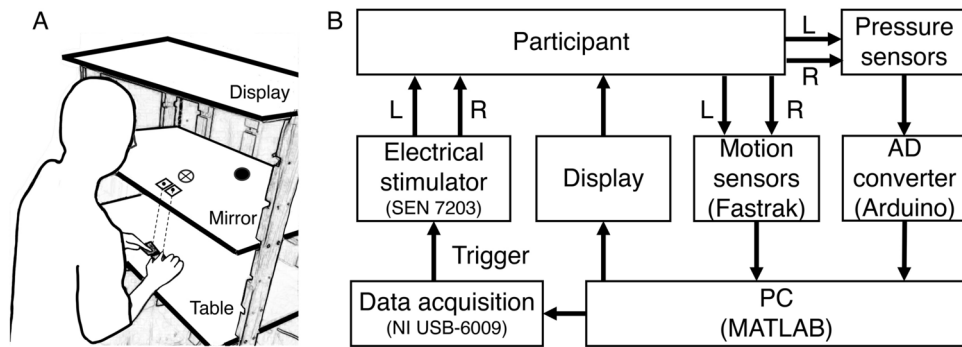
Fig. 7. Schematic illustration of the experimental setup. (**A**) A display was installed facing downward on a shelf situated above the participant's visual field. The picture was projected on a mirror placed halfway between the display and the table surface. By viewing the stimuli on a mirrored surface, the participants could gain the impression that the stimuli were on the same plane as their hands. The position of the hands was indicated by two black dots on the reflected display; these points corresponded to the position of three-dimensional motion-tracking sensors worn on both index fingers by the participant. Two square pressure sensors worn were set on the table, and the areas were displayed on the display to indicate the starting position. (**B**) The task was controlled using MATLAB on a PC. When participants placed both hands on the pressure sensors at the starting position, the pressure information was sent to the PC. The pressure information was used to control the timing of target presentation and electrical stimulation. The electrical stimulator received triggers from the PC via a data acquisition system.

Task protocol

At the beginning of each experiment, the participants were instructed to press the pressure sensor and focus their eyes on the fixation point (Fig. 3). After 300 ms, somatosensory electrical stimulation was applied to the unilateral wrist (left or right), bilateral wrist, or no stimulation at all, in random order (detailed settings for the somatosensory electrical stimulation are described below). One of three different trials, namely, unimanual, bimanual, and fixation reach, was initiated at random intervals of 0, 300, or 600 ms after the somatosensory electrical stimulation to prevent participants from predicting the target presentation time. The timing of the target presentation had a variance of approximately 15 ms due to the internal delay in the system. In the "unimanual reach trial," a target circle with a diameter of 4 cm would appear at one of nine positions on a semicircle approximately 27 cm away from the starting position. The targets were randomly presented at nine positions of 0°, 8°, 25°, 45°, and 75° to either side of the midline of the mirror (Fig. 1A)[3,11]. Because there are individual differences in PSE, we set a small range around the center. Participants were instructed to choose one hand after the target was presented and reach the target with the selected hand as quickly and accurately as possible within 650 ms. The other had to be held at the starting position. Furthermore, participants were instructed not to pre-determine the hand to be selected before the target was presented. When they left both hands 2.5 cm away from the starting position, the trial was identified as a failure and transited to the next trial. A disappearing target and sound indicated success if the index finger sensor was within the radius of the target in 650 ms. However, if the index finger sensor failed to enter the radius of the target within 650 ms, a sound indicating failure was played as the target remained visible. The "bimanual reach trial" required participants to simultaneously reach two targets on a semicircle with both hands within 650 ms to reduce the probability of using the same hand for any target. The "fixation-reach trial" involved changing the "+" mark to an "×" mark, where participants had to place the index fingers of both hands in the fixation circle within 650 ms to ensure fixation before the target presentation. Participants were allowed to move their gaze freely after target presentation and were instructed to return their hands to the starting positions after feedback sounds. No electrical stimulation was administered during the "bimanual reach" and "fixation-reach trials".

Measurements

The selected hand was defined as the hand that reached a distance 2.5 cm away from the start position before the other hand. To measure the hand choice, we calculated the participant's probability of choosing the right hand for each target. RT was defined as the duration between the target presentation and the release of the selected hand from the pressure sensor.

Somatosensory electrical stimulation settings

We used circular electrodes with a diameter of 3 cm along with an electrical stimulator (SEN 7203, Nihon Koden Corporation, Tokyo, Japan). The anodal electrodes were attached to the ventral distal end of the forearm on each side, whereas the cathodal electrodes were positioned 3 cm proximal to the anodal electrode[37]. In previous studies reporting somatosensory event-related potentials with electrical stimulation from the wrist, stimulus intensity was set around the motor threshold[13,38]. In the present study, the stimulus intensity was set at 80% of the motor threshold that would affect brain activity without inducing muscle activation, to avoid interfering with the reaching task. The stimulus intensity was determined by gradually increasing the intensity and visually

observing the abductor pollicis brevis twitch, which was defined as the motor threshold. The average intensity was 8.6 ± 2.2 mA for the left hand and 8.0 ± 1.7 mA for the right hand.

Before the commencement of each task block, we asked participants if the stimuli of the last task block induced pain. Each somatosensory electrical stimulation consisted of five consecutive 1-ms rectangular stimuli with an interval of 20 ms (50 Hz) (Fig. 8). We selected a stimulus frequency of 50 Hz and five consecutive stimulations as the stimulus has been shown to increase somatosensory evoked cortical magnetic fields[38].

Procedure

One block consisted of 120 trials, including 108 unimanual (9 targets on the semicircle displayed 12 times), 6 bimanual, and 6 fixation-reach trials. These were presented in a pseudo-random order. The four stimulus conditions (unilateral [left and right], bilateral, and no-stimulus) were randomly assigned three times at each target position. The participants performed six blocks. Before starting the task, participants completed three practice sessions, each consisting of 20 trials. The practice sessions consisted of two predetermined hand-choice sessions (only the right or left hand) in random order, followed by a free-choice session.

Analyses and statistics

To start each statistical analysis, the Shapiro–Wilk test was performed to confirm data normality and skewness was confirmed to be < 2 in absolute value. Mauchly's sphericity test was performed to test the spherical assumption; if it was rejected, the degrees of freedom were adjusted using the Greenhouse–Geisser method. Data above three times of standard deviation were excluded as outliers, along with data from failure trials. The RT data of one participant were excluded as outliers. The independent variable was the stimulus conditions (right/left/bilateral/no) for PSE, and the stimulus conditions and target position (center and extreme) for RT. Statistical analyses were performed using R software (version 3.6.1; The R Foundation, Vienna, Austria). Statistical significance was set at $P < 0.05$.

Hand choice probability
Hand preference was evaluated by calculating the probability of the right choice in each stimulus condition, where the right choice was assigned one, and the left hand was assigned zero for each position that presented the target. Using a logistic regression model, we determined that the angle of the target position, resulting in a 50% right-hand choice probability, represented the PSE (Fig. 1B). The fitting scores for the model were 89.4%, 88.2%, 89.2%, and 89.4% for the no, left, right, and bilateral-stimulation conditions, respectively.

Furthermore, to investigate the effect of the stimulation condition on the PSE, we performed a one-way repeated-measures ANOVA (stimulation conditions; right, left, bimanual, and no stimulation). In case of a statistically significant main effect, we performed multiple comparisons between stimulus conditions using a Shaffer-corrected paired t-test. In addition, a bootstrap method was employed with 10,000 resampled data points from all participants to calculate the 95% confidence interval of the PSE for each stimulus timing (0, 300, and 600 ms) to compensate for the relatively small amount of data available (84 and 6 data points for each participant for each target position).

RT
We divided our analysis into two separate RTs to examine the specific effects of electrical stimulation on hand choice: RTs around PSEs with competing hand choices and RTs at extreme targets with less competition. The median RT was determined for two targets in the vicinity of PSE (center target RT) and two extreme targets positioned at $\pm 75°$ (extreme target RT). A two-way repeated-measures ANOVA (stimulation condition and target position; center and extreme) was conducted to examine the effect of the simulation condition and target position on the RTs. When a statistically significant main effect was observed, multiple comparisons between stimulus conditions were performed using a Shaffer-corrected paired t-test.

Post-experimental questionnaire

We asked the participants to share their perceptions of the electrical stimuli during the task using a five-point Likert scale questionnaire. Consequently, we received responses from 11 participants. The questionnaire consisted of the following: (1) How aware were you of the electrical stimulation on your wrist during the task?:
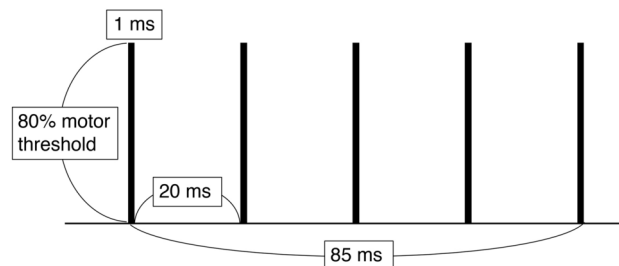

Fig. 8. Details of a somatosensory electrical stimulus. A somatosensory electrical stimulation consisted of five consecutive 1-ms rectangular stimuli with an interval of 20 ms. The total stimulus duration is 85 ms. The stimulus intensity is set at 80% of the motor threshold.

1. Not at all, 2. Not very much, 3. Neutral, 4. Somewhat, and 5. Very much. (2) Did electrical stimulation affect your hand choice? : 1. Not at all, 2. Not very much, 3. Neutral, 4. Somewhat affected, and 5. very much affected. (3) Did electrical stimulation facilitate the selection of the stimulated hand?: 1. Not at all, 2. Not very much, 3. Neutral, 4. Somewhat facilitated, and 5. Very much facilitated.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

KH and RO conceived of the study. KH, TT, and RO helped design the methodology. KH conducted the investigation. KH, XY, and TK performed the formal analysis. KH wrote the original draft. KH, TT, TK, and RO reviewed and edited the manuscript. RO supervised the study. KH and RO acquired funding.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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