Effects of motor style on timing control and EEG waveforms in self-paced and synchronization tapping tasks

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ABSTRACT

We investigated the effects of tapping style on motor performance and neural activity in self-paced and synchronization tapping tasks in three conditions (drum sticking [DS], one-finger tapping [1FT], and four-finger tapping [4FT]). In the synchronization task, participants tapped in synchrony with a metronomic sound. No significant differences were detected in the accuracy of timing control among the tapping styles, whereas larger potentials on EEG waveforms before tap onset were found in 4FT than in DS or 1FT; these may be readiness potentials for the motor commands required to control multiple fingers. As expected, tap intervals were more stable under the synchronization condition than under the self-paced condition, but no difference was detected in the neural activity evoked before tap onset. Larger neural potentials observed in the early stage after tap onset in DS might be involved in the sensory feedback associated with tool use.

1. Introduction

As rhythmic synchronization and rhythm production are seen universally in humans, these behaviors have been widely studied in the fields of psychology and neuroscience (e.g., [1–4]). In addition, synchronization of body movements to external rhythms has been applied in clinical rehabilitation (e.g., for patients with Parkinson’s disease [5]). Tapping with rhythmic synchronization can evoke neural activity in the motor area (see below), and neural activation of the motor cortex can have a direct effect on the outcomes of some types of clinical rehabilitation. For example, transcranial magnetic stimulation of the motor cortex improved motor performance in stroke patients [6]. Therefore, further research investigating neural activity in the motor area during rhythmic synchronization tasks, and identification of a motor style that elicits more neural activation in the motor area, could lead to a better rehabilitation method for patients with Parkinson’s disease or stroke, and others.

Moreover, synchronized tapping and self-paced tapping tasks have been used in studies of the perception and production of sound sequences [7]. Differences in motor style are involved in the accuracy of timing control during rhythmic synchronization tasks. One study showed that timing control was more accurate in drum sticking (DS) than in one-finger tapping (1FT) [3], and another demonstrated that timing control was more accurate in clapping than in bouncing [8]. These differences in motor outputs (such as timing control) among tapping styles may be a reflection of differences in the activity of the central nervous system, especially in the supplementary motor area (SMA) and the surrounding area, as a positron emission tomography (PET) study reported that SMA showed greater activation with five-finger than with two-finger tapping during a synchronization task [9]. In the neural activity, negative potentials (NPs) on EEG can be involved in motor control of the fingers. A previous study reported that when participants performed either a simple sequential movement (pulling a toggle switch down with the index finger) or a complex sequential movement (pulling the toggle switch down and then turning a knob located next to the switch on and off as quickly as possible), the NPs were much larger during the complex movement [10]. NPs arose prior (by 1–2 s) to finger movements and the signal source of them was identified in the motor areas and SMA, suggesting that NPs are motor readiness potentials and are involved in timing control of motor outputs [10–12]. In addition, NPs appear around the motor area on a topographic map, and a larger NP amplitude reflects stronger SMA activity [13]. Therefore, examining the accuracy and neural substrates of motor control based on tapping styles during a rhythmic synchronization task may provide further insight into sensorimotor coordination mechanisms, as the complexity of movements differs among tapping styles.

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Furthermore, several questions have already been raised in addressing differences in motor performance and in the neural substrates between synchronization and self-paced tapping tasks. For example, the accuracy of timing control during a self-paced task is worse than that during a synchronization task [[14], 1FT], although one study found no difference between these tasks [[4], DS]. Another study reported that the SMA was more activated during a self-paced task than during a synchronization task [[15], 1FT], whereas another reported no difference [[14], 1FT]. Therefore, it is reasonable to resolve this discrepancy with an empirical study.

To this end, we examined the effects of tapping style on timing control and on electroencephalogram (EEG) waveforms during self-paced and synchronization tapping tasks using three tapping styles (DS, 1FT, and four-finger tapping [4FT]). Synchronization error (i.e., the time between stimulus onset and tapping onset) and the inter-tap interval (ITI) were analyzed as indices to assess the accuracy of timing control in each motor style. We hypothesized that the variance in synchronization error would be larger in 1FT than in DS (cf. [3]), and that it would be largest in 4FT on the synchronization task. Likewise, similar variance in the ITI was expected between the self-paced and synchronization tasks.

Previous functional magnetic resonance imaging (fMRI) studies have shown that the SMA may be involved in synchronization and self-paced tapping [15]. However, it may be difficult to examine various tapping styles (e.g., DS) using fMRI because posture and movement are restricted in an MRI scanner. In addition, EEG may have an advantage for studies investigating rhythmic synchronization at the sub-second order. Thus, we were interested in NPs that appeared on the EEG just before motor outputs, which may have originated around the SMA [11,12]. As mentioned above, NPs were observed for 1–2 s prior to finger movements. However, synchronized tapping tasks usually require repetitive motor control at a sub-second rate. Therefore, we would obtain some potentials like NPs (the presence of the potentials would differ from the presence of NPs in the time scale) on the EEG before the finger movements performed in the tasks. We also hypothesized that this neural activity might be larger in 4FT than in the other tapping styles.

Sensory-motor coordination is essential for rhythmic synchronization tasks. Especially, considering the heightened somatosensory sensitivity attributable to tool use [16], greater sensitivity to sensory inputs may be necessary to detect vibrations of the tip of the drum stick during the fine motor control performed in DS compared to inputs generated directly from the skin surface during finger tapping. Therefore, we were also interested in the activity associated with early stage neural processing, known as somatosensory evoked potentials (SEPs). Electrical potentials evoked at 60–175 ms (the duration varies among studies) after the fingers touched objects, or after an electrical shock was administered to the median nerve of the upper limbs, were referred to as SEPs [17–19]. SEPs appeared around the motor area on a topographic map [20], and the signal source was shown to be located in the motor area and SMA [19,21]. We would also expect to see some differences in early stage potentials, which were presumably SEPs, between the tool-use (DS) and non-tool-use conditions (1FT and 4FT) in this study, because the sensory feedback would be different between those conditions.

2. Materials and methods

2.1. Participants

We enrolled 12 participants who had normal hearing (7 men and 5 women, aged 19–21 years; mean = 20.42, SD = 0.86). All were right-handed except one participant, who was ambidextrous but was right-handed in most of her activities. Participants had no specific music experience (e.g., formal training to play a musical instrument). We obtained informed consent from the participants according to the Declaration of Helsinki. All experimental procedures were approved by the Ethics Committee of Aichi University (approval no. 201602).

2.2. Stimuli

A sound note (800 Hz pure tone, 50 ms in duration) was used as the auditory stimulus during the synchronization task. Stimuli were presented as an isochronous sequence at 70 beats per minute (inter-stimulus onset interval [IOI]: 857 ms; 70 bpm allows humans to maintain synchronization easily [22] and avoids superimposing neural activities for perception and motor outputs on EEG [23], see below). The sound stream was created as a matrix and converted to a Windows PCM file (.wav format, 44.1 kHz sampling rate) in the MATLAB (MathWorks, Natick, MA, USA) program before the experiments. Then, the sound sequence was played back from a personal computer. This method guaranteed the accuracy of the duration and IOIs of the stimulus.

2.3. Apparatus

Under the DS condition, participants tapped a plate (7.0 × 7.0 cm) with a wooden stick (23.0-cm length). The average distance between the top of the stick tip and the surface of the plate was about 4.0 cm while the participants were hitting the plate. Under the finger-tapping conditions, participants tapped the keys of a keyboard (A-800PRO; Roland, Hamamatsu, Japan), which was used to acquire motor responses and was engineered not to produce any musical sounds. We used clips that were accessories from a CLIPHIT drum module (Korg, Tokyo, Japan) as a fine vibration sensor to detect tap responses in both the drum and keyboard conditions (mean latency between the hit and audio output was 0.33 ms; SD: 0.05 ms). This enabled us to record taps as sound pulses using an audio interface (Quad-Capture; Roland) and software (Cubase7; Steinberg, Hamburg, Germany). Tap onset was considered to occur when the finger reached the lowest point of the key stroke. The finite distance before the key closed was 1.5 cm. In addition, the outputs were received using an RP2.1 real-time processor (Tucker Davis Technology, Alachua, FL, USA).

The sound amplitudes from tapping with a wooden stick and striking the keyboard, measured at the position of the participant’s head, were as follows: DS: 84 dB; finger tapping with a vibration sensor: 74 dB; finger tapping without a vibration sensor: 51 dB. The background noise was 46 dB.

The sound stimuli were transmitted to earphones (EarPods, Apple, Cupertino, CA, USA) and the sound amplitude was adjusted to a comfortable level for each participant. When the processor received an input from the clips or the sound stimuli, it immediately sent a TTL output corresponding to those inputs to Brain Vision Recorder software (Brain Products, Munich, Germany) via the Brain Amp MR (Brain Products); this output was used as a marker to align the EEG data.

2.4. Procedures

The experiments began with the self-paced task, followed by the synchronization task; each task was combined with DS, 1FT (index finger), and 4FT styles, for a total of six conditions. In the 4FT condition, participants had to press four particular keys with four specific fingers, in the order index, middle, ring, and little finger. Ideally, we should have tested two, three, and five fingers in addition to 4FT. However, we had to limit the number of tasks to reduce participant burden. The six conditions took about 90 min (with EEG preparation) in total. Thus, we applied three styles that had been separately examined in the studies described above. Participants tapped with their dominant hand (right hand). The order of the tapping styles was counter-balanced among participants. Participants were given the opportunity to familiarize themselves with each tapping style as much as they wanted before the data were recorded.

In the self-paced task, participants were verbally instructed to tap at their own pace. In the synchronization task, participants were instructed...
to synchronize their tapping with the sound stimuli and to fix their eyes on a square (1.0 × 1.0 cm) on the wall about 70 cm in front of their face. Eighty sound notes were presented for each tapping style.

2.5. EEG recording

EEGs were recorded using a 32-channel Ag–Cl electrode cap (10–20 system, EasyCap, Brain Products) at a sampling rate of 1 kHz using a Brain Amp MR and Brain Vision Recorder. The reference was put at Oz, and the ground was located at FpZ. The impedances on all electrodes were confirmed to be <10 kΩ.

2.6. Analyses

2.6.1. Tapping data

A time window of 428 ms (1/2 of the IOI) was set before and after tap onset. The nearest stimulus onset to each tap in this window was regarded as the synchronization target for the tap response. When a tapping onset was outside the window, the trial was excluded from further analyses. We calculated the coefficients of variation (CVs) of the ITIs for the self-paced and synchronization tasks. In the synchronization task, the CV of the synchronization error was also calculated. These values were used to evaluate the accuracy of timing control. The CVs should be positive values, although synchronization errors can be negative. Therefore, the value of each synchronization error was shifted 428 ms in the positive direction (length of the time window) to calculate the CVs.

2.6.2. Off-line EEG analyses

After 0.1–40-Hz band-pass filtering, the EEGs were converted to an average reference off-line using Brain Vision Analyzer software and then aligned with the tapping onsets. Next, a baseline correction was made using the waveform from −250 to −150 ms before tapping onset. Epochs that exceeded ±100 μV were rejected to eliminate artifacts such as eye blinking. We speculated that significant activity would be observed in the left hemisphere because participants tapped with the right hand. Consistent with this speculation, the topographic maps exhibited noticeable activity in the anterior region of the left hemisphere (Fig. 1). Thus, we analyzed the neural activities recorded from the FC1 electrode. We defined the waveforms observed from −120 to −1 ms before tapping onset as “pre-negative activity” and calculated the average magnitude for the analyses. As mentioned in the Introduction, we hypothesized that the negative potentials would be larger in 4FT than in the other tapping styles. However, a previous study showed that a simple repetitive button press reduced NP magnitude [24], perhaps due to neural habituation [25]. Logically, the number of keystrokes performed by the index finger in 1FT is increased fourfold in 4FT. Therefore, we examined the possibility of neural habituation for the pre-negative activity. We compared pre-negative activity between the first-half trials (from trial 1–35) and the second-half trials (from trial 35–70) for each tapping style. In addition, the difference in onset of the pre-negative activity among tapping styles and conditions was examined. The onset was determined by visual inspection as in previous studies [15,26].

A distinctive pattern was seen on FC1 from 80 to 220 ms after tapping onset (see below). Therefore, we analyzed the peak magnitudes of the early stage potentials (presumably SEPs) under each condition.

An EEG source localization method (low-resolution electromagnetic tomography; LORETA), performed using Brain Vision Analyzer, was applied to BA4 (primary motor area) and BA6 (premotor area and SMA) to analyze pre-negative activity using a standard head model (based on Montreal Neurologic Institute (MNI) template 305) provided by Brain Products. The model is convenient for use with the software employed in this study and has been widely utilized for the analysis that we performed, although questions have been raised regarding the applicability of the model to non-Western subjects (e.g., [27]).

2.7. Statistical analyses

Differences in the CVs of the ITIs and synchronization error were examined using the Wilcoxon signed-rank test with a Bonferroni correction. The EEG data were analyzed using analysis of variance (ANOVA) with a Bonferroni correction with 2 conditions (self-paced and synchronization task) × 3 tapping styles (DS, 1FT, and 4FT). To test for neural habituation, differences in the amplitude of the pre-negative activity between the first-half trials and the second-half trials were analyzed using the paired t-test with the Bonferroni correction for each tapping style.

3. Results

Ideally, 80 taps should have been obtained for each tapping style during the self-paced and synchronization tasks. However, participants

Fig. 1. Topographic maps from −120 to −1 ms.
occasionally could not follow the sound sequence and did not react to the stimuli during the synchronization task. The maximum number of lost taps during a synchronization task was 10. Therefore, 70 available taps in each condition were taken from the beginning of the sessions and used for the behavioral analyses. The EEG waveforms occasionally contained artifacts, so the mean number of artifact-free EEG trials available for analysis was 59.81 (standard error (SE) = 1.53) for the self-paced task and 62.69 (SE = 1.19) for the synchronization task.

3.1. Tapping data

3.1.1. Variance in the inter-tap interval

The CV of the ITI was larger during the self-paced task than during the synchronization task (V = 529, p < .01; Fig. 2); however, it did not differ significantly among the tapping styles (DS vs. 1FT [V = 164, p = 1.00], 1FT vs. 4FT [V = 205, p = .36], DS vs. 4FT [V = 165, p = .62]).

3.1.2. Synchronization error

The CV of the synchronization error did not differ among the tapping styles (DS vs. 1FT [V = 24, p = .80], DS vs. 4FT [V = 23, p = .70], 1FT vs. 4FT [V = 36, p = 1.00], Fig. 3A). Negative mean asynchrony [28] was observed among all tapping styles during the synchronization task (Fig. 3B).

3.2. EEG

In the EEG waveforms (Fig. 4), distinctive patterns appeared before (pre-negative activity) and after tapping onset (putative early stage potentials, assuming that the potentials originated from somatosensory inputs generated by the tapping; see Introduction).

On the topographic maps, a distinctive pattern of activity was seen around the posterior frontal lobe of the left hemisphere (Fig. 1). Therefore, we applied the source localization method to the SMA and motor area of the left hemisphere.

3.2.1. Pre-negative activity

The main effect of tapping style on amplitude was significant (F (2, 22) = 8.60, p < .01). A post hoc test revealed that the amplitude was larger in 4FT than in DS (t (23) = 2.82, p < .05) and 1FT (t (23) = −2.78, p < .05; Fig. 5). This trend was consistent among the participants, except two (Fig. S1). No difference was detected between DS and 1FT (t (23) = −2.0, p = 1.00). The main effect of condition was not significant (F (1, 11) = 1.71, p = .22), nor was the interaction (F (2, 22) = .29, p = .75).

We found no differences in onset time among the tapping styles or conditions (F (2, 22) = 1.91, p = .17, F (1, 11) = 0.02, p = .90), and no interaction between the factors (F (2, 22) = 1.84, p = .18). Likewise, we detected no differences in the amplitude of the pre-negative activity for each tapping style between the first- and second-half trials (DS: t (11) = 0.64, p = 1.00; 1FT: t (11) = −0.01, p = 1.00; 4FT: t (11) = −0.12, p = 1.00), suggesting no neural habituation to the activity during the tasks.

3.2.2. Early stage potentials

The main effect of tapping style on the peak amplitude was significant (F (2, 22) = 3.65, p < .05). The amplitude was significantly larger in DS than in 4FT (t (23) = 2.61, p < .05) and marginally larger than that in 1FT (t (23) = 2.41, p = .07; Fig. 5). No difference was detected between 1FT and 4FT (t (23) = −0.29, p = 1.00). There was no main effect of condition (F (1, 11) = 0.10, p = .76) and no interaction effect (F (2, 22) = 0.73, p = .49).

3.2.3. Source localization

3.2.3.1. Left BA4. No main effect of tapping style (F (2, 22) = 0.49, p = .62) or condition (F (1, 11) = 4.77, p = .0514) was found; however, the interaction effect was significant (F (2, 22) = 5.53, p < .05). A post hoc test revealed greater activity during the self-paced task than during the synchronization task in 4FT (F (1, 11) = 12.65, p < .05). No differences were detected in any other factor or level.

3.2.3.2. Left BA6. There was no main effect of tapping style or condition (F (2, 22) = 0.11, p = .90; F (1, 11) = 0.14, p = .72), and no interaction effect (F (2, 22) = 0.10, p = .91).

4. Discussion

The CVs of the ITIs were larger during the self-paced task than during the synchronization task; however, pre-negative activity did not differ between the tasks. The CV of the ITI and synchronization error did not differ among tapping styles; however, the pre-negative activity was larger in the 4FT than in the DS and 1FT conditions. These results imply that the much greater neural activity in 4FT compared to 1FT and DS, which did not reflect the accuracy of timing control, represented the additional motor commands needed to control multiple fingers. The early stage potentials were larger during DS than during finger-tapping tasks, which is consistent with the hypothesis mentioned in the Introduction that SEPs would be larger in the tool-use task.

Previous studies have reported that NPs that originate from the SMA are involved in motor readiness [11,12]. However, one study showed a possible problem in this kind of experiment: NPs can be superimposed on auditory evoked potentials (N2) when auditory stimuli are presented with a short IOI (e.g., 500 ms) [23]. In the present study, the IOI was 857 ms, and N2 should have appeared about 250 ms after stimulus onset [23] so that the time lag would be sufficient to avoid contamination. In addition, the participants tapped 57.5 ms (average of all tapping styles) before stimulus onset in anticipation of the coming stimulus, so that pre-negative activity was elicited preceding the auditory inputs. Moreover, as shown in the topographic maps (Fig. 1), the pre-negative activities were larger in 4FT than in 1FT and DS on the self-paced task (with no auditory stimuli). Thus, it is plausible that the pre-negative activities were almost independent of the auditory responses.

We examined the possibility of neural habituation [24], which was negative. Therefore, the lower activity in 1FT and DS cannot have been attributed to neural habituation, even though the number of repetitive movements (up-down of an index finger with 1FT, or up-down of a wrist with DS) was four-fold that of 4FT (because the tap number assignment was divided by four fingers), which would create habituation much faster.

The pre-negative activity in this study was similar to NPs (or negative slope or Bereitschaftspotential). The pre-negative activity potentials changed toward the negative direction before movement onset. The topographic maps imply that the activity originated from around the anterior region of the left hemisphere. These characteristics are consistent with the characteristics of NPs reported previously (e.g., [10,13]). Alternatively, the components of the pre-negative activity in this study might differ from those of the NPs described in previous studies [11,12]. For example, a previous study evaluated EEG waveforms for NPs during

** Fig. 2. The coefficients of variation (CVs) of the inter-tap intervals (ITIs) were larger during the self-paced task than during the synchronization task (** p < .01). Error bars represent the standard error (SE).**
the period 0.3–1.5 s prior to motor outputs [12]. However, the task in the present study required repetitive motor outputs within a short period (every 857 ms) to entrain to the metronomic rhythm (entraining to a rhythm with a longer interval is difficult [e.g., 29]), so the time window to detect the pre-negative activity on the EEG waveforms was set to cover 800 ms (i.e., from 400 ms before to 400 ms after tap onset). This methodological difference may have led to a critical difference between the NPs and pre-negative activity in this study. Although the pre-negative activity was similar to the NPs, we could not determine whether the components of the pre-negative activity were consistent with the components of NPs.

The EEG source localization method detected no associations between the pre-negative activity and BA6. Instead, the analysis showed that the magnitude of the pre-negative activity in BA4 changed depending on the task condition. This result is inconsistent with previous studies [11,12]. A possible reason for this discrepancy is that we did not use high-density electrophysiological source localization (e.g. [30],) and/or we used the standard head model (cf. [27]). Therefore, we cannot exclude the possibility that the activity originated from BA6. Alternatively, the components of the pre-negative activity in this study
might differ from those of the NPs described in previous studies [11,12].

The magnitude of the early stage potentials was larger in DS than in 1FT and 4FT. Assuming that the potentials were SEPs, the larger potentials might have originated from the use of the drum stick, because the task requires greater sensitivity from the participants, as mentioned in the Introduction.

Our results reveal no differences in the synchronization error between DS and 1FT, in contrast to the results of a previous study [3]. We assume that this discrepancy may be attributable to the experimental setup. The sounds made by the wooden stick during DS were generally louder than the keystroke sounds during the finger-tapping tasks. However, in the present experimental setup, the vibration sensor was attached to a keyboard, so the keystroke provided louder auditory feedback than that generated by a normal keyboard. The louder natural feedback may have affected timing control, which is likely to have been discounted in previous studies. If this assumption is true, the results raise an important question for synchronization tapping tasks.

In conclusion, our findings support the idea that rhythmic training with a complex motor sequence, such as 4FT, is effective during clinical rehabilitation, given the need for additional neural motor commands (or greater pre-negative activity) to control multiple fingers. However, tapping training using a tool (such as a drum stick) may be an effective form of rehabilitation in some cases, because the method can elicit larger early stage potentials (or SEPs). It would be reasonable to consider a combination of these methods for clinical application. In addition, this study demonstrated that not only behavioral measurements but also records of neural activity are essential parts of a comprehensive experimental system to measure the complexity of tapping tasks.

CRediT authorship contribution statement

Kenta Tomyta: Methodology, Investigation, Formal analysis, Writing - original draft. Yoshimasa Seki: Supervision, Resources, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neulet.2020.135410.

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