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Two types of phase correction mechanism involved in synchronized tapping

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Abstract

We clarify internal phase correction mechanisms affecting timing control in a synchronization tapping task. Synchronization error (SE) was directly controlled within 450–1800 ms of the inter stimulusonset interval (ISI) with our experimental method. Two types of internal phase correction mechanism became evident. The first showed a strong negative correlation between SE change and change in inter taponset interval (ITI), suggesting a simple negative feedback mechanism. This correlation was observed under all ISI conditions. The second type showed a larger response with a low negative correlation and was observed only with long (1200–1800 ms) ISIs. Only the second mechanism was inhibited in a dual task condition. These results suggest that there are two types of internal phase correction mechanism.

Keywords: Timing control; Synchronized tapping; Phase correction; Attentional resources

Our rhythmic body movements such as hand or foot tapping can become synchronized with external stimuli when playing or listening to music. This timing control is an essential ability for coordinating action in a dynamic environment. To investigate these timing mechanisms, the synchronization tapping task in which the subject is required to synchronize their taps with periodic stimuli as precisely as possible has been widely used [9,3,5]. In this experimental task, two error correction mechanisms have been proposed to synchronize the stimulus-onset and the tap-onset [6,7,18,22,15,14]: phase correction controls the coincidence of tap timing with the stimulus timing, and the period correction synchronizes the tap period with the stimulus period.

These error correction mechanisms have been investigated by varying the inter stimulus-onset interval (ISI) during the synchronization tapping task [22,15,14,23,13,21,16]. However, when only the ISI is controlled, there is no clear distinction between phase correction and period correction. To distinguish between these two correction processes, the relationship between the stimulus-onset and the tap-onset must be directly controlled. However, previous experiments have only been conducted with a zero synchronization error (SE) [5]. Our experimental method allows direct control of SE [19,20] and is similar to another recently described procedure [4].

Negative asynchrony (NA) has been observed during the synchronization tapping task and is thought to be involved in phase correction mechanism. This interesting phenomenon shows that the onset of a subject's tap precedes the onset of a stimulus by a few tens of milliseconds, although the subject is unaware of this [9,3,8,1]. This suggests that timing control is not simply a passive reaction to the stimulus, but an active response based on internal anticipation of the timing of the next stimulus. Mates et al. [8] has shown that NA is observed when the ISI is between 450 and 3600 ms. Furthermore, the dual task method shows that attentional resources are involved in the generation of NA when the ISI is longer than 1800 ms [10]. These suggest that phase correction does not appear to be a single mechanism, but is hierarchical and depends on the length of ISI.

Our aim was to clarify the internal phase correction mechanisms involved in timing control during the synchronization tapping task. We directly controlled the SE, which allowed us to quantitatively analyse the effects of SE on phase correction. The effects of ISI and attentional resources on timing control were also investigated.

The subject's task was to synchronize their taps with a periodic auditory stimulus as precisely as possible. The SE for each

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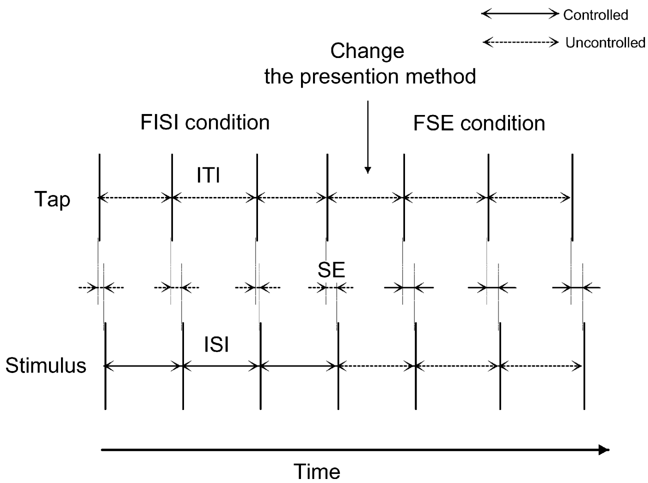

Fig. 1. Experimental procedure.

tap was directly and precisely controlled. This involved presenting the auditory stimulus at a fixed time interval following each tap, producing an externally controlled SE. The phase correction mechanism was analysed by measuring the relationship between SE, the controlled parameter, and the inter-tap onset interval (ITI), the observed parameter.

The ITI gradually decreases when the SE is zero [5]. This experimental condition is known as “Pseudo Synchronization” and the results suggest that the auditory stimulus is perceived to precede the onset of the tap. The internal phase difference is not an external SE, but an internal perception that may be controlled in the above SE-control method. If phase correction is a negative feedback mechanism [6,7], our method should elucidate the internal control dynamics in relation to timing perceptions.

Our experiments used several values of ISI to determine if phase correction was affected by the ISI [10]. Each trial consisted of two different parts. The subject tapped to a stimulus with a fixed ISI in the first half of each trial, whereas the SE was controlled during the second half of each trial. Using this hybrid task, the relationship between the phase correction mechanism and ISI was determined.

Each trial consisted of 60 taps, with the stimulus presentation changed after 20 taps (the first half), and with 40 taps in the second half. The ISI was fixed for the first 20 taps as in the typical synchronized tapping task (left side of Fig. 1). This is referred to as the fixed ISI (FISI) condition and was used to control the tapping period of the subject. For the 40 taps in the second half of each task, stimuli were presented at a fixed time interval following the onset of each tap (right side of Fig. 1). This is referred to as the fixed SE (FSE) condition. This makes it possible to directly control the SE between the stimulus-onset and the tap-onset with various ISIs. The subjects were not informed when the stimulus presentation method changed during each trial.

Five different ISIs were used in the FISI condition (450, 600, 900, 1200, and 1800 ms). Seven different SE values (0, −10, −30, −50, −70, −90, and −110 ms) were used in the FSE condition. All SEs were negative i.e., the auditory stimulus was presented after the onset of the subject’s tap. Under a combination of these conditions, 35 trials were conducted in a single session for each subject.

The dual task method [2] was used under the same conditions described above to examine the effect of attentional resources on phase correction. The primary task was the synchronized tapping task, and the secondary task was a silent reading task. The primary task alone is referred to as the single task condition, whereas the dual task condition is the simultaneous execution of both the primary and secondary tasks.

The Japanese language version of *The Cathedral and the Bazaar* by Eric S. Raymond [12] was used as the silent reading task. At the end of the experiment, the subject was asked several questions on the content of the text. The subject had to choose between two answers for each question. The mean percentage of correct answers was 85.2% with a range of 76.9–94.7%, showing that the subjects had closely attended to the silent reading task.

Six healthy males (mean age 25.2 years) volunteered for this study. All subjects were right handed and exhibited no hearing abnormalities. They all had experience of the synchronization tapping task, having participated in similar trials in the past. The experiment was conducted in a quiet room with the subject sitting in a chair with their eyes closed. The taps were made using the right index finger. Subjects were forbidden to count using any motion other than their right index finger and to do their tapping with subjective accentuation.

The experimental system was run on a PC (IBM, ThinkPad 560E) with a single-task OS (IBM, PC-DOS2000). Stimuli were transmitted to the subject via headphones connected to the PC. Stimulus duration was 100 ms and the frequency was 500 Hz. The sound pressure was set to an appropriate level to ensure that the auditory stimuli could be clearly heard. The button detecting the tap had a short stroke (<1 mm). The time measurement was done with a real time clock at a resolution of 1/2048 s. An auditory stimulus was generated at a fixed time interval after each tap, and the timing of taps and stimuli onsets were recorded on the PC.

Each trial consisted of 60 taps with a combination of conditions in the first and second halves of each trial. A session consisted of 35 trials. The subject was given a 5 s break between each trial, and trials were randomly ordered within a session. In the dual task method, a single task condition session was first conducted, followed by a dual task session. However, the order of trials was the same within the session for the single task condition and the dual task condition for the same subject. Each subject participated in 70 trials over the course of two sessions, and the six subjects participated in a total of 420 trials.

The ITI, ISI, and the SE for each tap were calculated. The data from the first five taps at the start of a trial were not used in the analysis to eliminate unstable data.

Typical time courses of SE and ITI observed with short and long ISIs are shown in Fig. 2. Three types of ITI responses were observed in the FSE condition. The first type was characterized by an increase in the ITI (Fig. 2a), the second type had a relatively constant ITI (Fig. 2b and d), and the third type had a decrease in the ITI (Fig. 2c, e, and f). Fig. 2f shows an especially large decrease in ITI.

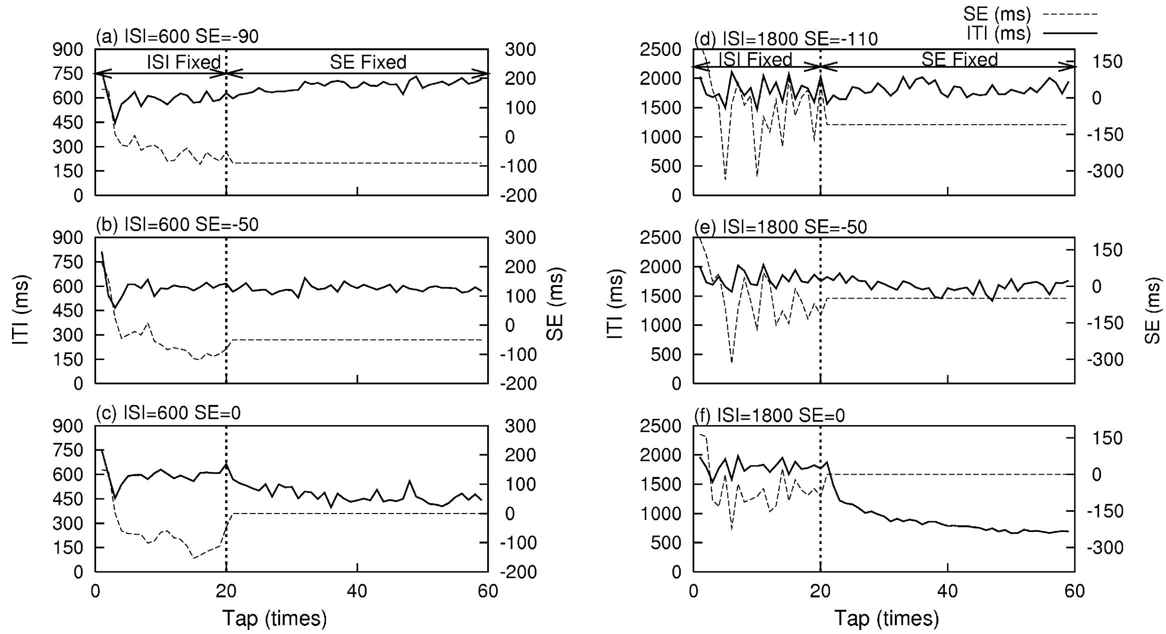

Fig. 2. Typical time course of ITI and SE in ISI = 600 and 1800 ms. The horizontal axis shows the tap and the vertical axis represents the ITI and SE The period left of the vertical broken line corresponds to the FISI condition. The period to the right corresponds to the FSE condition, and the SEs were fixed. In each ISI condition, across-subject data for mean ITIs in the FISI condition were 450, 596, 899, 1200, and 1799 ms, mean ITIs in the FSE condition were 417, 545, 813, 1065, and 1587 ms, and mean SEs in the FISI condition were −68, −74, −63, −77, and −91 ms.

We assume that these ITI responses reflect the subject's perception of the temporal order between the tap and the auditory stimulus because the subject was instructed to synchronize the tap with the auditory stimulus. If the ITI is increased in the FSE condition, then the subject's perception may be that the stimulus was delayed after the tap. If the ITI is unchanged, then the tap and the stimulus would seem to be simultaneous, and if the ITI decreased, then the stimulus would appear to precede the tap. However, these ITI responses did not always reflect the physical order between the tap and the stimulus because the stimulus was always presented after the tap in the FSE condition. Therefore, we should interpret these results as evidence for an internal perceptual relationship between the auditory stimulus and the tap response.

We aim to determine the internal phase correction mechanism by controlling the SE. However, SE is constant in the FSE condition and the phase correction itself cannot be observed. Therefore, the following data analysis was performed to extract the internal response to the fixed SE.

An important parameter measured is the SE change (ΔSE). This is the difference between the mean SE for 15 taps in the FISI condition and the fixed SE for the 40 taps in the FSE condition. Our hypothesis is that the ΔSE value is the input to the internal phase correction mechanism. We can express ΔSE as:

SE = (fixed SE in the FSE condition)

(mean SE in the FISI condition)

The other important parameter is the ITI change (ΔITI), which was obtained from the mean ITI for 15 taps in the FISI condition and the mean ITI of 40 taps in the FSE condition. The expression for ΔITI is:

ITI = (mean ITI in the FSE condition)

(mean ITI in the FISI condition)

We assume that the ΔITI reflects the perception of the subject, and can be regarded as an output from the phase correction mechanism. The mean ITI in both conditions and the mean SE in the FISI condition were calculated for each trial.

Fig. 3a–e show the relationships between the ΔSE and ΔITI. These relationships were obtained for all ISIs under FISI conditions. Each point in the graph corresponds to one trial, and each graph consists of 42 trials. These points were clustered by the "nearest neighbour method" [17] to quantitatively analyse their characteristics. There was only one cluster (cluster 1) in the ISI range of 450–900 ms, and its configuration was a straight line that passed through the origin. Moreover, in addition to the clusters with a similar structure observed in Fig. 3a–c, a second, rather different cluster (cluster 2), was observed at ISIs from 1200 to 1800 ms as shown in Fig. 3d and e. Cluster 1 had a strong negative correlation (mean $r = -0.73$, S.D. = 0.17) in the ISI range of 450–1800 ms, while cluster 2, in the ISI range of 1200–1800 ms, did not (mean $r = -0.25$, S.D. = 0.03). These two clusters are significantly different in their configuration ($p < 0.05$, t-test).

Cluster 1 was present at all ISI values and had a strong negative correlation that sloped downward to the right as shown in Fig. 3. This corresponds to a decrease in ITI as SE increases, and an increase in ITI when SE decreases. This cluster was observed over a wide range of ΔSE and its configuration was stable. This means that the ITI is adjusted to recover a stable SE value when it drifted, suggesting a

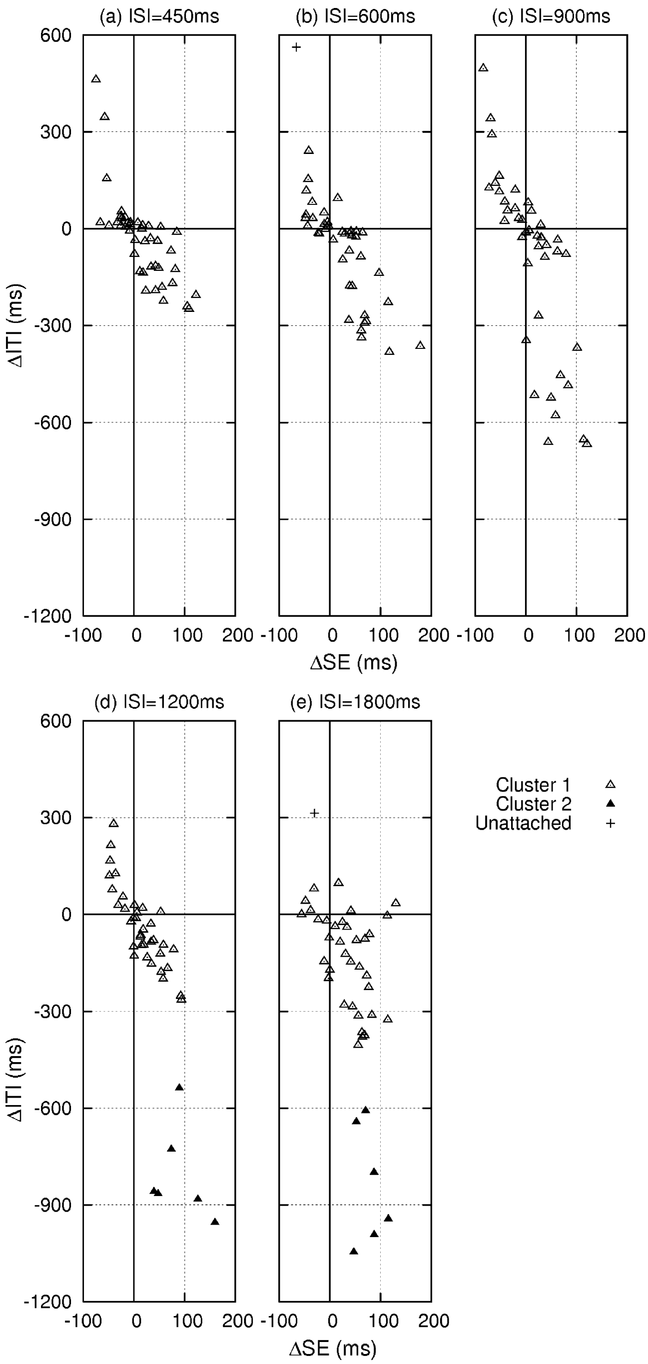

Fig. 3. Relationship between SE change and ITI change under the single task condition. The horizontal axis shows the change of SE and the vertical axis represents the change of ITI. Each point in a graph corresponds to a single trial. These points were clustered by the "nearest neighbour method", and a threshold value of a squared Euclid distance calculated from ΔSE and ΔITI was 200. The clusters were numbered in the order of the cluster with the largest number of points. All numbered clusters had more than one point.

negative feedback SE mechanism to maintain the internal synchronization of the tap with the auditory stimulus. In previous models of synchronized tapping, the phase correction has been assumed to be a negative feedback for the internal phase difference [7,14], and our experimental results directly support this mechanism.

Cluster 2 was generated under the longer ISI conditions (1200–1800 ms) and showed a weaker correlation and larger ITI change than was seen for cluster 1. Fig. 2f shows an example of such a significant ITI change. This cluster was observed in the region with a large positive ΔSE that exceeded 35 ms. Repp has already reported the overshoot response of ITI and found that this response only appeared when the ISI is substantially changed during synchronized tapping [15,14]. We found this response mainly in the ΔSE positive region where the subject perceives the stimulus as preceding the tap response. This suggests cluster 2 does not reflect a simple negative feedback mechanism for phase correction.

In the dual task condition, only one cluster was found under all ISI conditions. This cluster had a strong negative correlation in all conditions of ISI (mean $r = -0.75$, S.D. = 0.09) and we think that this was the same as cluster 1 observed in the single task condition. These results suggest that the mechanisms are different for clusters 1 and 2, and that attentional resources are necessarily involved in the generation of cluster 2. We have already shown that attentional resources are used in the timing control [10], and the finding of cluster 2 agrees with our previous report.

The control mechanism for synchronized tapping is considered to synchronize between the timing of the auditory stimulus and somatosensory feedback from the tap motion as described in the Mates' model [6]. This interpretation corresponds to cluster 1. However, cluster 2 is very different from such a symmetrical feedback mechanism. Here, the timing control is asymmetrical about internal synchronous timing (ΔSE = 0), suggesting the existence of an anticipation mechanism. Time before and after this internal synchronization may be interpreted as having a different meaning based on anticipation. Furthermore, this cluster 2 has threshold of about 35 ms, and it is similar to the cognitive threshold of temporal order judgement [11]. This kind of cognitive timing mechanism has not been considered in conventional simple feedback models of timing control.

We have shown that the internal phase correction mechanism can be divided into two stages. The first is an automatic control in which the attentional resources are not essential. This is observed at all ISI values with a stable negative feedback mechanism present over a wide range of SE changes. In contrast, the second mechanism requires attentional resources and is observed under the longer ISI conditions. This mechanism appears only when the SE changes are positive and large, suggesting internal anticipation of synchronized timing. We believe the first mechanism is related to the motor control level, while cognition is involved in the second mechanism. We here demonstrate that phase error correction is based on these two mechanisms.

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