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Control Mechanisms of Perceived Phase Error on Synchronized Tapping

Toward Communication Support Systems based on Psychological Timing Control

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Abstract—**In recent years, information technology rapidly increases the opportunity of human communication. However, communication supporting systems, such as tele-presence and CSCW, were mainly developed based on physical interaction and not on psychological one. In this article, we analyzed the psychological interaction mechanism of human timing control using synchronization tapping task. Particularly, we focused on the phase error correction, and the following 2 facts were found. 1) Perceived timing is not coincident with physical timing. 2) The perceived timing is controlled by two types of phase error correction mechanisms. One requires attentional resources and the other does not. These results suggest that timing control for human communication support system should be based on his/her perceived timing, and such psychological timing control mechanism is useful for realizing the human-like communication systems.**

I. Introduction

In recent years, information technology rapidly extends the opportunity of human communication, such as tele-presence [1][2], CSCW[3][4] and so on. However, these technologies mainly focus on the aspects of physical interaction in human communication. To realize human-like communication, it needs not only physical interaction but also psychological one. If psychological interaction does not work in such supporting system of human communication, it will not operate smoothly. In this study, we analyzed the psychological mechanism of timing control using synchronization tapping task.

This timing control is an essential ability to coordinate human action with dynamic environment including human behavior. In the studies of such synchronization phenomenon, synchronization tapping has been widely used to investigate the timing mechanism [5][6][7]. In this psychological task, subject is required to synchronize his/her taps with periodic stimuli as precisely as possible. To synchronize the stimulus-onset and the tap-onset, error correction mechanism of timing control is thought to be indispensable. In particular, two types of internal mechanism have been distinguished [8][9][10]. One is the phase correction that is to coincide the tap timing with the stimulus timing, and the other is the period correction that is to synchronize the tap period with the stimulus period.

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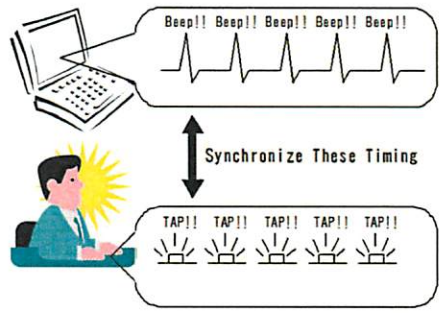

Fig.1: Experimental image of synchronization tapping task

These error correction mechanisms have been investigated by controlling the inter stimulus-onset interval (ISI) during the synchronization tapping task [11][12][13]. For example, Repp *et al.* observed the period correction process depending on awareness of ISI change during trials [11][12]. Thaut *et al.* changed the ISI to a cosine wave during trials and analyzed the subliminal phase correction process as a rhythmic entrainment [13]. However, in this experimental method in which only the ISI is controlled, the clear distinction between the phase correction and the period correction is difficult. For further investigation of these mechanism, the relationship between the stimulus-onset and the tap-onset (SE: synchronization error) should be directly controlled. We think this method enables to separate the phase correction process from the other error correction mechanism. However, experiments have only been conducted with SE=0 in former researches of the synchronized tapping [7].

In regards to the phase correction, the negative asynchrony (NA) is well known in the synchronization tapping task. This phenomenon is that the subject's tap precedes the stimulus by a few 10 ms, where the subject is unaware of it [14]. This phenomenon shows that timing mechanism is not a passive reaction to the stimulus, but an active action based on the anticipation of the next stimulus timing. Miyake *et al.* proved that the generation rate of NA depends on the ISI length. Moreover, using the dual task method [15], it was clarified that attentional resources are involved in the occurrence of NA if the ISI is longer than 2 s [16]. This study indicates that the phase error correction is not a single mechanism but a hierarchical one which is dependent on the ISI.

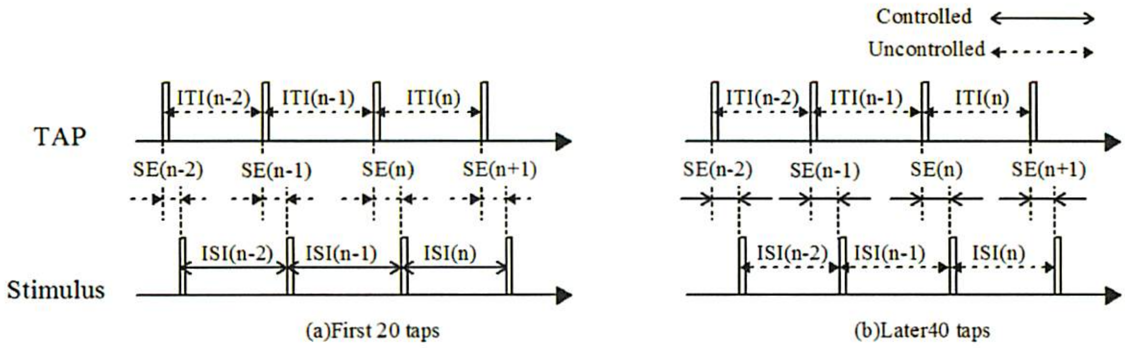

Fig.2 Stimuli presentation method in this experiment:

Therefore, the purpose of this study is to clarify the internal mechanism of phase error correction in the timing control of synchronized tapping. Specifically, a new experimental method was developed which can directly control the SE in the tapping process. And we try to quantitatively analyze the effects of the SE on the phase correction mechanism using this new experimental system. In addition, the effects of the ISI dependency and the attentional resources on this timing control are also estimated in relation with the former report by Miyake *et al.* [16].

II. METHODS

A. Experimental task

The experimental task was to synchronize the push of a button (tap) with a periodic auditory stimulus as precisely as possible. Since the purpose of this research is to clarify the phase error (SE) correction mechanism, the phase error in each tap should be directly controlled. Thus, a new method was developed wherein the auditory stimulus was presented at a fixed time interval (0 to 110 ms) after the subject's tap. Therefore, the phase correction mechanism could be analyzed through observation of the ITI with the SE controlled.

In the previous research, it was reported that the ITI gradually decreased when the SE was fixed to 0 [7]. This suggests that the auditory stimulus was perceived prior to the onset of tap. Therefore, the phase error which is not a physical one but a perceived one can be controlled by the above experimental method.

In addition, the experiment had to be conducted with multiple lengths of ISIs, because Miyake et al. suggested that phase error correction mechanism is affected by the ISI. Thus, the subject taps with a stimulus of a fixed period in the first half of the trial, and the SE is controlled during the tap in the last half of the trial. Further details are described below.

One trial consists of 60 taps, and the stimulus presentation methods were different in the 20 taps of the first half and in the 40 taps of the last half. ISI was fixed in the first 20 taps as similar to the typical synchronized tapping task (Fig.2a). This is referred to as the Fixed ISI (FISI) condition. The tap period of the subject was controlled based on this method. In the 40 taps of the last half, stimuli were presented after a fixed time interval from the onset of subject's tap (Fig.2b). This is referred to as the fixed SE (FSE) condition. It is thus possible to control the phase error (SE) between the stimulus and the tap.

Two different lengths of ISIs(450ms,1800ms) were used in the FISI condition. Seven different lengths of SEs between -110 to 0 ms of 0, -10, -30, -50, -70, -90, and -110 ms were used in the FSE condition. All of the SEs were negative because the auditory stimulus was presented after the onset of tap. Under a combination of these conditions, 14 trials were conducted in a single session for each subject. In addition, the subjects were not informed when the stimulus presentation conditions were changed during the trials.

The dual task method [15] was also used in the same condition described above in order to examine the effect of attentional resources on the phase error correction mechanisms. The first task was the synchronized tapping task as described above and the second task was a silent reading task. The condition only for the first task is referred to as the single session, and the condition that required the first task and the second task simultaneously is referred to as the dual session. Miyake et al. had suggested that attention has influence on the timing mechanisms. If the phase error correction requires the attentional resources, the responses will be different between the single session and the dual session.

The Japanese language version of *The Cathedral and the Bazaar* by Eric S. Raymond which is available online at (http://cruel.org/freeware/cathedral.html) was used for the silent reading task. After the experiment was finished, the subject was asked several questions on the content of the text. The subject had to choose between two possible answers for each question and the percentage of correct answers was then calculated.

B. Subjects and experimental system

Six healthy males in the 20s and 30s participated in the study as volunteers. All of the subjects were right-handed and exhibited no hearing abnormalities. They all had experience of the synchronized tapping tasks, having participated in

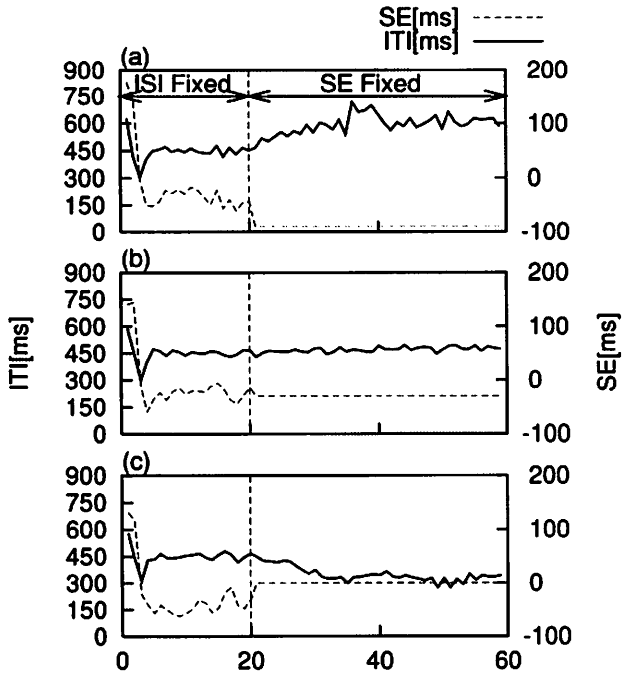

Fig.3 Example of SE and ITI time series: (a) ISI=450, Fixed SE=-90. (b) ISI=450, Fixed SE= -30. (c) ISI=450, Fixed SE=0

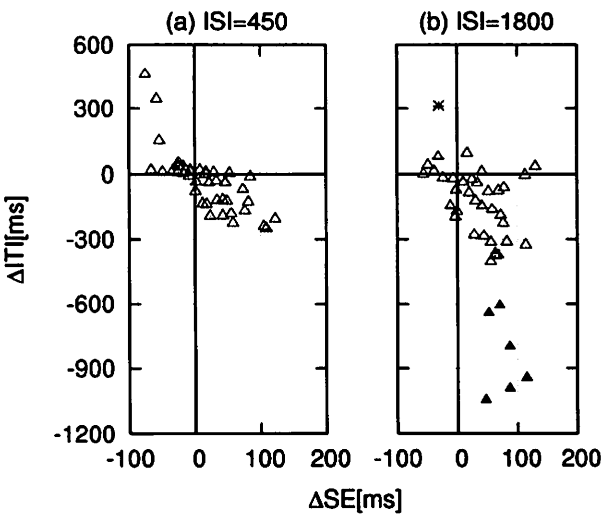

Fig.4. Scatter graph of ΔSE vs. ΔITI in single condition: White triangles show cluster1. Black triangle shows cluster2. Other points were not included clusters.

Table 1: Correlation coefficient of single session

ISI	Cluster1 Correlation coefficient	Cluster2 Correlation coefficie
450	-0.77	
1800	-0.43	-0.23

similar experiments. The experiment was conducted in a quiet room with the subject sitting in a chair and his/her eyes closed. The taps were made using the right index finger. Subjects were forbidden to count out with any motion other than their right index finger and to do split counting of the stimulus period.

The experimental system used in this study was constructed on a PC (IBM ThinkPad 560E) with a single task OS (IBM PC-DOS2000). The stimulus was transmitted to the subject via headphones which were connected to the PC. Duration of the stimulus was 100 ms and frequency was 500 Hz. The sound pressure was set to an appropriate level which ensured that the auditory stimulus could be clearly heard.

Tap-onset time and stimulus-onset time were recorded to the PC through a parallel port. The time measurement was done using a real time clock (RTC) with time resolution of 1/2048s. An auditory stimulus was generated at a fixed time interval after the tap-onset, and the software of this system was described by C language.

C. *Experimental procedures*

Each trial was made up of 60 taps, and 14 trials were conducted in a single session with a combination of conditions in the first half and the last half. The subject was given a 5-second break between each trial, and the experimental order for the trials within a session was random. In the dual task method, a single condition session is first conducted, and then a dual condition session is conducted. However, the order of trials was the same within a session for the single condition and dual condition for the same subject. Thus, a single subject participated in 28 trials over the course of 2 sessions, and the 6 subjects participated in a total of 168 trials.

The tap period (ITI: Inter Tap-onset Interval), the stimulus interval (ISI: Inter Stimulus-onset Interval) and the phase error between the tap and the stimulus (SE: Synchronization Error) for each subject were calculated from the tap and stimulus onset time, and their time series were analyzed. The data from the first 5 taps immediately after the start of a trial were not used for the analysis in order to eliminate the behaviorally unstable data.

III. Results

A. *Temporal development of SE and ITI*

The temporal development of SE and ITI is shown in Fig.2. Three types of ITI responses were observed in the FSE condition. The first type of response was characterized by an increase of the ITI (Fig.3a), the second type by no change of the ITI (Fig.3b) and finally the third type by a decrease of the ITI (Fig.3c).

We think that the responses reflect the subject's perception of the temporal order of the tap and the auditory stimulus because the subject was instructed to synchronize the tap and the auditory stimulus. Specifically, if the ITI is increased, then the subject's perception would be that the stimulus is delayed from the tap, if the ITI is unchanged, then the tap and the stimulus would seem simultaneous, and if the ITI is decreased, then the stimulus would precede the tap. However, these ITI responses did not reflect the physical order between the tap and the stimulus because the stimulus was always presented after the tap in the FSE condition.

B. Relationship between SE change and ITI change and its ISI dependence

The purpose of our research is to determine the phase error correction mechanism by controlling the SE and observing the ITI response. The method described below was applied in the analysis. The horizontal axis was the SE change (ΔSE) which was obtained as the difference between the mean SE of 15 taps in the FISI condition and the SE which was fixed for 40 taps in the FSE condition. This ΔSE value can be regarded as an input into the phase error correction mechanism.

ΔSE=(fixed SE in the FSE condition) – (mean SE in the FISI condition)

The vertical axis is the ITI change (ΔITI) which was obtained from the mean ITI of 15 taps in the FISI condition and the mean ITI of 40 taps in the FSE condition.

ΔITI =(mean ITI in the FSE condition) – (mean ITI in the FISI condition)

This ΔITI reflects the perception of the subject, and it can be regarded as an output from the phase error correction mechanism. Fig.4 shows the relationships between the ΔSE and ΔITI (ISI=450,1800ms). Each point corresponds to a single trial. Overall, the points are distributed along a straight line lower right through near the origin, and a strong negative correlation is shown. This is observed in a wide region of the ΔSE, and that configuration is also stable. It corresponds to a decrease of the ITI when the SE increases (the time difference between the tap and the stimulus decreases) and an increase of the ITI when the SE decreases (the time difference between the tap and the stimulus increases). This means that the ITI is adjusted so that the SE returns to its stable value when the SE has drifted, suggesting a negative feedback mechanism of SE. In addition, another group of points was observed which are at a large distance from the straight line distribution in the ΔSE positive region as seen in Fig.4b which correspond to the ISIs of 1800ms. Thus, it is speculated that the response of the ΔITI changes in the region of large ISIs. The ΔITI in regards to the same ΔSE was large for this response.

These points were clustered by the nearest neighbor method in order to quantitatively analyze these characteristics, and a threshold value of a squared Euclid distance was 200. The clusters were numbered in the order of the cluster with the largest number of points. A cluster which is made up of only one point was not numbered as a cluster. There is only one cluster (cluster 1) in the ISI = 450ms, and its configuration is a straight line which passes through the origin. Moreover, in addition to the clusters with a similar structure observed in Fig.4a, a second cluster (cluster 2) which is largely different from that configuration has been split at ISI = 1800ms as shown in Fig.4b.

Table1 showed the correlation coefficient and gradients of

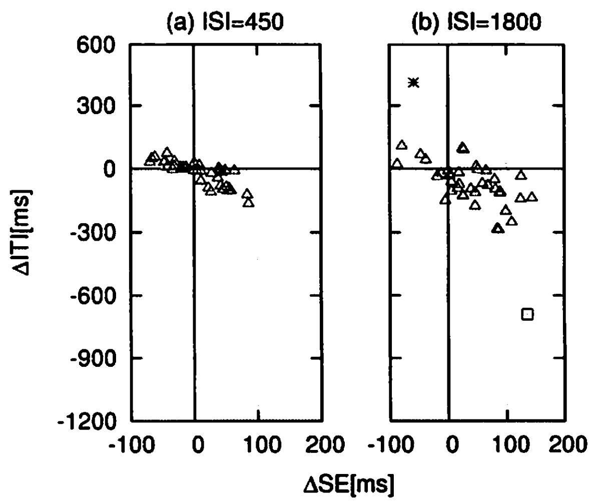

Fig.5. Scatter graph of ΔSE vs. ΔITI in dual condition: White triangles show cluster1. Other points were not included clusters.

Table 2: Correlation coefficient of dual session

ISI	Correlation coefficient
450	-0.80
1800	-0.60

all conditions. Cluster1 had strong negative correlation, but cluster2 did not and there is a significant difference between them in the configuration. Cluster 1 was observed in the entire ΔSE region, and cluster 2 was observed only in the positive region of ΔSE. In this ΔSE region, it was mainly observed in the region in excess of 35 ms. In addition, cluster 2 has a large ΔITI value in comparison with the response of cluster 1 with the same ΔSE.

C. Effect from attentional resources

The ISI region observed in cluster 2 is close to the ISI region which was found to be involved in the timing control with attentional resources in the research of Miyake et al. [9]. Thus, in order to examine the effect of attentional resources, the dual task method was used with a synchronized tapping task. The primary task is synchronized tapping and the secondary task was a silent reading task. In the silent reading task, after the session was finished, the subject answered several questions on the content of the text. The subject was given approximately 10 forced-choice questions to determine whether attentional resources were used in the silent reading task. The subject was forced to choose one correct answer from two possibilities for each question to determine whether attentional resources were used in the silent reading task. The mean percentage of correct answers was 85.2% with a range of 76.9% to 94.7%, and subject's attention was thought to be devoted to the silent reading task.

The results from the dual task method are shown in Fig.5. Only one cluster was formed in all ISI conditions. In addition, the relationship between ΔSE and ΔITI showed a configuration which passed through the origin with a strong negative correlation. The negative correlation and gradients were large in all ISI conditions (Table 2) and it is speculated that this was the same response as cluster 1 in section 3.B. In the dual task method conditions cluster 2 in section 3.B was not observed. These findings suggest that the generation mechanisms are different for cluster 1 and cluster 2.

IV. 4. Discussion

In this experiment, we controlled SE (Synchronization error) in synchronized tapping, and observed ITI (Inter Tap-onset Interval).The following results were obtained through this new experiment.

1) Three different cases were observed with the ITI decreasing, not changing and increasing depending on the SE value in the FSE condition in the last half of the trial.
2) Two types of responses were observed as the relationships between the SE change (ΔSE) and the ITI change (ΔITI) in the FSE condition.
3) One was the cluster (cluster 1) with a strong negative correlation between the ΔITI and the ΔSE, and this cluster was observed in the entire ΔSE region.
4) The other cluster (cluster 2) exhibited almost no correlation between the ΔITI and the ΔSE. This response was mainly observed in the positive area of ΔSE with 35 ms or higher. The ΔITI for the same ΔSE was larger than ΔITI with cluster 1.
5) Cluster 1 was observed in the all ISI regions, and cluster 2 was only observed in the ISI region of 1800.
6) Cluster 1 was only observed in dual task conditions.

Three different cases were observed with the ITI change (decrease, no change and increase) depending on the SE value fixed in the FSE condition. The direction of ITI changes is thought to correspond to the perceived order between the tap and the auditory stimulus. However, the auditory stimulus was always presented, in reality, after the tap. This finding demonstrates that the perceived order differs from the actual presentation order. Accordingly, we should interpret these obtained results as the relationship between the auditory stimulus and the tap response on the subject's perception.

Thus, we analyzed the phase error correction mechanism from the standpoint of the subject's perception. For this reason, two parameters (ΔSE and ΔITI) were defined and the relationship between the both was analyzed. These results revealed two different types of relationships. One was cluster 1 which exhibits a strong negative correlation, and the other was cluster 2 which exhibited a weak correlation and a larger ΔITI than that with the cluster 1.

Cluster 1 was observed at all ISI lengths and had a strong negative correlation which sloped to the lower right as shown in Fig.3 and Fig.4. This cluster was observed over a wide range of ΔSE and its configuration was stable. This means that the ITI is adjusted to recover the stable SE value when it is drifted, suggesting the negative feedback mechanism for the SE. Even in the previous models of synchronized tapping, the phase correction has been assumed as the negative feedback [8], and this is the experimental result that supports the mechanism. In addition, we think that the error correction dynamics is stable and the time resolution is high, because the cluster 1 passed close to the origin and the correlation was strong as shown in Fig.4. There are a number of models of the timing control[8],[11],[12], and our results support the model with a high resolution [12] for cluster 1.

Cluster 2 was observed in the long ISI conditions, and weak correlation and large ITI change were observed in the region with a large positive ΔSE exceeding 35 ms. Repp reported on the overshoot response of ITI [15] and found this type of response is generated when the stimulus period is largely changed in synchronized tapping. Accordingly, this cluster 2 may be related to the results of Repp. This response was observed herein mainly in the ΔSE positive region. The ΔSE positive region is a region in which the subject perceives that the sound precedes the tap. This asymmetrical time perception had also been suggested in previous research [13], and the asymmetrical mechanism in the phase correction is speculated. However, it might be related to the fact that the observable region for the negative ΔSE was narrow in our experimental method.

Cluster1 was observed in all ISI lengths, however, cluster2 appeared only in ISI = 1800ms. Moreover, cluster 2 was not observed under the dual task conditions. The dual task method [10] is a procedure designed to examine the influence from the attentional resources. Our findings suggest that the generation mechanisms are different for responses of cluster 1 and cluster 2. Miyake et al. [16] had clarified the effect of attentional resources by finding that the synchronized tapping is affected by the dual task method under a long ISI condition. These results indicate that attentional resources are not involved in the generation mechanism of cluster 1 and involved in cluster 2.

The attentional resources are related to the working memory [15] and it is on the prefrontal cortex [17],[18]. In addition, it has been reported that the time perception mechanism of 1 second or more uses the prefrontal cortex [19]. Therefore, the neural mechanism which generates cluster 2 may be in the prefrontal cortex. On the other hand, it has been suggested that the time perception mechanism with high time resolution resides in the cerebellum . Considering that the cluster 1 mechanism has a high time resolution, the neural mechanism for cluster 1 may be located in the cerebellum.

From these results, we showed that the phase error correction mechanism can be classified into two types. The first mechanism is an automatic control mechanism in which the attentional resources are not involved. A stable negative feedback mechanism appears over a wide range of SE changes, and the time resolution is high. This is thought to be related to the motor control level. Moreover, the second mechanism requires the attentional resources, and this was observed only when the SE changes were large. Thus, the involvement of the cognition level should be considered. Accordingly, the possibility is high that phase error correction is realized based on these dual mechanisms.

The timing mechanism has been divided into the phase correction and the period correction [9]. Repp *et al.* reported that the phase correction mechanism is automatic while the period correction mechanism is not automatic [20]. Our results suggest that attentional resources are involved even in the phase correction when the ΔSE is large. However, the ITI changed substantially in the last half of the trial under our experimental method. Thus, the possibility that the period correction has an effect on this phase correction mechanism cannot be neglected. Further analysis is needed.

We studied the mechanism of timing control in human's time perception. As a result, it was shown that the timing control of perceived time is different from that of physical time and we clarified the mechanism of such psychological interaction, particularly, the phase error correction mechanism. Nowadays, communication systems mainly develop based on physical interaction. However, to realize smooth and human- like communication support, it was clear that both physical and psychological interaction mechanism are indispensable. Our result showed the importance of internal timing control.

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