Subjective Timing Control in Synchronized Motion of Humans

A Basic Study for Human-Robot Interaction

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Abstract. The purpose of this paper is to clarify the internal phase correction mechanisms for timing control in a synchronization tapping task. Here, the synchronization error (SE) is directly controlled using our experimental method, and its response is measured as the temporal development of the inter tap onset interval (ITI). As a result, two types of internal phase correction mechanism are revealed. The first type shows a strong negative correlation between SE change and ITI change, suggesting a simple negative feedback mechanism. The second one does not show this correlation and disappears under the dual task condition. These results suggest that there are two types of timing control mechanism in the phase correction of tapping task.

1 Introduction

Humans adapt flexibly to a dynamic environment. The timing control mechanism plays an important role in obtaining such an adaptation process, and the importance of timing control becomes clear if one considers coordinated human behavior, such as music, sports and communication.

For example, Condon *et al.* showed that the mutual interaction between speech rhythm and body rhythm plays an important role in the communication between mother and infant [1]. Matarazzo [2], Webb [3] and Nagaoka [4] reported that the duration of utterance, the speed of utterance and the reaction time are synchronized among speakers. Furthermore, psychological estimation of the influence from timing of utterance, nodding and gesture is also studied in human-robot interaction (HRI) [5][6].

However, these timing mechanisms have been studied from an external viewpoint which is based on objective time. There are no reports about subjective timing from an internal viewpoint. Therefore, a new horizon of communication science and a new technology for realizing natural HRI are expected to be developed by the

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research of this subjective timing mechanism. From these backgrounds, the purpose of this study is to clarify the subjective timing control as a basic study for HRI.

In order to investigate this timing mechanism, a *synchronization tapping task* [7-9] in which the subjects are required to synchronize their taps with periodic stimuli as precisely as possible, has been widely used. The most interesting finding is the phenomenon that the onset of each tap *precedes* the onset of stimulus by several 10 msec [10-12]. This anticipatory phenomenon is called "*Negative Asynchrony*," and has been replicated in a number of studies. The pressing-in-advance phenomenon, for which the subject is unaware, demonstrates that the motor command to the finger is generated before the onset of auditory stimulus, suggesting a processing of subjective timing control.

Previous studies of this synchronization tapping task can be separated into two categories. The first category is the modeling of this timing mechanism [13-16]. The most important one was proposed by Mates [14][15], which is characterized as a subjectively controlled negative feedback model. The second category is its neural basis [17-19] and two types of timing process have already been clarified; a *physically controlled process* and a *cognitively controlled process* [20][21]. Here, we define the timing control requiring attentional resources as a cognitively controlled process, not requiring a physically controlled process.

However, since Mates' model is described by perceived subjective variables, such as internal phase error and internal period error, it is difficult to compare Mates' model with its externally observed variables. Therefore, we developed a new experimental method which is able to control internal phase error directly and investigated the subjective timing mechanism based on the Mates' model. Furthermore, in relation with our previous studies about timing process, we also investigated the influence of attentional resources to the timing mechanism, by applying the dual task method [22].

2 Experimental Task

2.1 Mates' Model

In this study, we are investigating the subjective timing control mechanism based on Mates' model. The reason why we adopt Mates' model is that timing mechanism of humans is explained by internally perceived subjective timing, and this model is systematically developed from previous timing control models.

This Mates' model can explain the timing mechanism in synchronization tapping as shown in Fig. 1. Upper part of the dash line and lower part of the dash line shows externally observable physical event and internally perceived subjective event, respectively. The subscript *i* stands for internal variables. We make all variables which describe Mates' model into Table 1.

The Mates' model consists of two different mechanisms. One is the period error correction Eq. 1 and the other is the phase error correction Eq. 2.

$$T_i(n) = T_i(n-1) - \beta \cdot [T_i(n-1) - \{S_i(n) - S_i(n-1)\}] \qquad (1)$$

$$R_i(n+1) = R_i(n) + T_i(n) - \alpha \cdot e_i(n) \tag{2}$$

where T_i is the intrinsic period of the internal timekeeper. S_i is the perceived internal timing of the external stimulus. R_i is the initiation timing of the internal motor command. e_i indicates the internal synchronization error (internal phase error) which is defined as the time difference between S_i and R_i. β and α are coefficients of feedback gain.

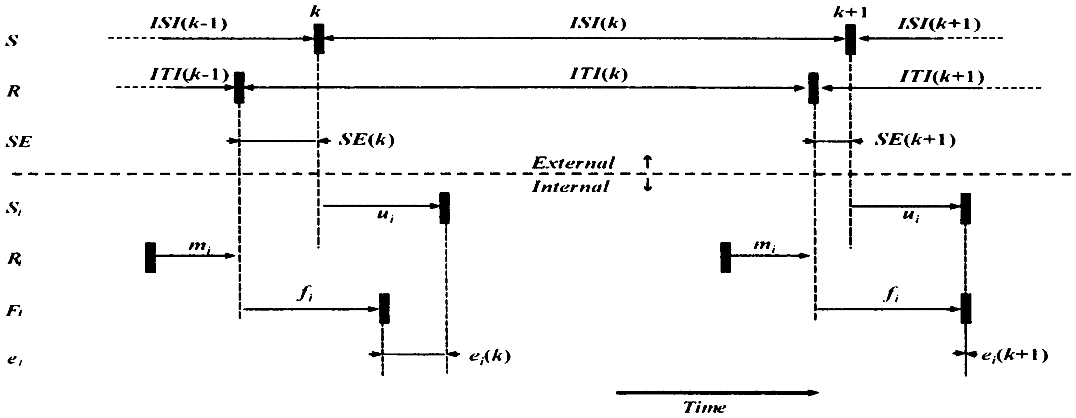

Fig. 1 Time scheme and definition of external (upper part) and internal (lower part) temporal variables of sensorimotor synchronization process and time diagram of the hypothesized mechanism of subjective synchronization [15]

Table 1 Variables of sensorimotor synchronization model [15]

Variable	Type	Description
External variables		
S	Event	Occurrence of stimulus onset
ISI	Interval	Inter stimulus-onset interval
R	Event	Occurrence of motor response onset
ITI	Interval	Inter tap-onset interval
SE	Interval	Synchronization error
Internal variables		
u_i	Interval	Transduction delay of stimulus
m_i	Interval	Motor delay in execution of motor act
f_i	Interval	Transduction delay of feedback information from already executed onset of motor act
S_i	Event	Temporal central availability of stimulus
R_i	Event	Initiation of motor command
F_i	Event	Temporal central availability of feedback
e_i	Interval	Internal synchronization error (time difference between temporal central availability internal representations of some aspects of stimulus and response)
t_i	Interval	Internal timekeeper (reference) interval

Here, we define ΔT_i and Δe_i as follows.

$$\Delta T_i(n) = T_i(n+1) - T_i(n) \tag{3}$$

$$\Delta e_i(n) = e_i(n+1) - e_i(n) \tag{4}$$

Then, Mates' model can be transformed into Eq. 5.

$$\Delta T_i(n) = -\beta \cdot \Delta e_i(n) - \alpha \cdot \beta \cdot e_i(n) \tag{5}$$

This means that Mates' model is a feedback control system. The change of the intrinsic period of the time keeper is modified based on the internal phase error and the change of it.

2.2 Transformation of Variables

Since Mates' model was described by internally perceived variables, it is difficult to directly verify the relevancy by measuring externally observed variables of the tapping task. Therefore, we should define the relationship between external variables and internal variables by transformed Mates' model.

First, we define the external variables that are used in synchronization tapping task. As shown in following, three variables, Inter Stimulus-onset Interval (*ISI*, Eq. 6, Inter Tap-onset Interval (*ITI*, Eq. 7) and Synchronization Error (*SE*, Eq. 8) are defined. Here $S(n)$ indicates the n-th stimulus onset and $R(n)$ indicates the n-th tap onset.

$$ISI(n) = S(n+1) - S(n) \tag{6}$$

$$ITI(n) = R(n+1) - R(n) \tag{7}$$

$$SE(n) = R(n) - S(n) \tag{8}$$

Here, we introduce two hypothesis. One is that we consider neurotransmission delay as constant. Mates treated transduction delay of stimulus and of feedback as random. However, the clear account or mathematical basis of them are not shown by Mates. Therefore, we these regard transmission delay as conatant.

$$\begin{aligned}
\Delta T_i(n) &= T_i(n+1) - T_i(n) \\
&= \{R_i(n+2) - R_i(n+1) + \alpha \cdot e_i(n+1)\} \\
&\quad - \{R_i(n+1) - R_i(n) + \alpha \cdot e_i(n)\} \\
&= ITI_i(n+1) + \alpha \cdot e_i(n+1) - ITI_i(n) - \alpha \cdot e_i(n) \\
&= \Delta ITI_i(n) + \alpha \cdot \Delta e_i(n)
\end{aligned} \tag{9}$$

Here, in Eq. 9, considering the constancy of the transduction delay between motor command and tap motion is constant, the perceived internal $\Delta ITI_i(n)$ can be replaced with the external variable $\Delta ITI(n)$. Therefore, from Eq. 9, we obtain the following.

$$\Delta T_i(n) = \Delta ITI(n) + \alpha \cdot \Delta e_i(n) \tag{10}$$

Using this relationship between internal variable and external variable, Mates' model Eq. 5 is transformed into Eq. 11.

$$\Delta ITI(n) = -(\alpha + \beta) \cdot \Delta e_i(n) - \alpha \cdot \beta \cdot e_i(n) \tag{11}$$

Furthermore, it is necessary to relate internal phase error $e_i(n)$ to externally observable variable. Thus, we introduce the other hypothesis as below. In this experimental task, subjects were instructed to control their internal synchronization error as low as possible. This means that *SE* is considered to be the time difference between externally observed synchronized state and internally perceived synchronized state. This is also supported by the negative asynchrony phenomenon. Thus, by regarding the averaged *SE* as the timing of the internally synchronized state, it becomes possible to consider the time difference between tap onset and the averaged *SE* as the internal phase error. Therefore, e_i is able to be defined as following, by using external variables.

$$e_i(n) = 0 \Leftrightarrow SE(n) = mean\ SE \tag{12}$$

And, internally perceived phase error e_i is able to be defined as following, by using external variables *SE*(n).

$$e_i(n) = SE(n) - mean\ SE \tag{13}$$

By these two hypothesis, Mates' model can be related to externally observable variable.

2.3 Design of the Experimental Task

In this study, we define a modified synchronization tapping task which is composed of two different stages (Fig. 2). In the first stage (FISI condition), subjects conduct the normal synchronization tapping task under fixed *ISI* condition for realizing the internally synchronized state. The time difference between the internal synchronized state and the external synchronized state is defined by calculating the mean of *SE*. This mean *SE* is regarded as the timing that internal phase error e_i is 0. In the second stage (FSE condition), we experimentally control the synchronization error *SE* to the averaged *SE* in order to fix the internal phase error to 0. Then *SE* is changed by ΔSE to fix the internal phase error e_i at ΔSE. By this method, we can control the internally perceived synchronization error. In this experimental task, by analyzing the relationship between the controlled variable (ΔSE) and the response variable (ΔITI), the internal timing mechanism Eq. 11 is investigated to verify Mates' model.

The internal phase error is controlled at 0 in the m-th tap and is controlled at ΔSE after the (m+1)-th tap.

$$e_i(m) = 0, e_i(m+1) = \Delta SE \tag{14}$$

Here, the Eq. 11 is described as follows.

$$\Delta ITI(m+1) = -(\alpha + \beta) \cdot \Delta SE \tag{15}$$

After the (m+2)-th tap, using an integer k, with ($k > m+1$),

$$e_i(k) = \Delta SE, e_i(k+1) = \Delta SE \tag{16}$$

the Eq. 11 becomes as follows.

$$\Delta ITI(k) = -\alpha \cdot \beta \cdot \Delta SE \tag{17}$$

Therefore, if the timing mechanism is realized based on Mates' model, it is expected that ΔITI and ΔSE have a linear relationship as shown in Eqs. 15 and 17. Thus, we can analyze the relationship between Mates' model and experimental data. It is possible to compare relationship between ΔITI and ΔSE obtained in this experiment, with Mates' model directly. Therefore, it becomes possible to analyze timing mechanism quantitatively.

3 Methods

3.1 Procedure

Subjects were instructed to tap in synchrony with the periodic auditory stimuli as precisely as possible. They pressed a button using their right index finger. One set consists of 30 taps. We used 25 taps for analysis, excluding the initial unstable 5 taps. These 25 taps are divided into the first 20 taps, the following 1 tap and the remaining 4 taps. In these initial 20 taps, subjects conducted the normal tapping task with the fixed *ISI* condition (FISI condition). Here, we measured *SE* and calculate SE_1 defined as the time difference between the internal synchronized state and the external synchronized state, as shown in Eq. 18.

$$SE_1 = (\textit{mean SE in the FISI condition}) \tag{18}$$

Then, in the following 1 tap, the internal phase error was fixed to 0 by controlling *SE* at SE_1 (FSE-1 condition). For the remaining 4 taps, the internal phase error was fixed to ΔSE by controlling *SE* at SE_2 (FSE-2 condition) as shown in Eq. 19.

$$SE_2 = SE_1 + \Delta SE \tag{19}$$

In this experiment, 900msec *ISI* was used in the FISI condition. Thirteen different ΔSE (-90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75 and 90msec) were used in the FSE-2 condition.

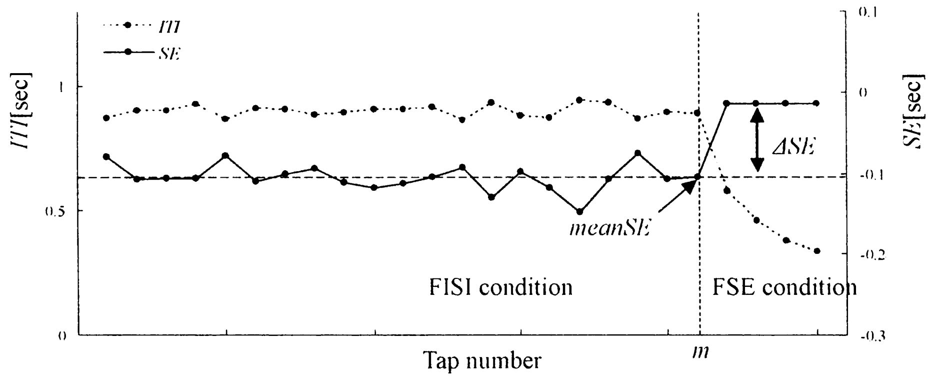

Fig. 2 Design of the experimental task

3.2 Data Analysis

Due to fluctuations of observed variables, it is difficult to verify Eqs. 15 and 17 independently. Thus, we newly define ΔITI_α as a response to the change of the internal phase error, and use for analysis. This ΔITI_α is amount of *ITI* change per one Tap, calculated from the slope of regression line of *ITI* change in the fixed *SE* condition.

3.3 Dual Task Method

In this study, we used the dual task method [22] to estimate the influence of attentional resources to the timing mechanism. We compared the single task condition (normal tapping) with the dual task condition (normal tapping with silent reading). In the single task condition, subjects conducted the synchronized tapping task with their eyes closed. In the dual condition, the subjects had to silently read text, that was scrolling in front of them, on a computer screen. After each trial, the subjects were tested concerning the contents of this text (Table 2). The Japanese language version of "The Mouse in the Mountain" written by Norbert Davis was used for this silent reading task. Furthermore, the test results were compared to that of only silently reading (Table 3). As a results, percentage of correct answers in reading task with tapping significantly decrease from that of without tapping($p<0.05$). Therefore, it is considered that attentional resources were consumed completely in silently reading.

Table 2 Percentage of correct answers in reading task with tapping

Subjects	A	B	C	D	E	F	G	Average
Percentage(%)	87.5	83.3	66.7	75.0	78.6	75.0	58.3	74.9

Table 3 Percentage of correct answers in reading task without tapping

Subjects	A	B	C	D	E	F	G	Average
Percentage(%)	92.3	91.2	91.2	83.3	80.0	88.2	90.9	88.2

3.4 Subjects and Experimental Setup

Seven healthy male (23-25 years old) participated in this tapping experiment. The tapping system was implemented on a computer (IBM, Thinkpad 535) with a single task OS (IBM, PC-DOS2000). The duration of each auditory stimulus was 100msec and the frequency was 500Hz. The Subjects were instructed to press a button using their right index finger. The subjects were also prohibited from timing the tapping by counting to themselves while tapping or by making rhythmical physical movements. The subjects conducted the experiment with sitting down in the quiet, bright and euthermic room.

4 Results

4.1 Temporal Development of SE and ITI

An example of the temporal development of SE and ITI is shown in Fig. 3. Horizontal axis is the tap number. Vertical axis is the size of SE and ITI. Solid line and dash lines indicate temporal development of SE and ITI, respectively. When ΔSE as the controlled variable was 0, ITI as the response variable did not change (a). Furthermore, ITI decreased and ΔITI_a was negative when ΔSE was positive (b). ITI increased and ΔITI_a was positive when ΔSE was negative (c).

4.2 ΔITI_{α} as the Response to ΔSE

In Fig. 4, horizontal axis and vertical axis are ΔSE and ΔITI, respectively. As shown in Sect. 2.3, if the timing mechanism coincides with Mates' model, the re-lationship between ΔITI_{α} and ΔSE is expected to be linear. In Fig. 4, most parts of the data are linearly distributed around the point of origin (the regression line is superimposed). However, there are also other clusters, analyzed by cluster analysis (Ward method). Here, a continuous cluster is defined as one cluster. As a result, they were divided into three clusters. Furthermore, to investigate the relationship

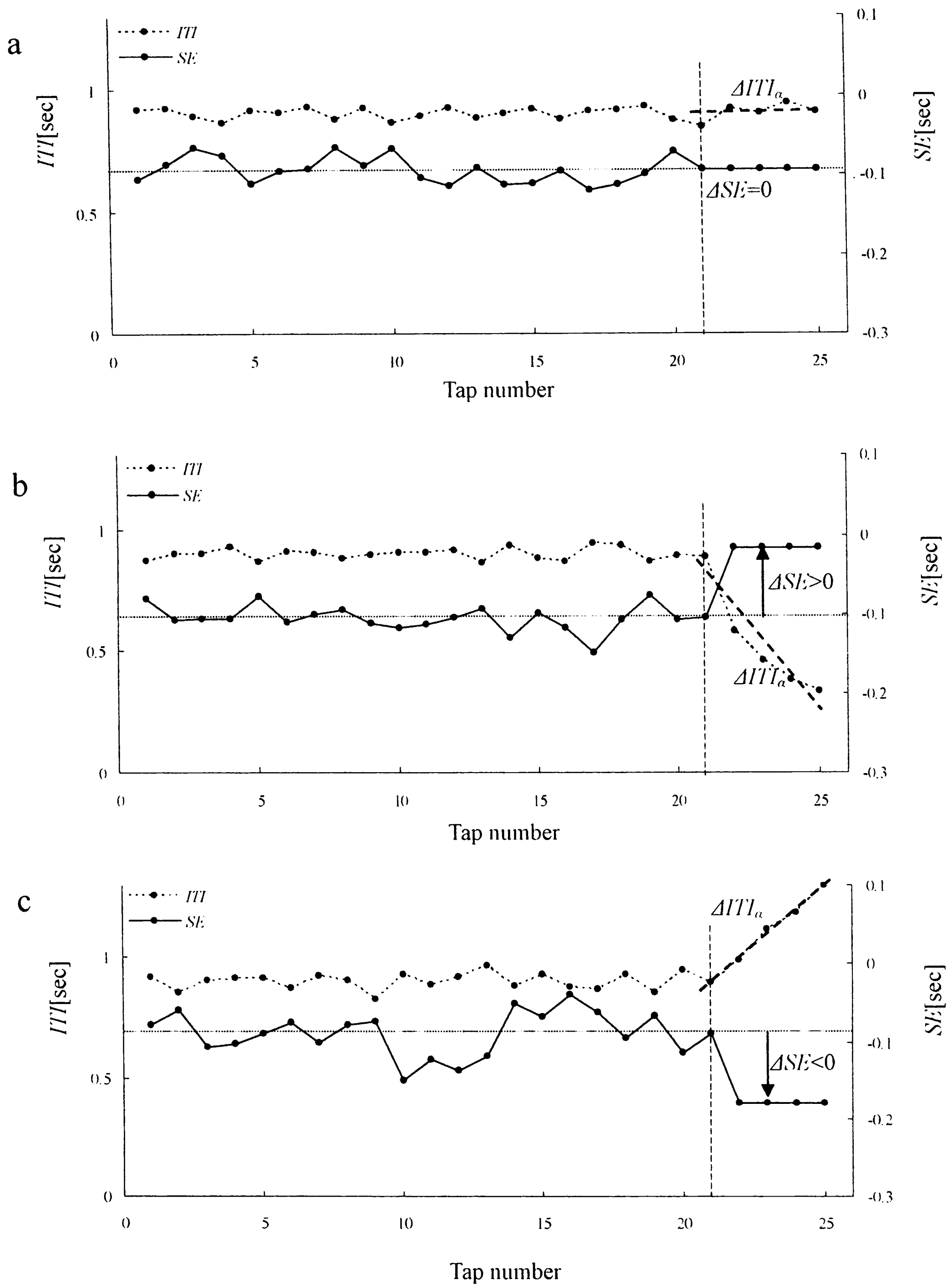

Fig. 3 Temporal development of SE and ITI **a**: $\Delta SE=0$ **b**: $\Delta SE>0$ **c**: $\Delta SE<0$

between the clusters and attentional resources, we compared the single task condition (tapping with attentional resources) with the dual task condition (tapping without attentional resources).

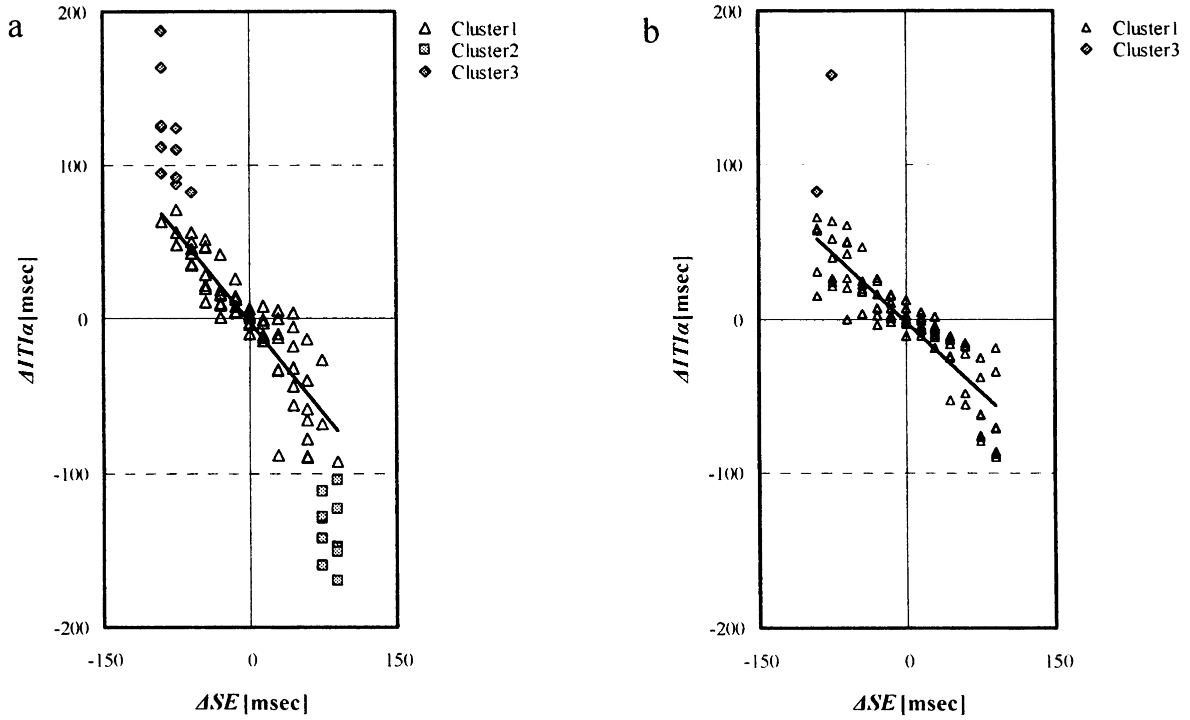

Fig. 4 Relationship between ΔSE and ΔITI_α **a**: single task condition **b** : dual task condition

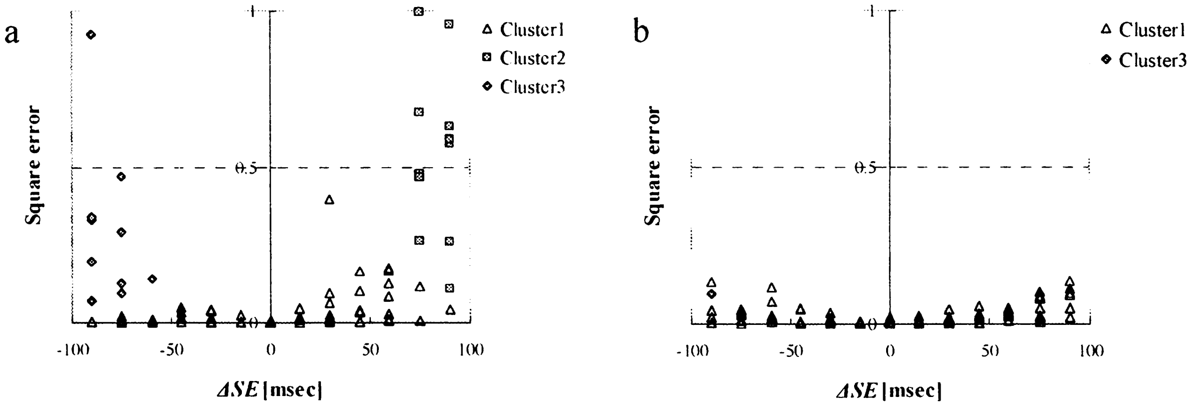

Fig. 5 Square error for regression line derived from Cluster 1 **a**: single task condition **b** : dual task condition

Single task condition shows three clusters. The first one (Cluster 1) is linearly distributed around the point of origin, indicating a strong negative correlation between ΔITI_α and ΔSE. This shows no difference between the single task and the dual task condition. The second one (Cluster 2) is distantly distributed from the linear distribution when ΔSE is positive. The third one (Cluster 3) is also distantly distributed from the linear distribution when ΔSE is negative. This means that the negative feedback mechanism is dominant in Cluster 1, not in Clusters 2 and 3.

Furthermore, these three clusters were observed in the single task condition but only Cluster 1 was significantly observed in the dual task condition.

As for the high linearity of Cluster 1, we calculated the square error for the regression line deviated from Cluster 1 as shown in Fig. 5. The region which is widely deviated from regression line coincided with that of Cluster 2 and 3 obtained from cluster analysis in Fig. 4. Furthermore, one way ANOVA ($F_{2,88}$= 67.60; $p<0.01$) and post-hoc analysis showed that there are significant differences of square error between Cluster 1 and Cluster 2, and also Cluster 1 and Cluster 3 ($p<0.05$). These results strongly suggest that Clusters 2 and 3 deviate from the regression line of Cluster 1.

5 Discussion

5.1 *Characteristics of the Current Study*

The current study has two characteristics. First, we directly controlled the internal phase error in the timing control mechanism to verify Mates' model. Since Mates' model is described by internal variables, it is considered to be difficult to test it. However, we could describe it by using externally controlled variables and observables in our methodology. Second, we investigated the relationship between the timing mechanism and the influence of attentional resources by applying the dual task method.

5.2 *Comparing to Mates' Model*

If the timing mechanism observed in this synchronization tapping experiment coincides with Mates' model (Sect. 2.3), the relationship between ΔITI_α and ΔSE is expected to be linear. However, Cluster 1 was linearly distributed around the point of origin, while Cluster 2 and 3 widely deviate from regression line of Cluster1. These results suggest that the dynamics of Cluster 1 fits to the Mates' model as a feedback control mechanism, however, those of Clusters 2 and 3 do not.

5.2.1 Domain Which Fits to the Mates' Model

Cluster1, fitting to the Mates' model, was observed in both the single task condition and the dual task condition. As for the neural base of this timing mechanism, since the Cluster 1 was not influenced from the attentional resources in the dual task method, it is suggested that the timing mechanism of Cluster 1 is realized based on a physically controlled process. In this process, the cerebellum is thought to play an important role [23-25].

Additionally, this negative correlation becomes stronger in the single task condition than in the dual task condition. Though attentional resources are not necessarily needed in this domain, those results suggested to regulate the feedback gain itself.

5.2.2 Domain Which Does Not Fit to the Mates' Model

In contrast, Clusters 2 and 3, not fitting to Mates' model, were mainly observed in the single task condition and decreased or disappeared in the dual task condition. Silent reading (in dual task condition) uses *working memory* [26][27], holding instantaneous information and correcting information. Specifically, it is suggested that this task is performed by a *phonologic loop*, which is the subsystem of working memory. The text read silent is held temporally in a *phonologic store* within the phonologic loop. The phonologic store is known for holding sense of time and rhythm information [28]. Therefore, it is suggested that the timing mechanism in the Clusters 2 and 3 are related to this phonologic store.

Additionally, in the previous study, a synchronization tapping task with complex stimulus sequence, feedback works stronger in a perceptible stimulus sequence than in a non-perceptible one [29]. This also supports the above discussion.

6 Conclusions

This study focused on the temporal structure of interactions, and aimed to clarify the subjective timing control mechanism in humans, as a basic study for realizing natural HRI. Thus, we analyzed the timing mechanism observed in the synchronization tapping experiment by comparing Mates' model and investigated the influences from attentional resources to the control mechanism from internal viewpoint. Specifically, a novel experimental method which controls the internal phase error directly was used to clarify the relevancy of Mates' model, and the dual task method was also employed to control the attentional resources.

As a result, we found two types of subjective timing control mechanism. One that showed strong negative feedback control which fits to Mates' model. It had no influence from attentional resources. Another that did not fit to Mates' model is influenced from attentional resources. This suggests that human flexibly adapt to a dynamic and complex environment by using a dual process of subjective timing mechanism; a physically controlled one and a cognitively controlled one. Mates' model does not consider this latter cognitive process. From these results, subjective timing control by extending the Mates' model is thought to be required for realizing natural human-robot interactivity.

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