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Two Types of Anticipatory-Timing Mechanisms in Synchronization Tapping

Yoshihiro Miyake[1], Yohei Onishi[1] and Ernst Pöppel[2]

1 Introduction

Mutual coordination of timing is required to produce synchronous cooperative behavior between humans, and an anticipation mechanism related to external events is thought to be indispensable to generate such movement. The importance of this timing control becomes clear if one considers, for example, playing together in a musical ensemble. However, it has been reported that a time difference exists between awareness of cognitive synchrony and physical synchrony, such as a negative asynchrony phenomenon (see next paragraph). Analysis of this anticipatory mechanism should be performed, not only to elucidate the physical process, but also to understand the underlying cognitive process in which a higher brain function, such as attention (Kahnemann 1973), is involved.

The synchronization tapping task has been used as the simplest method for examining the timing mechanism. In this experiment, the subject is required to synchronize his/her finger movement with a periodic auditory or visual stimulus. The most striking demonstration of anticipatory timing control occurs when the onset of each tap precedes the onset of stimulus by several 10ms (Stevens 1886; Woodrow 1932; Fraisse 1966; Kolers and Brewster 1985; Peters 1989; Mates et al. 1994; Aschersleben and Prinz 1995). This pressing-in-advance phenomenon, of which the subject is unaware, demonstrates that the motor command to the finger is generated before the onset of the auditory stimulus, suggesting a process of anticipatory timing control. The negative time offset caused by tapping in advance is referred to as negative asynchrony – a phenomenon that is always observed in the synchronization tapping task in response to a periodic stimulus.

To examine this type of phenomenon, Mates et al. (1994) conducted a synchronous tapping experiment using a periodic auditory stimulus within a range of 300 to 4,800ms. They confirmed that negative asynchrony was observed for

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[1] Department of Computational Intelligence and Systems Science, Tokyo Institute of Technology, Midori, Yokohama 226-8502, Japan

[2] Institute of Medical Psychology, Ludwig-Maximilian University of Munich, Goethestr. 31, Munich 80336, Germany

all of the above stimulus intervals with a difference in the degree of its occurrence. They found that the upper limit for the generation of stable, negative asynchrony with little fluctuation is 2 to 3s for the interstimulus-onset interval (ISI). It was also reported that if the ISI limit is exceeded, reactive responses become mixed with the negative asynchrony.

Synchronization tapping tasks and other types of time-discrimination tasks and time-reproduction tasks (Ivry 1996, 1997; Pascual-Leone 2001; Rao et al. 1997) have demonstrated that the cerebellum plays an important role in neural mechanisms that support perception of time intervals under 1s. Higher brain functions contribute to the perception of time intervals that exceed 2 to 3s (Kagerer et al. 2002; Brown 1997). Mangles et al. (1998) conducted a series of experiments on time perception under 2 sets of conditions – short (400ms) and long (4s) time intervals – in subjects with injuries to the cerebellum and prefrontal cortex. They found that subjects with an injury to the prefrontal cortex exhibited a deterioration of performance only on the long-duration discrimination tasks. They also discovered a deficiency in the subjects' working memory. These findings suggest a multi-component timing mechanism (Ivry 1997) and the importance of working memory in the perception of long time periods.

Experiments by Mates et al. (1994) did not clarify the role of working memory or the contribution of these two types of timing mechanisms to the occurrence of negative asynchrony. Miyake et al. (2001) proposed the hypothesis of a dual-anticipation mechanism in sensory-motor coupling. An experiment supporting this hypothesis was recently reported by Zelaznik et al. (2002). The experiment presented here was designed to determine the effects of higher brain functions like attention on a synchronization tapping task.

A number of cognitive models have been proposed to explain the relationship between the perception of a time interval exceeding 2 to 3s and attention. Among these, the "attention-allocation model" is based on the premise that decision-making time is determined by the extent of attentional resources allocated to the temporal-information processing system in contrast to the mental-activity processing system unrelated to time (nontemporal information processing) (Brown 1997; Macar and Casini 1999). Central activation of working memory is involved in this allocation of attention (Baddeley 1986, 1998a, b; Osaka 2000). According to Kahnemann's attention-capacity model (1973), there are limited attentional resources, and these resources determine the limits in the processing of perceptual information. Attention is a critical resource in the execution of mental activities, and it can be appropriately allocated to each separate task according to the tendencies and intentions of each individual during the simultaneous execution of multiple tasks. In this condition, it is possible to quantify the amount of the attentional resources that has been allocated based on the magnitude of the mental processing involved.

We examined the range of ISI affected by attention in a synchronization tapping task based on the above models. If the subject's attention is directed toward processing of information other than tapping during a synchronization tapping task, it becomes difficult for the subject to focus the amount of attention required for the execution of the tapping task due to the limited capacity of attentional resources. If the amount of attention required in the tapping task exceeds the remaining resources, sufficient processing resources cannot be allocated to the temporal-information processing system, the ability to make temporal decisions becomes disrupted, and anticipatory timing control is thought to be affected.

2 Methods

A dual-task method (Baddeley 1986) was used to control the subject's attention. In this experiment, the processing capacity required for executing the primary task was reduced by having the subject engage in an additional (or secondary) task while still performing the primary task. Well-known examples of these types of test are the reading-span test (Daneman and Carpenter 1980; Osaka and Osaka 1994), which measures the capacity of working memory when a subject is simultaneously reading a short sentence aloud and engaged in a word-memory task. Another is the articulatory-suppression method, which examines the organization of coding of auditory information when a subject is engaged in a cognitive activity like memory while simultaneously repeating a word, such as "a" or "the" (Saitoh 1997). We employed a word-memory task as the secondary task to control the subject's attention.

The word-memory task was used to restrict the target of attention control to short-term memory and to determine the correlation between attention and negative asynchrony in the synchronization tapping task. This type of transient memory has been regarded as a function of working memory and is often employed as a secondary task to divert the attentional resources of the subject. In this study, the difference in the number of memorized words was regarded as the difference in the amount of attentional resources and attention capacity that was available in the tapping task. The memory task involved two different numbers of words as a secondary task. If the attention capacity required by the memory task corresponds to the processing resources that are used in the synchronization tapping task, some type of interference would appear between the two, and the difference in the number of memorized words is thought to reflect the occurrence rate of negative asynchrony.

The subjects were asked to press a button in synchrony with the onset of a periodic pulse auditory stimulus as their primary task. A total of ten different ISIs were used in this study, and this task was performed under the following two conditions. Each trial had a fixed ISI auditory stimulus for the controlled condition (N condition), then repeated for each of the ten durations of ISI. During the trials, the subjects were required to manually press a button precisely at stimulus onset. The word-memory task (M condition) was conducted parallel to the the control task (N condition). The details are explained in the following section(s).

2.1 Tapping Task

The subjects were all right-handed and were required to press a button with their right index finger in synchrony with the onset of a periodic pulse auditory stimulus. A total of ten different ISIs were used in this study: 450, 600, 900, 1,200, 1,500, 1,800, 2,400, 3,600, 4,800, and 6,000 ms. The sequence of ISIs was randomized for each subject. The duration of each auditory stimulus was 100 ms, and the frequency was 500 Hz. The acoustic pressure was set at an appropriate magnitude that allowed the subjects to clearly hear the auditory stimulus. It was the same for each subject throughout all the trials.

2.2 Definition of Parameters

The data measured during this experiment were stimulus onset and tap onset. The main target of analysis was the time difference between the stimulus onset and the tap onset, defined as synchronization error (SE). This reflects the temporal relationship between stimulus and action. A positive SE indicates that the tapping onset lagged behind the stimulus onset. As demonstrated by Mates et al. (1994), tapping can be divided into 2 types, that with negative asynchrony and that reactive to stimulus. Therefore, the former is referred to as anticipatory tapping and the latter, as reactive tapping. The relationship between these two parameters is shown in the Figure 1a.

2.3 Subjects

Six healthy male university graduate students in their 20s volunteered to participate in this study. They all had experience in synchronization tapping tasks. All of the subjects were right-handed and had normal hearing.

2.4 System

The system used in this experiment was loaded onto a personal computer with a single task OS (PC-DOS2000, IBM). The stimulus sound was transmitted to the subjects via headphones from an external sound source connected to the PC through a parallel port. In addition, the button that the subjects pressed was connected to the PC via a parallel port. The program used in the study was developed using the programming language C. A built-in real time clock (RTC) with a time resolution of 1 ms was used to measure the time when the button was pressed and the time of auditory stimulus presentation.

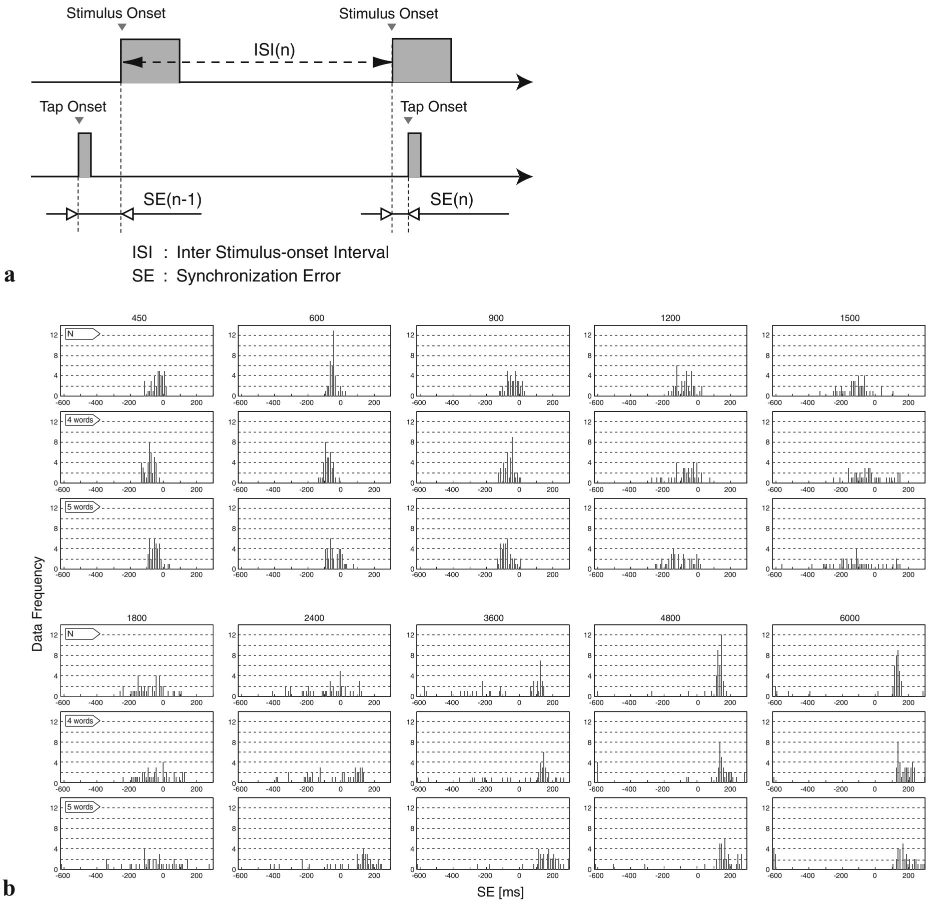


Fig. 1. Synchronization Error distribution. **a** Temporal relationship between tapping onset and stimulus onset. The time difference between the stimulus onset and the tap onset was defined as Synchronization Error *(SE)*. Negative SE indicates that tapping precedes the stimulus onset and corresponds to anticipatory tapping. The time difference between two successive stimulus onsets was defined as the Interstimulus-onset Interval *(ISI)*. The duration of each stimulus was 100 ms. **b** SE distribution for every Interstimulus-onset interval *(ISI)* of subject A is shown. The upper figure corresponds to the normal condition, the lower two figures correspond to the memory condition. Here N represents normal synchronization tapping, and 4 words or 5 words represent tapping with 4- or 5-word memory tasks, respectively. The number at the head of each figure represents ISI [ms]. (From Miyake et al. 2004, with permission)

2.5 Procedure

The task was to press a button in coordination with a periodic-pulse auditory stimulus. This task was conducted under the following two conditions:

(1) N (control) condition: Each trial consisted of a set ISI auditory stimuli and was conducted for ten different ISIs. During each trial, the subjects were requested to press a button the moment they heard an auditory stimulus. Each trial lasted 1 minute so that a memory task could be performed as a secondary task. By changing the number of trials corresponding to the ISIs, data from a total of 40 taps could be collected for each ISI. Since the objective was to observe a steady reaction in the subjects, data recording began 10s after the onset of the initial tap in each trial.

(2) M (memory-task) condition: Tapping was performed in the same manner as under the N condition in parallel with the word-memory task. The subjects were asked to remember a word using a Japanese phonetic character, which consisted of 3 to 5 morae. A "morae" is a syllable representing a Japanese word. All of the words were meaningful, but the combinations used in each trial were selected to make it difficult to create meaningful associations between words. In addition, the subjects were instructed not to memorize the words using the storytelling method (a method of memorization in which a story is created using the displayed words to shift the words into long-term memory). Either four or five words were displayed in each trial. The mean number of morae was 3.69 for the 4-word condition and 3.68 for the 5-word condition. The trials commenced simultaneously when the subject pressed the space bar on the computer keyboard. Once the space bar was pressed, the word set was displayed in the center of the monitor screen (IBM ThinkPad 535) for 3s. The monitor then blacked out, and an auditory stimulus was immediately presented. The subjects were required to perform tapping for a 1-minute period while remembering the words. Immediately after completion of the tapping, the subjects were asked to recite the retained words. The order of the words was not considered relevant. Subjects A, B, and C performed the experiment in the order of the N condition – 4-word condition followed by 5-word condition, whereas subjects D, E and F performed the experiment in the order of the N condition – 5-word condition followed by 4-word condition.

The subjects were also instructed not to time the tapping by counting to themselves while tapping or by making rhythmic physical movements. Each trial was conducted after a suitable interval to ensure that the subject's concentration was not adversely affected by fatigue resulting from the preceding trials.

3 Results

3.1 Correct Response Rate for Word-Memory Task

The correct response rates for the word-memory tasks for each subject are shown in Table 1. The values for each subject are the mean values for each trial. The

TABLE 1. Correct response rates for memory task. The value for each subject is the subject's average value of all trials (from Miyake et al. (2004), with permission)

Correct response rate for memory task		
Subject	4 words (%)	5 words (%)
A	100.0	96.4
B	92.0	77.3
C	98.9	90.9
D	100.0	94.6
E	98.9	92.8
F	100.0	98.2
Average	98.3	91.7

correct response rate among subjects was 98.3% for 4 words and 91.7% for 5 words. The difference between the mean values for the 2 groups was significant at $P < 0.05$ on Wilcoxon sign rank sum test. There was an exceptionally large drop in performance observed for subject B. Memorization of 4 words could be executed almost perfectly by each of the subjects, whereas there was a difference in scores for the 5-word memorization task, which appeared to be more difficult. This result suggests that the attentional resources required to memorize 5 words exceeded or was close to the capacity limit.

3.2 Distribution of Synchronization Errors (SE)

The data obtained in this experiment were stimulus onset and tap onset. Synchronization error (SE), the time difference between the stimulus onset and the tap onset, was analyzed as an index reflecting the temporal relationship between stimulus and response.

The SE distribution at each ISI is shown in Figure 1b for Subject D. The negative SE indicates that the tap precedes the auditory stimulus. The shape of the SE distribution for the N condition can be divided into 3 types. First, the SE distribution for the small ISIs from 450 to 1,500 ms is focused around a shift in the negative direction with a small spread. This distribution corresponds to anticipatory tapping, i.e., tapping that generates a stable negative asynchrony. As the ISI increased, the dispersion of the distribution increased, and a sharp peak on the positive side occurred in the distribution from 4,800 to 6,000 ms. This positive peak reflects reactive tapping, i.e., tapping that occurs reflexively after hearing the stimulus. Anticipatory tapping with a large negative SE and reactive tapping was mixed in the intermediate ISIs from 1,800 to 3,600 ms. Almost the same distribution was seen under the M condition, but reactive tapping occurred from around 1,800 ms under the M condition with both 4 and 5 words, while reactive tapping occurred with an ISI of 3,600 ms under the N condition.

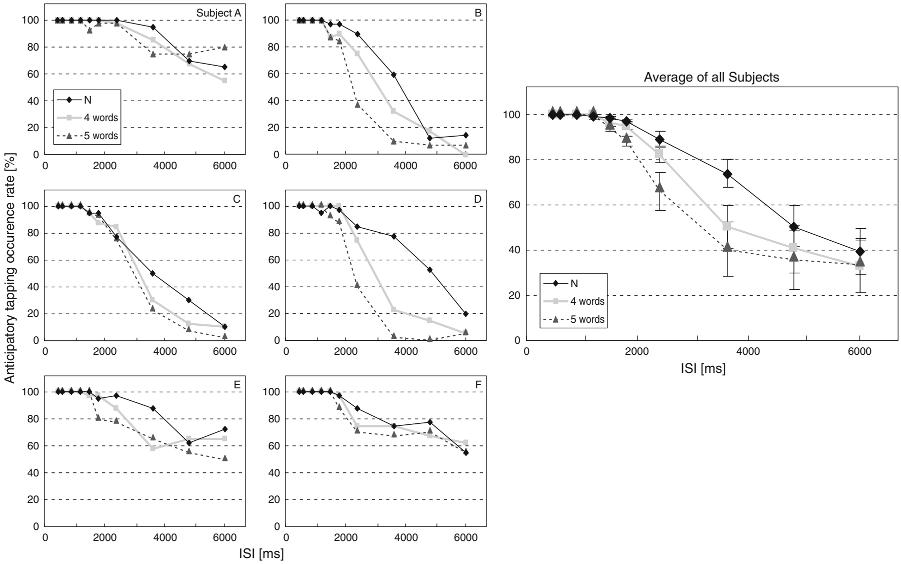
3.3 Separation of Reactive Tapping and Its Occurrence Rate

Our objective was to obtain information on anticipatory timing control, and we did not analyze reactive tapping that was simply a reflexive movement. For this reason, it was necessary to distinguish between the two types of tapping modes. The examination of the SE distribution for ISI = 6,000 ms shown in Figure 1b demonstrated that almost all the taps were reactive. Since the SE that preceded the auditory stimulus exhibited a large shift in the negative direction, distinguishing between the two types of tapping was relatively simple. Only those taps that were thought to have been reactive in tapping at an ISI of 6,000 ms were selected. The SE mean value of all subjects was calculated based on the SE mean for each subject and was 151 ms below that of the N condition (standard deviation among subjects = 15.7). Thus, the cut-off between the two types of tapping was defined as the value after subtracting 3 times the standard deviation from the mean value. SE = 100 ms was uniformly fixed as the threshold for all subjects and ISIs. SE values larger than this were classified as reactive tapping, and all others were classified as anticipatory tapping.

The percentage of anticipatory tapping observed at each ISI for each subject and the mean among subjects were calculated under the N condition, 4-word condition, and 5-word condition (Fig. 2a). This percentage was defined as the anticipatory-tapping-occurrence rate. Almost 100% of tapping at an ISI below 1,500 ms under the N condition was found to be anticipatory. The anticipatory-tapping-occurrence rate tended to decrease as the ISI increased above 1,800 ms. Mates et al. (1994) found that the time capacity of 2 to 3 s corresponded to the ISI at which reactive tapping begins. It was also found that almost 100% of tapping was anticipatory at an ISI below 1,500 ms under the M condition for both 4 words and 5 words. The anticipatory-tapping-occurrence rate for a higher ISI was smaller than that under the N condition. In addition, if 4- and 5-word conditions are compared, there was almost no difference at a short ISI up to 1,500 ms, but the anticipatory-tapping-occurrence rate at higher ISIs was less for 5 words than for 4 words.

Figure 2b shows the results of a *t* test on the mean value of the anticipatory-tapping-occurrence rate among all subjects for the combinations of N-4 words, N-5 words, and 4–5 words at each ISI. A significant difference in the occurrence rate of anticipatory tapping was observed only at 3,600 ms under the N-4 words condition, whereas a significant difference was observed from 1,800 to 3,600 ms under the N-5 words condition. In addition, the occurrence rate was significantly lower for 5 words at 1,800 compared to that for 4 words. Since the correct response rate under the 5-word condition for the word-memory task was significantly lower than that under the 4-word condition, the N-5 words condition was selected as the dual-task condition to measure the influence of attentional resources.

These findings demonstrate that when tapping is performed with an ISI of 1,500 ms or less, memory tasks are not affected by attentional interference, but are adversely affected with an ISI in the range of 1,800 to 3,600 ms. Furthermore,



a

t-test of anticipatory tapping occurrence rate

ISI	N–4 words	N–5 words	4–5 words
450	–	–	–
600	–	–	–
900	–	–	–
1,200			–
1,500		#	
1,800		*	*
2,400	#	*	#
3,600	*	*	
4,800			
6,000			

b

Fig. 2. Occurrence rate of anticipatory tapping. **a** Anticipatory tapping was defined as tapping with an SE less than 100 ms. Left figures show the data from 6 subjects, and the right figure shows the average among 6 subjects. Abbreviations are the same as those in Figure 1. The error bar shows the Standard Error of all subjects. **b** *t*-test of anticipatory tapping occurrence rate. This shows the results of a *t*-test on the mean value of the occurrence rate of anticipatory tapping among all subjects, for the combinations of N-4 words, N-5 words and 4–5 words at each ISI. "*" and "#" indicate significant differences at $P < 0.05$ and $0.05 < P < 0.10$, respectively. The blank column shows other results. We tested all the ISIs except 450, 600, 900 ms (all conditions), and 1,200 ms (4–5 words), because the occurrence rates under these conditions were almost all 100% in this range. (From Miyake et al. 2004, with permission)

with an ISI of 4,800 ms or longer, the effect of attention was small, and the occurrence rate for anticipatory tapping was extremely low. It seems that this region should be considered the domain of reactive tapping, as shown in Figure 1b. It was determined that the synchronization tapping in the stimulus period of 6 s or less can be divided into 3 categories: (i) anticipatory tapping that is unaffected by the subject's attention; (ii) anticipatory tapping that is affected by the subject's attention; (iii) reactive tapping.

However, in the region of 1,800 to 3,600 ms, which is affected by attention, despite an increase in the occurrence rate of reactive tapping under the influence of the memory task (secondary task), not all tapping was reactive. In this ISI range, there was competition between the tapping task and the memory task for the use of attentional resources. This determines the processing efficacy, or, in other words, a "trade-off relationship" exists. This finding corresponds to the "attention capacity hypothesis," which was initially explained.

4 Discussion

The objective of this research was to examine the interference effect of a secondary task on a synchronization tapping task to determine the ISI range that affects attention in the anticipatory timing-control mechanism. The results of this research yielded the following information.

- The negative-asynchrony-occurrence rate was not affected by a secondary task in an ISI range of 450 to 1,500 ms.
- In the ISI range of 1,800 to 3,600 ms, the negative-asynchrony-occurrence rate was significantly reduced by the simultaneous execution of a secondary task.
- The negative-asynchrony-occurrence rate was extremely low in the ISI range of 4,800 to 6,000 ms.

The N condition used in this study was essentially the same as that used in the experiment by Mates et al. (1994). The properties of the SE distribution that are shown in Figure 1b coincide closely with their results. They reported that reactive tapping began to appear at an ISI of 2 to 3 s and that the properties of the negative asynchrony changed in the same range. However, they did not determine the mechanism underlying this phenomenon. The results obtained in the present study using an experiment that took attention into consideration indicated that changes in negative asynchrony depended on two timing mechanisms that qualitatively differ and exist in the ISI regions of 450 to 1,500 ms and 1,800 to 3,600 ms.

The reduction of attentional resources by the execution of a secondary task did not significantly affect the negative-asynchrony-occurrence rate in the 450 to 1,500 ms ISI range. The simultaneous execution of a synchronization tapping task and a secondary task could be within the range of the capacity limit of attentional resources required by both tasks according to the attention-capacity model that was initially proposed. The correct response rate under the 5-word condition for the word-memory task was significantly lower than that under the 4-word condition, where the correct response rate was close to 100% (Table 1). This finding suggests that the attentional resources required to memorize 5 words exceeds or is close to the capacity limit. Therefore, the finding that the tapping task remained unaffected suggests that there is an independent timing-control mechanism for attentional resources in this ISI range.

Movements that can be executed independent of mental processing are referred to as "automatic" (LaBerge and Samuels 1974; Laberge 1975), and regulation of movement through the spinal cord is known to be involved in these movements. For example, there are rhythm generators in the brain stem and spinal cord, such as the central pattern generator (CPG), that produces rhythmic muscle activity like walking (Pearson 1976). These generators are thought to correspond to a timer function that sends periodic pulses in time-perception and production-pacemaker models (Ivry 1996). The possibility has been suggested that tapping in this ISI range is controlled in a feed-forward manner based on the analysis of SE's autocorrelation coefficient (Miyake et al. 2002). It was previously reported that feedback is not received directly from the periphery in the lateral cerebellum, which is responsible for timing control of movement, but that an extremely simple forward control exists (Kawato 1996). These mechanisms may be involved in the automatic anticipatory tapping that was observed in this research.

The synchronization tapping task in the ISI range of 1,800 to 3,600 ms was substantially affected by the lowered attentional resources resulting from the secondary task. However, despite the increase in the occurrence rate of reactive tapping under the influence of the memory tasks, not all tapping became reactive. In addition, a difference was observed in the extent of decrease in the occurrence rate of reactive tapping depending on the number of words to be remembered. These findings indicate a trade-off relationship. The tapping task and the memory task in this ISI range compete with each other for attentional resources and determine the processing efficiency. Consequently, it is necessary to consider what type of processing is involved in the attentional resources that have been diverted by the secondary task to determine the generation mechanism for anticipatory tapping in this ISI range.

The processing that is required in word-memory tasks can be limited to the word-retention activity that accompanies maintenance rehearsal. This type of maintenance rehearsal is thought to be performed by the phonemic loop function, which is a subsystem of working memory (Baddeley 1998a, b). The obtained phonemic information (of a word) is automatically entered in the phonemic storage that is one of the lower-level systems in the phonemic loop and possesses a 1-to-2-s memory buffer. This phonemic storage is related to the maintenance of information concerning rhythm and time intervals (Brown 1997; Saitoh 1997). The phonemic-similarity effect in memory tasks, which is said to be based on the phonemic loop function, has been reported to be lost during the tapping task (Saitoh 1993). The premotor and supplementary motor areas are also involved in the phonemic loop (Osaka 2000), suggesting a relationship between the phonemic loop and motion control.

In this way, the tapping task and word-memory task may compete for the allocation of phonemic storage capacity. This is just a hypothesis, but the fact that stable tapping control is possible in the ISI range of 2 to 3 s during a normal tapping task can be explained by this hypothesis. However, if a secondary task results in an overflow in the phonemic storage capacity, time anticipation may become difficult, regardless of the ISI. The results of this research, in which there was no apparent influence of the memory task at ISIs of 1,500 ms or less, contradicts this hypothesis. We propose that anticipatory timing control is achieved through the interaction between time perception based on phonemic storage and automatic movement mechanisms in the actual timing control.

Our research was aimed at furthering psychological analyses related to the time-perception mechanism in anticipatory timing synchronization, which is thought to be indispensable in cooperative activity among humans. The results demonstrated for the first time the presence of two types of anticipatory mechanisms in the synchronization tapping task from the standpoint of attention involved in time perception. One is anticipatory tapping influenced by attention and seen at the ISI range of 1,800 to 3,600 ms, and the other is the automatic tapping mechanism that is not affected by attention and is seen at the 450-to-1,500-ms range. Accordingly, this anticipatory timing mechanism can be considered a dual process in which the anticipatory mechanisms work together based on the processing of the implicit automatic anticipation and the explicit processing of temporal information.

Finally, exactly how this type of perception- and movement-integrative process is involved in higher-level brain functions, such as attention and awareness, is an extremely complex problem. Pöppel et al. have already tackled the problem of integrating information in the temporal region through the framework of a "time window" (Pöppel 1971, 1988, 1997; Szelag et al. 2002). Humans integrate information in this 3-s time window and generate a state of awareness that corresponds to a "subjective present." The anticipatory timing mechanism is closely related to this type of temporal integration, and the findings of this study suggest that this time window is formed by a dual process of anticipation. If the physiologic foundation for this temporal-perception mechanism can be clarified through imaging techniques such as f-MRI, it may be possible to construct a model for the neuronal mechanism demonstrated in this study. We also expect this to be related to the technology that supports cooperative processes among humans within the range of cognitive time.

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