Acoust. Sci. & Tech. **22**, 3 (2001)

PAPER

Temporal control mechanism of repetitive tapping with simple rhythmic patterns

Masahi Yamada[1] and Shiro Yonera[2]

[1]*Department of Musicology, Osaka University of Arts,*
Higashiyama, Kanan-cho, Minamikawachi-gun, Osaka, 585–8555 Japan
[2]*Graduate School, Kyushu Institute of Design,*
4–9–1 Shiobaru, Minami-ku, Fukuoka, 815–8540 Japan

(*Received 12 May 2000, Accepted for publication 16 February 2001*)

Abstract: In previous studies, it was shown that the temporal control in equal-interval tapping is governed by a memory mechanism, which preserves the information of the preceding 20 intervals to determine the interval of the present tap. In the first stage of the present study, an equal-interval tapping experiment was carried out. The results of the experiment confirmed that the 20-interval memory mechanism governs the temporal control of single-finger equal-interval tapping for various tempi. In the following stages of the present study, simple rhythmic patterns were constructed with long and short time values with a 2 : 1 ratio. The temporal fluctuation in repetitive tapping of these rhythmic patterns was analyzed using Fourier analysis and autoregressive models. The results showed that the 20-interval memory mechanism also governs the temporal control of the tapping for the simple rhythmic patterns: In the case of a rapid tempo, the 20-interval memory mechanism is active for the long time value, whereas in the case of a slow tempo, it is active for the short time value. The point at which the memory mechanism switches between the long and short time values is located around a tempo in which the short time value corresponds to 350 ms.

Keywords: Rhythm perception, Time interval, Memory mechanism, Temporal control, Temporal fluctuation

PACS number: 43.66.Mk, 43.75.Cd

1. INTRODUCTION

Musical rhythms consist of various kinds of time values. However, these rhythms are based on the sequence of equal time intervals. Various kinds of rhythms are obtained by subdivision of some parts of the equal interval sequence, and more complex rhythms can be obtained by combining some parts of the subdivided ones.

The musicologists Cooper and Mayer (1960) defined a *pulse* as one of a series of regularly recurring, precisely equivalent stimuli. Based on the pulses, they also defined accents, meters and beats, and analyzed the complex structure of musical works using these concepts. Fraisse (1982) reviewed psychological experiments concerned with rhythmic perception and behavior. In his article, he defined *cadence* as the rhythm produced by the simple repetition of the same stimulus at a constant frequency. He described the cadence as the most easily perceived rhythm, and attributed the basis of all rhythms to it.

As seen above, a series of regularly recurring stimuli is the most basic style of musical rhythms. Musha *et al.* (1985) suggested a new paradigm to estimate the perceptual process for the basic rhythms. They requested non-musicians and an amateur pianist to tap castanets at a sequence of equal time intervals under two sets of conditions: Under one set of conditions, the subjects synchronized their tapping to the ticking of a metronome (metronome tapping), and under the other set of conditions, they did not listen to the metronome during their tapping (free tapping). Using Fourier analysis, Musha *et al.* analyzed the temporal fluctuation in the tapping. The results showed that in the case of free tapping, the power spectrum of the fluctuation indicated that the power of the fluctuation was small and constant in the high frequency region above 0.1 Hz. Whereas in the low frequency region below 0.1 Hz, the power of the fluctuation increased as the frequency decreased. The critical phenomenon at 0.1 Hz implied that the temporal controllability of the tapping was excellent for periods less than 10 s, but for periods over 10 s the controllability decreased as the period increased. Musha *et al.* suggested that temporal control in free tapping is governed by a memory of approximately 10 s.

Because the tempi used in the experiment of Musha *et al.* were limited to 300–500 ms/tap, Yamada (1996) pointed out the possibility that the memory capacity corresponds not to a real time of 10 s, but to a given number of taps. Yamada carried out free tapping experiments with various tempi ranging from 180 to 800 ms/tap. In his experiments, using the right index finger, musicians tapped an aluminum board at equal intervals. The results showed the same critical phenomenon in the power spectra of the temporal fluctuation, as with Musha *et al.* However, the critical phenomenon was not generally observed at a period of 10 s, but instead at a period of approximately 20 taps for all tempi and subjects. Moreover, Yamada applied auto-regressive (AR) models to the fluctuation. The best AR model was defined as the model that minimized the value of Akaike's Information Criteria, AIC (Akaike, 1969). The order of the best AR model was distributed around 20 for all tempi and subjects. Yamada concluded that the memory capacity, which governs equal-interval tapping, is not 10 s, but 20 taps, i.e., the preceding 20 intervals of the tapping is preserved and used to determine the interval of the present tap.

Both non-musicians and an amateur musician participated in the experiment of Musha *et al.* (1985), while only musicians participated in the experiments of Yamada (1996). Yamada and Tsumura (1998) investigated the temporal controllability in equal-interval tapping as a function of musical training. In their experiment, skilled pianists and novice pianists tapped at equal intervals under two conditions; using only the right middle finger and also with using multiple fingers. The results showed that in the case of single-finger tapping, skilled and novice pianists alike demonstrated the same temporal controllability and the critical phenomenon of 20 taps was found in the spectra for both groups. However, in the case of multiple-finger tapping, there were significant differences between the two groups: The temporal controllability of the skilled pianists did not change from single-finger tapping, while that of the novice pianists significantly decreased. These results suggested that single-finger equal-interval tapping is governed by the 20-interval memory mechanism, which is unaffected by musical training. Years of piano lessons only improve the ability to coordinate multiple finger motions.

Yamada (1996) and Yamada and Tsumura (1998) observed the critical phenomenon at a period around 20 taps in the spectrum of the temporal fluctuation. However, results from such an observation have a degree of uncertainty, because different observers may choose different critical periods for the same spectrum. A more definite method for estimating the critical period in the spectrum is required. Therefore, in the first experiment of the present study, we confirm that both the critical period, which is estimated using the weighted least squares method, and the order of the best AR model, consistently illustrate the 20-interval memory mechanism that governs single-finger equal-interval tapping. Then, in the subsequent two experiments, it is examined whether and how this 20-interval memory mechanism is active for the temporal control in repetitive tapping with non-equal-interval simple rhythmic patterns.

2. EXPERIMENT 1

In the experiments of Yamada (1996) the subjects tapped with the right index finger over a wide range of tempi, whereas in the experiment of Yamada and Tsumura (1998) the subjects used the right middle finger for a single tempo of 250 ms/tap. In order to confirm that single-finger equal-interval tapping is consistently governed by the 20-interval memory mechanism, we requested the subjects to tap at equal intervals in various tempi using their right middle fingers.

2.1. Method

Five students from the Department of Musicology at the Osaka University of Arts participated in the experiment as subjects. All subjects had experience in playing the piano and other instruments, but only at intermediate levels. The subjects tapped an aluminum board placed on a table with the right middle finger in tempi of 180, 370 and 800 ms/tap, and a spontaneous tempo; the tempo that was the most comfortable for the subjects.

The subjects were instructed to make an effort to maintain both constant intervals and intensity. They were also instructed not to imagine specific rhythms, e.g., two-beat or three-beat rhythms, or to count the number of taps during the tapping. One trial of tapping consisted of 721 taps. Before each trial, except for the spontaneous tempo, metronome ticking was presented for 20 s to demonstrate the tempo. The metronome ticking was produced by a computer system with a 48 kHz D/A converter. Each tick consisted of a 4,000 Hz tone with 6 ms triangular envelope. The metronome ticking was presented through headphones at 73 dB(A). One session consisted of five trials at the same tempo. These five trials for the same tempo were performed successively in one session, but each subject performed the four sessions (tempi) in a random order. A 3-min rest interval separated each trial and a 20-min rest interval separated each session.

Small speakers attached to the aluminum board converted the pressure of the finger to a voltage. The computer system converted this voltage to numeric data with a 12 kHz sampling A/D converter and measured the inter-onset intervals (IOIs) of the tapping. The voltage was also used to produce clicking sounds that each subject used to monitor his/her own tapping. The clicking sounds were monitored at about 73 dB(A) through the same headphones as with the metronome ticking. The entire experiment was carried out in a soundproof room.

2.2. Critical Period in the Power Spectrum of the Fluctuation

The waveform of the temporal fluctuation was obtained by plotting the IOI as a function of the tap order. Because the IOI was not generally stable during the initial 100 taps, these 100 taps were removed and the IOI waveform of the following 600 taps was used for the analysis. The IOI waveforms of the 600 taps were divided into three parts of 200 taps, and the waveform for each segment was decomposed into Fourier components by DFT with Hanning window. The power spectra of the temporal fluctuation in the tapping were averaged out for each tempo by subject.

The solid line in Fig. 1 shows an example of the averaged power spectrum. The spectra for all tempi and subjects showed that the power decreased as the frequency increased in the low frequency region, whereas the power was constant or increased slightly as the frequency increased in the high frequency region. In the spectrum in Fig. 1, the critical frequency, which indicates the boundary between the high and low frequency regions, is observed around ten cycles. The power of the frequency component indicates the difficulty of temporal control for the frequency, and the correlation between the frequency, f [cycles] and period, p [taps] is $p = 200/f$. Therefore the spectral features imply that temporal control is excellent for short periods of less than approximately 20 taps, but for periods over 20 taps, the controllability decreases as the period increases. This was true for all tempi and subjects in the present experiment and consistent with Yamada (1996) and Yamada and Tsumura (1998).

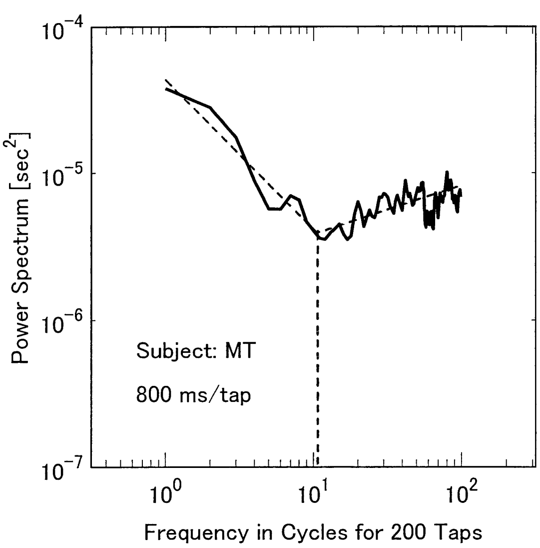

Fig. 1 An example of the power spectrum of the temporal fluctuation in equal-interval tapping.

Table 1 The critical period in the power spectrum for equal-interval tapping is shown in taps.

Tempo	Subject SY	MT	HM	SO	AU	Mean
180 ms/tap	22.2	23.1	21.5	21.5	17.4	21.1
370 ms/tap	25.6	20.9	17.5	14.9	17.7	19.3
800 ms/tap	25.2	19.3	18.1	24.0	15.0	20.3
Spontaneous tempo	23.3	18.7	16.2	17.1	24.7	20.0
Mean	24.1	20.5	18.3	19.4	18.7	20.2

In the present study, the critical frequency was determined by the following method: The spectrum was divided into the high and low frequency regions at an arbitrary frequency. Then the regression line was estimated for each of the two regions, using the weighted least squares method. In this method, because more points were included in the higher frequency areas than in the lower frequency areas in the same bandwidth on the logarithmic scale, the squared residual of a frequency component was weighted by the reciprocal value of the frequency. Using this method, the pair of lines that showed the minimum value in residual sum of the weighted squares was defined as the regression lines for the given dividing frequency. Then, the best regression lines for the spectrum were defined as the regression lines that minimized the residual sum of the weighted squares for all dividing frequencies. The critical frequency was defined as the point where the best regression lines intersected.

Using the method described above, the critical frequency f [cycles] was determined for each tempo by subject. Then, the critical period p [taps] was calculated using the correlation $p = 200/f$. Table 1 shows that the critical period is distributed around 20 taps in a range of 15–27 taps, but the period does not systematically vary with the tempi or subjects. Indeed, analysis of variance (ANOVA) indicated that both the effects of tempo ($F[3, 12] = 0.26$) and subject ($F[4, 12] = 2.00$) were insignificant for the significance level of $p < 0.05$.

2.3. Order of the Best Auto-Regressive Model

Yamada (1996) applied AR models and AIC to the IOI fluctuation to determine the critical phenomenon observed in the spectrum. AR models show that the present data is determined by the weighted sum of several previous data samples along with some noise (1).

Table 2 The order of the best AR model for equal-interval tapping.

Tempo	Subject					Mean
	SY	MT	HM	SO	AU	
180 ms/tap	25	20	20	16	19	20.0
370 ms/tap	22	15	17	13	18	17.0
800 ms/tap	19	17	24	17	15	18.4
Spontaneous tempo	17	13	20	18	22	18.0
Mean	20.8	16.3	20.3	16.0	18.5	18.4

$$x(i) = \sum_{k=1}^{N} a_k x(i-k) + \xi_i \qquad (1)$$

Generally, the data samples fit the AR model better as the AR order, N, increases, i.e., the residual of the estimation decreases. The model that minimizes the AIC value has a small value in N and also a small value for the residual of the estimation (Akaike, 1969). Yamada (1996) defined the best AR model as the model that minimized the AIC value, and showed that the order of the best AR model was distributed around 20.

In the present study, the same method was applied to the IOI fluctuation and the order of the best AR model was obtained for each tempo by subject. Table 2 shows that the order is distributed around approximately 20 and does not vary with tempi or subjects, as with the results in Table 1. ANOVA indicated that both the effects of tempo ($F[3,12] = 0.90$) and subject ($F[4,12] = 2.23$) were insignificant.

The results in Table 2 illustrate that the 20-interval memory governs the temporal control in equal-interval tapping with the middle finger for various tempi, as well as in the tapping with the index finger, which was already shown in Yamada (1996). The fact that the order of the best AR model in Table 2 agrees with the critical period in Table 1, implies that the critical period in the power spectrum also indicates the memory capacity which governs the temporal control in equal-interval tapping. In conclusion, the present experiment showed that single-finger equal-interval tapping is governed by the 20-interval memory mechanism for various tempi.

3. EXPERIMENT 2

Now the question is whether the 20-interval memory mechanism also governs the tapping of more complex musical rhythms. In order to determine this, we constructed two kinds of simple, three-beat rhythmic patterns using two kinds of time values and examined whether and how the memory mechanism governs the tapping of the rhythmic patterns, in the present experiment.

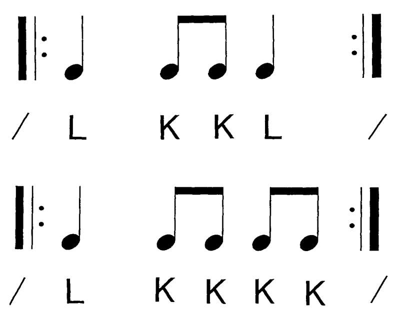

Fig. 2 Construction of the rhythmic patterns in Experiment 2. The long time value, L, corresponds to an interval of 400 ms, and the short time value, K, corresponds to 200 ms. These three-beat rhythmic patterns were repeated 240 times.

3.1. Method

Two simple, three-beat rhythmic patterns of /LKKL/ and /LKKKK/ were constructed with a long time value L (*lang* in German), and a short time value K (*kurz* in German), where L corresponded to 400 ms and K corresponded to 200 ms (Fig. 2). Five students from the Department of Musicology at the Osaka University of Arts participated as subjects. Two of the subjects had participated in Experiment 1, and all had similar levels of musical training as the subjects in Experiment 1. In one trial, the subjects repetitively tapped one of the rhythmic patterns with the right middle finger for a period of 720 intervals of L's value. To demonstrate the designated rhythm and tempo, the synthesized rhythmic pattern of /LKKL/ or /LKKKK/ was presented for 20 s before each trial, but it was not presented during the tapping. Each subject carried out five trials for each rhythmic pattern. The other experimental conditions were identical to Experiment 1.

3.2. Summation Process for Subdivided Intervals

In the rhythmic patterns, two consecutive Ks can be regarded as the two halved intervals of L. The two consecutive intervals that corresponded to Ks were combined and the resulting interval was treated as it was for L. We define this process as the summation process for subdivided intervals (SPSI). The IOI fluctuation that corresponded to L was obtained by SPSI. Then, the initial 100 intervals of L were removed and the following 600 intervals were divided into three parts, and the IOI fluctuations for the 200 intervals of L were analyzed in the same way as in Experiment 1.

3.3. Results and Discussion

Figure 3 shows an example of the power spectrum of the temporal fluctuation for the /LKKL/ rhythm. In this spectrum, a spike component appears at a frequency of approximately 67 cycles. This frequency corresponds to

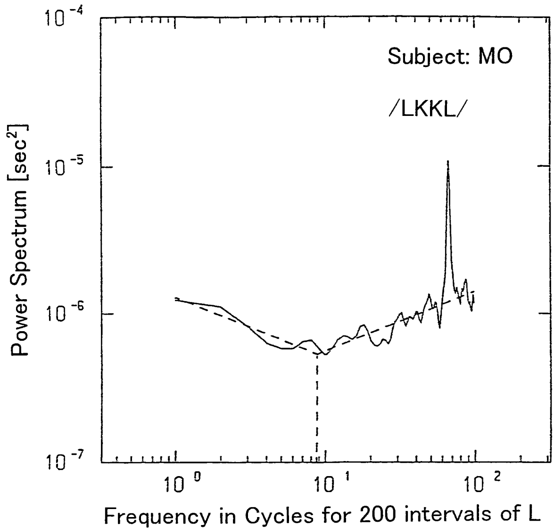

Fig. 3 An example of the power spectrum for the /LKKL/ rhythm. The frequency is shown in cycles for 200 intervals of L.

Table 3 The critical periods in the power spectra for the three-beat rhythmic patterns are shown in number of intervals that correspond to the long time value, L.

	Subject					
Rhythm	MO	MY	MT	AU	YA	Mean
/LKKL/	22.9	18.8	25.3	21.6	15.6	20.8
/LKKKK/	20.7	18.2	23.4	21.4	22.0	21.1
Mean	21.8	18.5	24.4	21.5	18.8	21.0

Table 4 The orders of the best AR models for the three-beat rhythmic pattens. The model was applied to the temporal fluctuation that corresponded to the long time value, L.

	Subject					
Rhythm	MO	MY	MT	AU	YA	Mean
/LKKL/	24	18	25	18	22	21.4
/LKKKK/	21	21	21	20	21	20.8
Mean	22.5	19.5	23.0	19.0	21.5	21.1

the period of three intervals of L.

Yamada (1996) conducted an experiment, in which accented tapping of an equal-interval three-beat rhythm was used; using their left hands the subjects slapped their left thighs once every three equal-interval taps of their right index fingers. The results showed that the spectrum for the three-beat accented tapping contained the same spike component as Fig. 3. Thus, the spike component observed in Fig. 3 implies that the first L in every cycle of three taps is significantly longer than the following two intervals of L. Yamada also showed that the spike component does not correlate with the memory capacity: The order of the best AR model was independent of the accents. The effect of accents only appeared in the auto-regressive coefficients, a_k in Eq. (1). The coefficients of a multiple of three, $a_3, a_6, a_9, \ldots$, were significantly larger than the other coefficients. This means that the present interval is more deeply dependent on the third, sixth, ninth etc. preceding intervals than the other intervals, but the memory capacity of 20 intervals is unaffected by the accents.

In the present experiment, eliminating the components in the 1/4-octave band centered on 67 cycles, the weighted least square method was applied to the remaining frequency components and the critical period was determined for each spectrum. Table 3 shows that the critical period for each rhythmic pattern by subject is distributed around 20 intervals of L. ANOVA indicated that both the effects of rhythmic pattern ($F[1,4] = 0.04$) and subject ($F[4,4] = 1.88$) were insignificant.

AR models and AIC were also applied to the IOI fluctuation. Table 4 shows that the resulting order for each rhythmic pattern by subject is again distributed around 20. Once again, ANOVA indicated that both the effects of rhythmic pattern ($F[1,4] = 0.19$) and subject ($F[4,4] = 1.36$) were insignificant.

The results in Tables 3 and 4 demonstrate that the 20-interval memory mechanism is active for L but not for K.

4. EXPERIMENT 3

In Experiment 2, the rhythmic patterns were tapped in only one tempo ($L/K = 400/200$ ms). Moreover, both of the rhythmic patterns were three-beat rhythms. In order to determine if the 20-interval memory is consistently active for the long time value, we construct a two-beat rhythmic pattern with the long and short time values, which was tapped in various tempi, in the present experiment.

4.1. Method

A two-beat rhythmic pattern of /LKK/ was constructed, where the ratio of L to K was fixed at 2 : 1 (Fig. 4). Ten students from the Department of Musicology at the Osaka University of Arts participated in the experiment as subjects. Three of the subjects had participated in Experiment 1, and four of them in Experiment 2, with one who had participated in both experiments. The

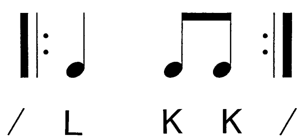

Fig. 4 Construction of the two-beat rhythmic pattern in Experiment 3.

subjects tapped the rhythmic pattern with the right middle finger at tempi of $L/K = 300/150$, 400/200, $700/350$ and 1,000/500 ms. SPSI was applied to the intervals observed in the experiment and the resulting IOI fluctuation of L was analyzed in the same way as in Experiment 2.

4.2. Results and Discussion

In the spectra, a spike component appeared at the highest frequency of 100 cycles for 200 taps. This spike component implied that the first L in every cycle of two intervals of L was significantly longer than the following one. Excluding the components in a 1/8-octave range of 92–100 cycles, the critical period was calculated using the weighted least squares method. Table 5 shows the critical period for each tempo by subject.

As can be seen, for the rapid tempi of $L/K = 300/150$ and 400/200 ms, the critical period is distributed around 20 intervals of L. ANOVA showed that both of the effect of tempo ($F[1,9] = 2.47$) and subject ($F[9,9] = 0.40$) were insignificant for the two rapid tempi. However, for the slow tempo of $L/K = 1,000/500$ ms, the critical period is distributed around 10 intervals of L. Table 5 also shows that, in the case of the intermediate tempo of $L/K = 700/350$ ms, the critical period is distributed around 10 intervals for five subjects (YA, SK, MO, AU and NN), while the period is distributed around 20 intervals for the other five subjects.

Table 6 shows the order of the best AR model, which is applied to the IOI fluctuation of L for each tempo by subject. The results are consistent with Table 5: For the rapid tempi of $L/K = 300/150$ and 400/200 ms, the order is distributed around 20, whereas the order is distributed around 10 for the slow tempo of $L/K = 1,000/500$ ms. For the tempo of $L/K = 700/350$ ms, the order for five of the subjects is distributed around 20 and the order for the other five is distributed around 10.

The results in Tables 5 and 6 suggest that, in the case of a rapid tempo, the 20-interval memory mechanism is active for L, whereas the mechanism is active for K in the case of a slow tempo. The point at which the memory mechanism switches between L and K is located around a tempo of $L/K = 700/350$ ms. However, the results can be interpreted in another way: In the case of a rapid tempo, the 20-interval memory mechanism is active for L, but in the case of a slow tempo, a 10-interval memory mechanism is active for L. If this interpretation is true, the temporal control for K should be worse than for L, because the intervals for L are controlled by the memory mechanisms for either fast or slow tempi. Thus, the temporal controls for L and K were compared based upon the coefficients of variation.

Before applying SPSI, some of the intervals corresponded to L and the others to K, whereas after applying SPSI all of the intervals corresponded to L. The coefficient of variation for L was calculated using the intervals after applying SPSI (Table 7). On the other hand, the coefficient of variation for K was calculated using the intervals that corresponded to K before applying SPSI (Table 8).

As previously stated, the spike component that ap-

Table 5 The critical period in the power spectrum for the two-beat rhythmic pattern is shown in number of intervals that correspond to the long time value, L.

Tempo L/K (ms)	Subject										Mean
	YA	SK	MO	AU	NN	SY	HM	MY	MN	EK	
300/150	19.0	21.1	23.4	21.3	16.2	23.3	19.7	18.2	13.8	20.8	19.7
400/200	25.3	20.6	23.5	17.4	24.1	21.0	24.6	17.7	26.2	21.9	22.2
700/350	7.9	10.7	10.5	8.3	6.8	20.7	20.5	16.3	19.6	17.8	13.9
1,000/500	11.2	7.3	7.3	11.4	13.9	10.6	3.6	9.2	7.6	11.4	9.4

Table 6 The order of the best AR model for the two-beat rhythmic pattern. The model was applied to the temporal fluctuation which corresponded to the long time value, L.

Tempo L/K (ms)	Subject										Mean
	YA	SK	MO	AU	NN	SY	HM	MY	MN	EK	
300/150	18	28	20	15	23	22	19	18	24	17	20.4
400/200	22	18	25	21	14	20	20	15	15	21	19.1
700/350	8	8	12	12	10	20	20	15	16	21	14.2
1,000/500	10	12	8	12	14	12	12	10	8	11	10.9

Table 7 The coefficient of variation for the long time value, L. The coefficient was calculated using the intervals after applying the summation process for subdivided intervals (SPSI).

Tempo L/K (ms)	Subject										Mean
	YA	SK	MO	AU	NN	SY	HM	MY	MN	EK	
300/150	3.9	3.0	3.7	3.7	4.2	3.7	4.7	4.7	3.2	4.5	3.93
400/200	3.9	2.5	3.2	3.3	4.0	3.6	3.9	3.5	3.1	3.9	3.49
700/350	3.3	2.6	2.6	3.0	3.6	3.7	3.2	3.1	2.9	3.5	3.15
1,000/500	2.7	2.7	2.1	2.4	2.4	2.5	2.7	2.3	2.1	2.6	2.45

Table 8 The coefficient of variation for the short time value, K. The coefficient was calculated using the intervals that corresponds to K before applying SPSI.

Tempo L/K (ms)	Subject										Mean
	YA	SK	MO	AU	NN	SY	HM	MY	MN	EK	
300/150	6.7	6.7	9.9	7.2	6.4	6.5	11.1	6.8	8.4	6.9	7.66
400/200	6.5	7.4	8.8	8.1	6.9	10.8	10.3	7.0	7.6	6.3	7.97
700/350	4.7	3.5	3.7	4.2	4.5	6.4	5.2	5.6	6.2	5.3	4.93
1,000/500	3.6	3.1	2.7	3.7	3.3	3.7	3.4	3.3	3.4	2.8	3.30

pears in the power spectrum illustrates that the first L in every cycle of two Ls is significantly longer than the following one. It is thought that this feature increases the value of the coefficient of variance for L, while it does not affect the coefficient for K. This is because all of the intervals of K are subdivided intervals of the second L in the cycles of two Ls.

In spite of this effect, Tables 7 and 8 show that the coefficient for K tends to show a larger value than the coefficient for L. However, between the rapid and slow tempi, the significance of the difference between the coefficients for K and L is quite different: For the rapid tempi of $L/K = 300/150$ ms and 400/200 ms, the coefficient for K is almost double that of L. This means that, in the two rapid tempi, the intervals for K are controlled less accurately than for L. This illustrates that the subdividing process for L into two Ks is not accurate, but L can be accurately determined by the preceding 20 intervals of L. This is also true for the subject group of SY, HM, MY, MN and EK at the tempo of $L/K = 700/350$ ms.

On the other hand, for the slow tempo of $L/K = 1{,}000/500$ ms, the coefficient for K is slightly larger than L. This means that, for the slow tempo, the intervals of K can be controlled as accurately as L. If a 10-interval memory mechanism controls the intervals for L and does not for K, the coefficient for K should show significantly larger values than for L. Therefore, these results illustrate that the 20-interval memory mechanism is active for K. This control results in a small value for the coefficient of variance for K, and consequently, the coefficient for L, which is the result of combining the two controlled intervals of K, also shows a similarly small value. This was also true for the subject group of YA, SK, MO, AU and NN at the tempo of $L/K = 700/350$ ms.

5. GENERAL DISCUSSION

The present study showed that the point at which the memory mechanism switches between L and K is located around a tempo of $L/K = 700/350$ ms. These results are consistent with the results of Hibi (1983).

Hibi inserted a temporal distortion in a sequence of equal intervals, and determined the threshold of the distortion for detection. The results showed that the threshold was high in the rapid tempo region and low in the slow tempo region. The threshold switched between the high and low values at a tempo of 333 ms/interval. He illustrated that, in the case of a rapid tempo, the perceptual process grouped every several intervals, and thus the detection of the distortion was difficult. On the other hand, in the case of a slow tempo, the grouping process was not active, and the detection of the distortion was easy. The tempo of 333 ms/interval Hibi showed is very near the tempo of 350 ms of K in the present study. For the present study, this consistency suggests that when K is shorter than 350 ms, two consecutive Ks are grouped into one L.

These results are also consistent with knowledge regarding musical experiences. When a score is first read, it is played at a slow tempo. At that time, the beats are counted for a short time value in the score. After practice, the score is played at a fast tempo, and at this stage, the beats are often counted for a longer time value.

In the case of rapid tempi, Hibi suggested that a grouping mechanism took place for the quasi-equal interval stimuli. On the other hand, in the present study, no evidence for the grouping mechanism was shown in the case of equal-interval tapping. This discrepancy should be studied further.

Yamada and Tsumura (1998) showed that in the case of multiple-finger equal-interval tapping, novice pianists demonstrated significantly inferior controllability to the skilled pianists. As well as the multiple-finger equal-interval tapping, the non-equal-interval rhythmic tapping may need more complex motion of muscles than the single-finger equal-interval tapping. Therefore, in the case of non-equal-interval tapping, there is a possibility that some differences exist in the temporal control between musicians and non-musicians. As such temporal control of non-equal-interval rhythmic tapping should be studied as a function of musical skill.

In the present study, all rhythmic patterns were constructed with two time values with a 2 : 1 ratio. Further studies, in which various kinds of rhythms are used, are required to investigate whether and how the 20-interval memory governs the tapping of rhythmic patterns.

REFERENCES

Akaike, H. (1969). "Fitting autoregressive models for prediction", *Ann. Inst. Stat. Math.* **21**, 243–247.

Cooper, G. W. and Mayer, L, B. (1960). *The Rhythmic Structure of Music* (The University of Chicago Press, Chicago), pp. 3–4.

Fraisse, P. (1982). "Rhythm and tempo", in *The Psychology of Music*, D. Deutsch, Ed. (Academic Press, Orlando), Chap. 6, pp. 149–180.

Hibi, S. (1983). "Rhythm perception in repetitive sound sequence", *J. Acoust. Soc. Jpn.* (*E*) **4**, 83–95.

Musha, T., Katsurai, K. and Terauchi, Y. (1985). "Fluctuations of human tapping intervals", *IEEE Trans. Biomed. Eng.* **BME-32**, 578–582.

Yamada, M. (1996). "Temporal control mechanism in equaled interval tapping", *Appl. Hum. Sci.* **15**, 105–110.

Yamada, M and Tsumura, T. (1998). "Do piano lessons improve basic temporal controllability of maintaining a uniform tempo?", *J. Acoust. Soc. Jpn.* (*E*) **19**, 121–131.

Masashi Yamada received his B.A. in Music from Osaka Univ. of Arts in 1982, B.S. in Mathematics from Osaka Pref. Univ. in 1987, and his M. Design and Ph. D. from Kyushu Institute of Design in 1987 and 1998, respectively. He joined Osaka Univ. of Arts in 1987 and is currently an Assistant Professor. In 1992, the ASJ awarded him the Awaya-Kiyoshi Prize and the Sato Paper Prize in 1999. His research interests include musical acoustics and the psychology of music.

Shiro Yonera was born in Tokyo in 1974. He received his B.A. in Music from Osaka Univ. of Arts in 1997. Since 1999, he has been pursuing his Masters degree at Kyushu Institute of Design. He is presently researching rhythm perception using tapping tasks. He is a member of the ASJ.