メトロノームに合わせる打叩の時間的制御機構解明とそのコンピュータ・シミュレーション

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研究ディレクター：山田　真司
（音楽学科　講師）

共同研究者：中山　一郎（音楽学科　教授）　奥原　光（音楽教育学科 助教授）　荒川　透（教養課程 助教授）

研究助言者：柳田　益造（同志社大学工学部 教授）　岩宮眞一郎（九州芸術工科大学芸術工学部 教授）　津崎　実（京都大学大学院情報学研究科 助教授）

研究補助者：橋本　裕美
（音楽学科　副手）

ABSTRACT

Ten subjects tapped in equal intervals at various speeds with and without metronome ticking. The inter-onset intervals in the tapping were measured and the temporal fluctuation in the intervals was analyzed. The results suggest that in cases without the metronome a 20-interval memory mechanism governs the temporal control of the tapping. In cases with metronome the 20-interval memory mechanism also dominated the short period fluctuation, however for the long periods, the rigid timing of the metronome suppressed the fluctuation. A computer program simulated these two control mechanisms. The temporal fluctuation that was produced by this program showed similar spectral features as the fluctuation human produced.

1. INTRODUCTION

Musha and his colleagues (1985) requested non-musicians and an amateur pianist to tap castanets at equal intervals under two conditions. In one condition, the subjects listened to metronome ticking while tapping (metronome tapping). In the other condition, they listened to the metronome only before tapping but not while tapping (free tapping). In the case of free tapping, power spectrum of the temporal fluctuation showed that the amplitude of the fluctuation was small and consistent in the high frequency region above 0.1 Hz, while it increased as the frequency decreased in the low frequency region below 0.1 Hz. The amplitude or power of the fluctuation indicates the difficulty of temporal control and the frequency of 0.1 Hz corresponds to a period of 10 sec. Therefore, the critical phenomenon in the spectrum of free tapping implied that the temporal controllability was excellent for a period less than 10 sec, but for periods over 10 sec, the controllability worsened as the period increased.

On the other hand, for metronome tapping, the power was large and consistent in the high frequency region above 0.1 Hz similar to free tapping, while it never increased as the frequency decreased in the low frequency region below 0.1 Hz. The power of the low frequency components was still as large as the power of the high frequency components, or the power decreased as the frequency decreased. Musha and his colleagues suggested that the critical phenomena of 0.1 Hz indicated that temporal control in equal interval tapping is govermed by a memory of 10 sec.

Because the speed Musha et al. used was limited to 300-500 ms/tap, Yamada (1996) pointed out that the memory capacity may correspond to the tap number of 20-30 taps rather than the real time of 10 sec. Thus, Yamada performed experiments of free tapping in various speeds ranging from 180 to 800 ms/tap, and as a result, showed that the critical period appeared at approximately 20 taps for all speeds and for all subjects. Moreover, Yamada applied auto-regressive (AR) models to the temporal fluctuation of free tapping. The best AR model was determined as the model which minimizes the value of Akaike's Information Criteria (Akaike, 1969). The order of the best AR model was also approximately 20 for all speeds and for all subjects. Yamada concluded that the memory capacity, which governed equal-interval free tapping was not 10 sec but 20 taps, i.e., the preceding 20 intervals of the tapping is preserved and used to determine the interval of the present tap.

Yamada and Tsumura (1998) investigated the temporal controllability in equal interval tapping as a function of musical training, using skilled and novice pianists as subjects. As a result, when they tapped with one finger, skilled and novice pianists showed the same temporal controllability and the critical phenomenon of 20 taps was commonly observed in the spectra. However, when multiple fingers were used, there were significant differences between the two groups: The control by the skilled pianists was as excellent as their single-finger tapping, while novice pianists showed quite poor control. These results suggested that the critical phenomenon of 20 taps observed in single-finger free tapping correlated with a basic feature of temporal control which did not change with musical training.

The series of experiments by Yamada and his colleague showed the 20-tap memory governs the free tapping with various speeds. On the other hand, although Musha et al. performed both free tapping and metronome tapping experiments, the speeds were limited to 300-500 ms. Therefore, the control of equal interval tapping with metronome ticking at various speeds remains to clarify.

Thus, in the present study, both free and metronome tapping experiments were performed at various speeds to estimate the temporal control of metronome tapping, with regard to the control of free tapping.

2. EXPERIMENTAL METHOD

Ten students majoring in music participated as subjects. The subjects were instructed to use the right middle finger to tap an aluminum board placed on a table with intervals as equals as possible. All subjects had intermediate experience in playing the piano and the other instruments. Each subject tapped at equal intervals at the speeds of 200, 370, 800 ms/tap and a spontaneous speed, i.e., the most comfortable speed for the subject to tap in equal intervals. The subjects were also instructed neither to count the number of taps nor to imagine musical rhythms during the tapping.

In metronome tapping, the subjects listened to the metronome ticking during the tapping. On the other hand, in the case of free tapping for the fixed speeds of 200, 370 and 800 ms/tap, the speeds were demonstrated for 20 sec prior to each trial through the use of metronome. The metronome ticking was not present during in free tapping of the spontaneous speed.

The metronome ticking was produced by a computer system with a D/A converter of 48 kHz. Each tick consists of the 4000 Hz tone with the triangle time envelope of 6 ms. The metronome ticking was presented through headphones at 73 dB(A). Small speakers attached to the aluminum board transformed the tap pressure 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 allow each subject to monitor the clicking sounds of his/her own tapping. The clicking sounds were monitored at about 73 dB(A) using the same headphones used to present the metronome.

One trial of tapping consisted of 1701 taps. Since the IOI was not stable in the initial 100 taps for some cases, rather stable IOI fluctuation of 1600 taps, from the 101st to the 1700th taps, was used for analysis for all tapping trials.

Experimental design was as follows: The entire experiment consisted of four blocks with each block corresponding to one of the four speeds. Each block also consisted of two sections (free tapping section or metronome tapping section). The order of the blocks was randomized for each subject. The order of the sections was also randomized for each block and for each subject with the exception of the spontaneous speed block. In the spontaneous speed block, the free tapping section was performed firstly, then the average speed of the spontaneous speed was calculated and used for the metronome tapping to follow. Each subject carried out seven trials for each section. A 5-min rest period separated the trials, and the subjects took rests between sections and between blocks for at least 20 min. Each subject performed one to three sections a day and completed the entire experiment within seven to ten days.

Therefore the experiment obtained 35 trials for each speed and condition.

3. RESULTS AND DISCUSSION

The IOI was plotted as a function of the order of the taps. The temporal fluctuation of the 1600 taps previously mentioned was decomposed into Fourier components by DFT with Hanning window, and the power spectrum was calculated for each trial. The power was averaged over every 1/2-octave band, and then the resulting spectra were averaged over the same speed and the same condition in a logarithmic scale.

3.1. Free Tapping

The power spectra of the temporal fluctuation for free tapping showed the following features: In the high frequency region above about 80 cycles for 1600 taps, the power was consistent or slightly increased as the frequency increased. On the other hand, the power increased as the frequency decreased in the low frequency region below about 80 cycles. The power of a frequency component indicates the difficulty of temporal control for that frequency and the correlation between the frequency, f [cycles] and period, p [taps] is, p=1600/f. Therefore the spectral feature showed that the temporal control in free tapping was excellent for a short period less than about 20 taps but the control worsened as the period increases in the long period region above about 20 taps. This spectral feature illustrated the control by the 20-tap memory described in [1].

$$IOI\ (i) = \sum_{j=1}^{20} a_j \cdot IOI\ (i-j) + \xi_i , \qquad [1]$$

where IOI(i) shows i-th interval, a_i and ξ_i denotes coefficients and noise terms respectively.

The power spectra for free tapping also show that the spectrum for a slower speed located in the higher spectral position on the power axis. Yamada (1997) showed that the coefficient of variation of IOI in free tapping is consistent (distributed around 4.3 %) for various speeds. The mean IOI in a slow speed is long, consequently the standard deviation and the power in the fluctuation is large. Therefore, the spectral positions for free tapping with different speeds in Fig. 1 are consistent with Yamada (1997).

In a conclusion, the spectra for free tapping suggest that the temporal control of free tapping is characterized by the 20-tap memory and the consistent coefficient of variation of IOI.

3.2. Metronome Tapping

In the case of metronome tapping, there were no significant differences between different speeds, in the low frequency region below about 50 cycles. In this region, the spectra showed a steep slope which implied that the power rapidly decreased as the period increased. This spectral feature of steep slope was interpreted as follows: The timing of each tap should synchronize with the timing of each metronome tick. However, human cannot achieve perfect synchronization. The timing of each tap, t(i) can be described by [2].

$$t(i) = k \cdot i + \zeta_i , \qquad [2]$$

where k is the inter-ticking interval of the metronome, and ζ_i denotes random noise. Then, the inter-onset intervals of the tapping, IOI(i) is described by [3].

$$IOI(i) = k + \zeta_i - \zeta_{i-1} \qquad [3]$$

The power of spectral components of random noise is consistent for all frequencies, and the power of the first order differential of the random noise is proportional to frequency. The steep slope shape in the low frequency region shows this proportional correlation between the power and the frequency.

On the other hand, the spectral feature was quite different between different speeds in the high frequency region above about 50 cycles. For example, the spectrum of 200 ms/tap showed a decreasing slope above about 50 cycles, although in the case of 800 ms/tap it still showed the steep slope below about 500 cycles, with the slope decreasing above 500 cycles.

Why did such differences occur in the high frequency region? Let's look at the pair of the spectra for free and metronome tapping in each speed. In the cases of 200, 370 ms/tap and spontaneous speed, the spectral features show that the power of metronome tapping increases as the frequency increases in the low frequency region. However, once the power reaches the spectrum of free tapping, the power of the metronome tapping coincides with the spectrum of the free tapping above that frequency.

The metronome tapping was different from the free tapping with regard to the existence of the metronome. Therefore the excellent control of metronome tapping in the low frequency region corresponded to the consistent suppression of the fluctuation by synchronization mechanism with the metronome. This control mechanism was consistently active in metronome tapping. However, the 20-tap memory mechanism which governs free tapping is also active in metronome tapping. The apectra suggested that the two mechanisms were both active in metronome tapping and the fluctuation of a frequency component is determined by better control of two mechanisms for the frequency, in the speeds of 200, 370 ms/tap and spontaneous speed.

In the case of 800 ms/tap, the power of metronome tapping was significantly larger than that of free tapping in the high frequency region. This suggested that metronome tapping was governed only by the synchronization mechanism with the metronome. Why the 20-tap memory mechanism was not active in the slow speed of 800 ms/tap still remains to be studied.

4. SIMULATION

A computer program simulated the two control mechanisms shown in [1] and [3]. The program produced 1000 fluctuations for the case of the tempo of 370 ms/tap and the power spectrum was calculated for each of these fluctuations, Then these spectra were averaged over the 1000 simulations in a logarithmic scale. The resulting power spectrum showed almost similar as the spectrum of the fluctuation human produced.

5. CONCLUSION

In the present study, it is confirmed that the temporal control of free tapping at various speeds is governed by a 20-tap memory. In the case of metronome tapping, a synchronization mechanism with the metronome additionally takes place in the temporal control.

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