Temporal development of dual timing mechanism in synchronization tapping task

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Abstruct

It is well known that the sensory-motor coupling represents negative asynchrony phenomenon in which motion timing precedes the onset of stimulus. In our previous researches, the tapping task has been investigated by spectrum analysis of synchronization error(SE) and discovered two frequency characteristics in their behavior. Therefore, in this report, we made an improvement on the time-series analysis and it was shown that asynchronous behavior in synchronization tapping task is composed of two different dynamics. One has self-similar structure, and the other is periodic.

1 Introduction

We have developed man-machine interface for supporting human based on man-man communication or cooperation 1)-4). In human relationship, a cognitive synchronization is not necessarily correspond to real-time one. For example, it is well known that two persons perform predictive motor behavior to facilitate synchronous with each other in a face-to-face communication 5). Not only that, even on a stand-alone man, predictive synchronization between physical response and periodc stimuli, so-called "Negative Asynchrony", is widely observed 6)-8). It means that motor output precedes sensory input by tens of milliseconds. Making full use of these internal timings, that is "subjective" time, human seems to predictively behave which can make up for various and unavoidable physical delay.

This human behavior brings not only scientific interest to us, but also complicated technical problem to development of human-interface. Whereas, if human interface can coincident with user's internal state which subjective timing is a part of, the user has prospects of getting more usability and interactivity. To find out human's "simultaneity" process between real-time and internal time, we have researched the phenomenon with synchronization tapping task 9), one of the simplest experiment as the sensory-motor coupling.

Recently, researches of temporal sense and timing control with brain function have taken a progressive turn. Focusing on the interference between predictive motor behavior and

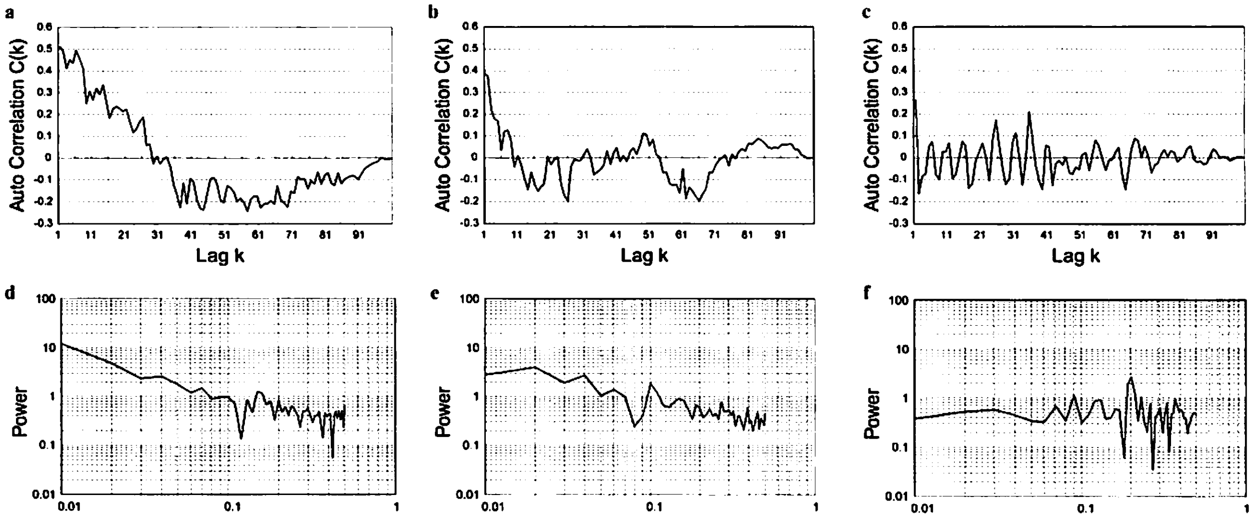

Figure 1: Typical autocorrelation (a,b,c) and spectrum patterns (d,e,f) of Synchronization Error (SE) by using frequency analysis

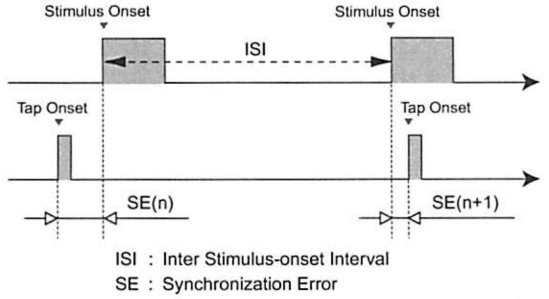

Figure 2: Timing-Chart of temporal relationship between taps and clicks.

attention capacity [10], synchronization tapping study suggested dual temporal control system [11]. One influenced attention resource is concerned with tap timing in longer interval (nearly 1~2s or more) of pacing signal. And the other is implicitly achieved without this mental resource in shorter interval (less than 1s). Another studies with fMRI gave an indication of two differential timing manager in human brain, all the same. These were automatic and cognitive [12].

Meanwhile, from the aspect of kinetic analysis, our previous tapping study extracted two opposite frequency characteristics from a fluctuation of asynchrony. There were the "$1/f^n$-Feature", a power being in inverse proportion to frequency and depending on no unique frequency (**Fig.1a,d**), and the "Periodic-Feature", a power distribution being composed of frequency-specific significant peak and white noise (**Fig.1c,f**) [13]. Afterward, preliminary tapping experiment observed that the opposite features and their combination (**Fig.1b,e**) intricately took turns behaving on each time slot of a long trial.

These new findings opened our eyes to the possibility of the asynchrony being dynamical process which requires us of non-static approach. However, even recently timing-control model [14][15] has made no mention of such vision. Likewise, our study remained static approach, because of assuming fixed waveform. Then we analyzed temporal development in a fluctuation of the asynchrony.

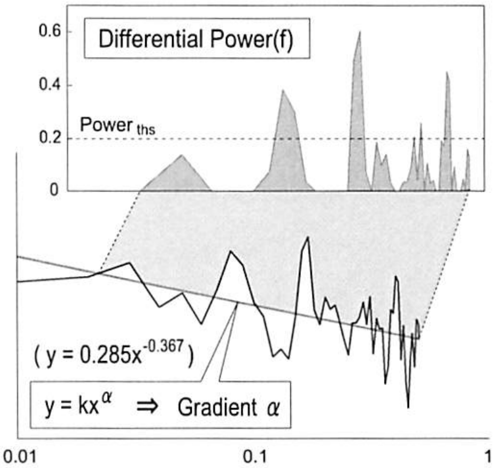

Figure 3. Extraction method of two attribute values from power spectrum.
Gradient α: Slope of regression line on log-log plotting.
Power(f) : Shift length from the line on log-log plotting.

2 Method

2.1 Overview

The past spectrum analysis of synchronization error on finger tapping [13] had an assumption that the asynchrony is steady waveform. This research extends our previous analysis to the Short-Time Fourier Transform (STFT) by recording long-term fluctuation of tapping asynchrony. This approach must provide two fixed attributes of spectrum pattern to temporal development with discrete time.

2.2 Parameters

A time difference between the auditory stimulus onset and the finger tap onset was defined as the Synchronization Error (SE). A predictive tapping makes the SE negative. A time difference between the neighboring two auditory stimuli was defined as the Inter Stimulus-onset Interval (ISI). ISI is a controlled variable and SE is a measurand in this experiment (see **Fig.2**).

2.3 Tapping experiment

According to former studies of synchronized tapping task [9][11][13], our measurement system provided subjects with a cyclic pacing signal, and detected right index finger tappings as their responses to an accuracy of 1/2048 second. The

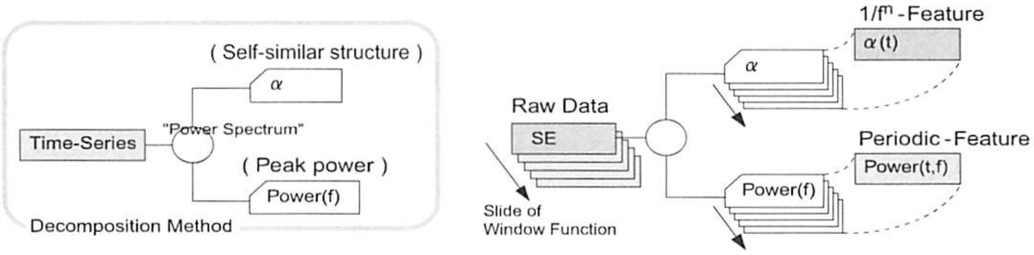

Figure 4: Block-drawing of analitical approach. How to combine STFT and our "decomposition" method.

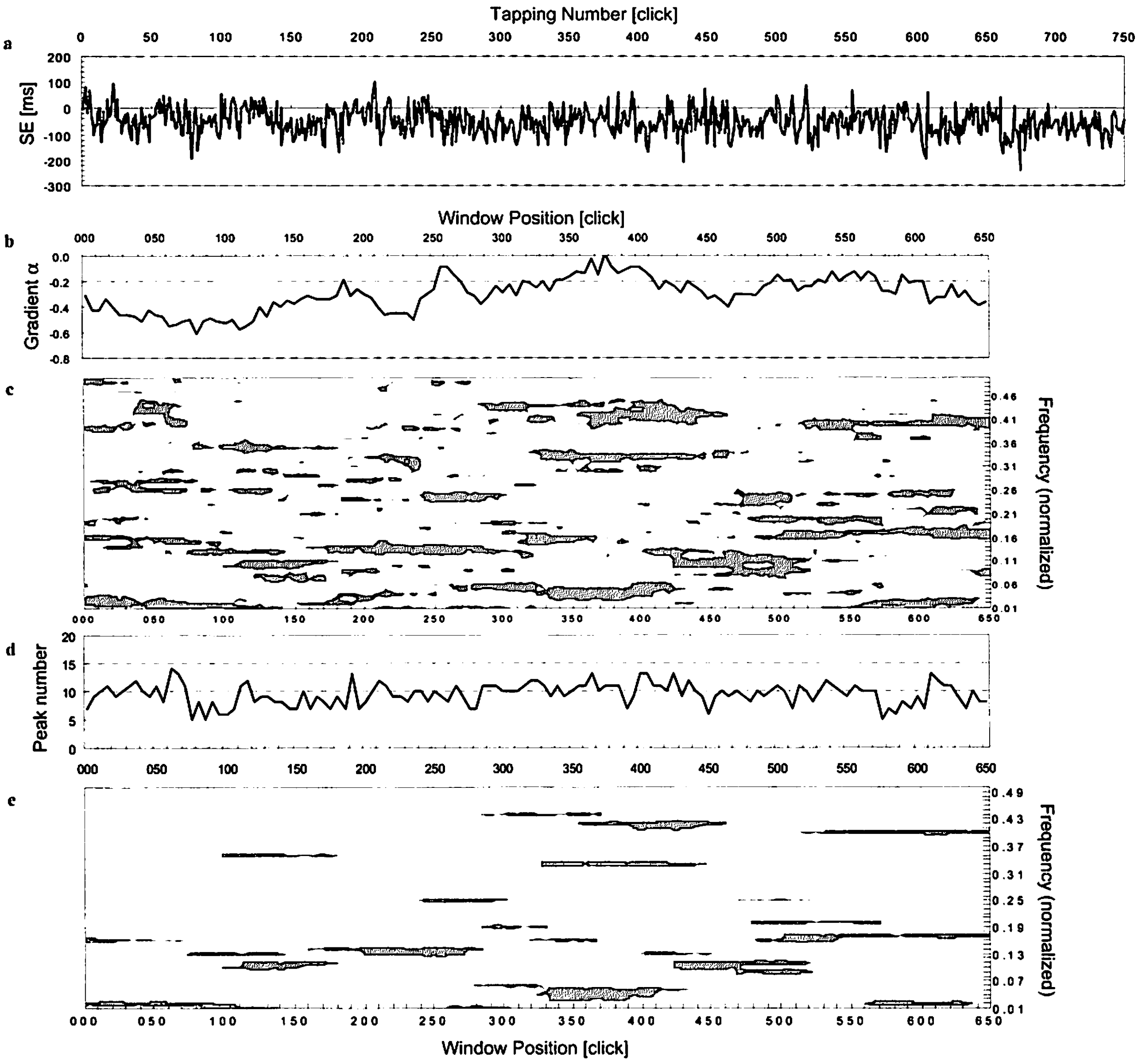

Figure 5: Raw and analized datum of tipical example in ISI=1500. **a** SE distribution. **b** α(t) distribution. **c** Power(t,f) distribution. **d** Peak(t) distribution. **e** long-time maintained Power(t,f) distribution in same frequency. Gray zoning is power threshold (0.2) of peak judgement.

click as a means of pacing signal has a 100ms duration and a 500Hz frequency.

The nine participants in this research are composed of trained male volunteers without a hearing disability and a movement disorder in their finger. They are dextral and twentysomething students. These subjects are required to tap an index finger against mechanical switch in exact timing with click.

The ISI was set intermittently to 450, 600, 900, 1200, 1500, 1800, 2400, 3600ms in each trial and was fixed throughout the trial. We provided the subjects with 765 clicks and measured 750 SEs without lead 10 SEs and final 5 SEs.

2.4 Analysis

On the assumption that, most spectrum patterns of SE fluctuation comprehend a self-similar power structure, so called "1/fn-Feature" [3], we prepare a first order approximation from log-log plotted power spectrum of SE. However, among trials or sometimes time slots of one trial, each gradients of power-law relation are so variant that the gradients are described by the variable "Gradient α" relative to $y=kx^{\alpha}$, the proximity function. **Fig.3** shows two attribute variables, the α and Power(f) as the function of frequency. The latter is defined by the difference between raw power distribution and its first order approximation on each *f*, but confined to zero or positive. Then, the Power(f) is simplified whereby following expressions.

$$Peak(f) = 1 \quad (Power(f) \geq Power_{ths})$$

$$Peak(f) = 0 \quad (Power(f) < Power_{ths})$$

$$Peak = \sum_{f=0.01}^{0.5} Peak(f)$$

The "Peak" indicates how many peaks of power spectrum exceed a power threshold. We settled the threshold 0.2 by way of experiment. This decomposition corresponds to dividing structure of power spectrum into two orthogonal attribute values, and removes obscurities from appraisal method [13] for characteristic of complicated spectrum pattern.

The window function of STFT was rectangle, 100 clicks width, and 5 clicks interval of slide. Under the condition in which STFT derived the temporal development of power spectrum from long-term SE fluctuation (**Fig.4**), these two variables which describe characteristics of one spectrum pattern were extended to α(t) and Power(t,f) with discrete time t_n. As shown in the section 2.3, the t_n consists of $t_0 \sim t_{130}$.

3 Result

3.1 temporal development of power spectrum

Fig.5 shows typical profiles of time-series in a certain tapping trial (ISI 1500ms). This set of figures consists of raw distribution of SE (**Fig.5a**), α(t) plotting (**Fig.5b**), Power(t,f) plotting (**Fig.5c**) and Peak plotting (**Fig.5d**). Meanwhile, only Fig.5c represents in contour with altitude-axis as a power value. Gray regions hold 0.2 as threshold and above power. Horizontal axes in Fig.5b,5c express discrete time t which is supplied by sliding interval of STFT window.

In the negative a(t), absolute value is so large that a means substantial upgrade of a first order approximation, that is, contribution ratio of low-frequency power. a=-1.0 is equivalent to 1/f fractuation. It is known from previous frequency analysis that the middle-range ISI (nearly 1500ms) leads a to nearly between -0.3 and -0.4 [13]. The analysis has assumed that the waveform is fixed. However, the a(t) covers a broad range of a which fluctuates between white noise (on or about a=0.0) and $1/f^{0.6}$ (a=-0.6) (see Fig.5b).

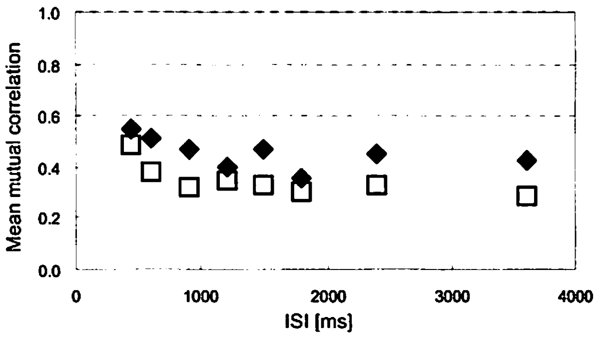

Figure 6: Mutual-correlation between α(t) and Peak(t) with respect to ISI. Black diamond corresponds to whole Peak(t). White rectangle corresponds to the filtered Peak(t) without "stable" peak powr (n=9).

ISI	450	600	900	1200	1500	1800	2400	3600
F-test							*	
t-test		*	*		*	*		*

Table 1: Cell marked "*" shows significant differences by p < 0.05 between two groups in Fig.6.

Meanwhile, periodicities on the same trial are shown in Fig.5c. For example, gray region in which a frequency of SE fluctuation has one-third of given ISI is maintained from t_{64} to t_{90} (equivalent to 320~450 click in window position of STFT). This time length of stable periodicity corresponds in about 5 minutes or more. To extract such stable peaks of power we removed the peak which was not maintained while 40 clicks with same frequency from hole Power(f). An application of this approach into Fig.5c makes **Fig.5e**. The figure shows long-time maintained peaks of power.

3.2 relationship between two temporal developments

This report decomposed power spectra into orthogonal binary attributes. The above section 3.1 viewed each of two variables. Then, this section explores the relationship between them.

In particular, we computed mutual-correlation C(k) between Peak(t) and α(t) every one trial, and extracted a maximum value in a series of C(k). **Fig.6** shows a between-subjects

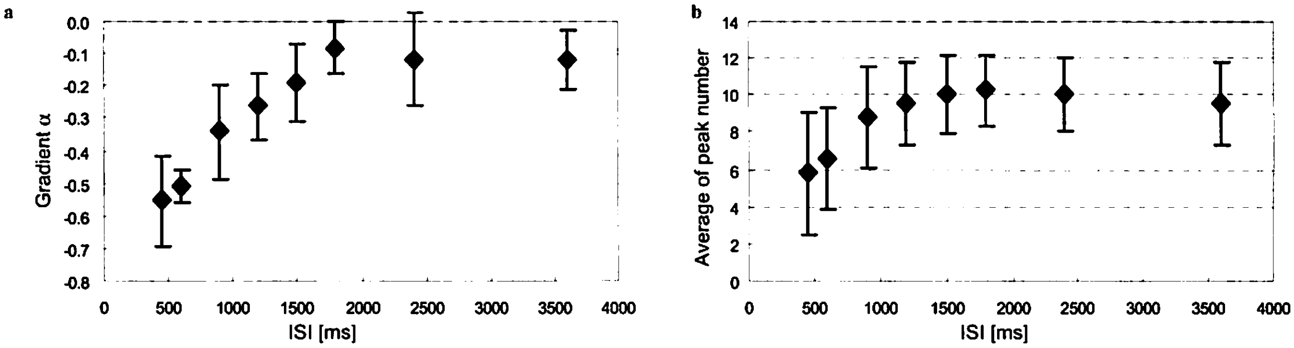

Figure 7: Between-subjects mean of moving average deviation with respect to ISI. **a** α(t). **b** Peak(t)

	Heavy gradient	Light gradient
Many specific peaks		*
A few specific peaks	*	

Table 2: Relationship between two attribute variabules on SE fluctuation is marked by *.

average of the values on every ISI. Because of the STFT providing 131 points of t_n, the correlation over $2/\sqrt{131}$ (nearly 0.17) is regarded as 95% statistically-significant. Thus, the correlation between α(t) and Peak(t) had statistically significance (P<0.05), in any ISI settings.

However, the Fig.6 includes two patterns of plotting. The black diamond is proper for an ordinary correlation between α(t) and Peak(t). The white rectangle is a correlation between α(t).and the filtered Peak(t) which is derived from the Power(t,f) without long-time maintained peaks, such as what is shown in Fig.5e.

Removing the stable periodicity from power spectrum, mutual-corration C(k) between α(t) and Peak(t) descends (Fig.6). Furthermore, this decreasing has statistically significance (P<0.05), in many ISI settings (see **Table 1**).

3.3 spectrum attribute's response to ISI

The above sections showed the two plofiles of temporal development on SE fluctuation and its significant relationship in each other. Now, what factor does modify these two attributes, the α(t) and Peak(t)? To narrow the possibility of causes, this section looks into the possibility of the modify being one-way drift or not for a long-time. Therefore we computed the following analysis.

Both moving average deviations are computed by a(t) (see **Fig.7a**) and Peak(t) (see **Fig.7b**), to be compared with given response respect to ISI 13). Besides, the Peak(t) which counts number of peaks passing threshold 0.2 on each discrete time t is condensed variable of Power(t,f).

The running average of α(t) reached maximum gradient of $1/f^{\alpha}$ spectrum in the shortest ISI (=450ms). Generally, shorter ISI leads a to substantial upgrade, almost 0.55 or less. On the contrary, decreasing in the mean α(t) characterized the power spectrum as white noise with minimal gradient, at longer ISI (Fig.7a).

However, mean Peak(t) with respect to ISI were formed of plateau shape which had broad hilltop between ISI=1200 and ISI=2400. An appearance of peaks had a difficulty to perform at both high and low intervals of the pacing click (Fig.7b).

A qualitatively similar result was observed in the frequency analysis of tapping task 13). At the same time, Quantitatively, the profiles of the α relative to ISI in past study are within the bounds of standard deviation of the moving average of a(t), with the exception of ISI=900.

4 Discussion

This study proposes an analytical method which can reveals temporal developments of the asynchrony in the synchronization tapping task, one of the sensory-motor coupling. Computed by the STFT method, we procured a temporal development of a power spectrum from prolonged period of SE fluctuation.

To eliminate an obscurity in empirical and qualitative evaluation of a spectrum pattern, each power spectrum on discrete time t_n dissolves orthogonal binary components, defined as "self-similar structure" and "significant power". The former variable, α, shows gradient of inverse proportion between power-law relationship, that is, the contribution ratio of low-frequency in whole power distribution. The latter, Power(f), is proper for differential power distribution which exceeds the former. Applying this method to every spectra, we derived time-series of these attribute variables, the α(t) and the Power(t,f). In addition, we derived Peak(t) as a simplification of the Power(t,f).

We examined temporal development of the asynchrony on each trials by STFT and the "decomposition" approach. The α(t), a gradient parameter, swings dynamically from white noise to roughly $1/f^{0.6}$ (see Fig.5b). The Power(t,f), a differential power-law distribution, retains prominent power peaks in fixed frequency over several minutes (see Fig.5c).

Next, we computed mutual-correlation C(k) between α(t) and Peak(t). The between-subjects mean C(k) performed statistically significance (P<0.05) across ISI range. According to a definition, the α is zero or negative. **Table 2** shows a pair of relationship between α(t) and Peak(t). So this correlation describes attribute X in relation to attribute Y (or latter in relation to former).

[1] X; decrease of the contribution ratio of low-frequency
on whole power structure (close by white noise)
Y; increase of significant power peak
[2] X; increase of the contribution ratio of low-frequency
on whole power structure (close by 1/f fluctuation)
Y; decrease of significant power peak

However, it is not necessarily the case that α(t) and Peak(t) have maximum mutual-correlation in shortest time-lag k, because of the most correlation being obtain from across C(k).

In the synchronization tapping task, two control mechanisms of movement timing have been suggested with and without engagement of higher brain function 11). The hetero-activated area in human brain has given an indication of the same dual timing mechanism 12). In the previous research we observed duality on frequency characteristc by frequency analysis of asynchrony [13]. Our results proposes the long-time SE fluctuation is self-changing between two behavior. One is a self-simillar structure in power spectrum. The other is a periodicity with specific peak of power.

Finally, we computed moving average of the $\alpha(t)$ and of the Peak(t) per ISI. These mean variables respond to ISI parameters in trial, just as past frequency analysis [13] which have an assumption that the SE fluctuation is a fixed waveform did, qualitatively and almost quantitatively.

Moreover, removing the long-time maintained peak of power leads the correlation C(k) to reducing. It is possible that increase and decrease of the "stable" periodicity is related to the $\alpha(t)$.

Still this method of spectrum decomposition remains arbitrary, our study is finding temporal structure in developments of $\alpha(t)$ and Power(t,f), and associations between those components. This approach and findings are expected to become a new foothold for making above "dual mechanisms" hypothesis clear.

5 Summary

Our study partially provides that a string of timings in periodic finger motion which relatives to human's internal time sense has constitutive properties, for the first time. These are described by temporal development of "self-similar structure" and "significant power". Moreover, these time-series of two attribute variables are not individual but interconnected.

The traditional approach, such as a statistical analysis or a frequency analysis which requires fixed waveform of fluctuation of asynchrony, can never derive our conclusion. We consider that our study will become a steppingstone to dynamical and systematic approach toward human's internal time sense and process.

In the past, an installation of sensory-motor coupling experiment absorbs a certain problem, by using a real-time-based event or timing which divides trials into control condition and experimental condition. Such installation masked out of variety of subject's internal time sense, that is, "subjective" time. In other words, one real-time-based trigger may leads two subjects to separate responses with separate processes. There is a possibility that they have different internal states, respectively. To some extent, our observation and estimation approach will leads to a part of advancement on that delimitation.

Furthermore, now we can draw human's internal condition by movement timing which is currently obtained without massive and non-relocatable instrumentation system. The convenient monitoring system like this will give further interactivity on users to developments of human interface, hereafter.

We expect these advantages.

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