Synchronization of periodic movements with external events and interlimb coordination: phase entrainment or phase resetting?*

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Abstract *The aim of this study is to investigate of the synchronization of periodic rhythmic movements with single discrete movements as reaction to external trigger signals. The underlying coordination principle derived from the experimental results is supposed to be either phase entrainment or phase reset. In phase entrainment, the response is more probable to occur during the phase, when the periodic rhythm is in the same direction as the discrete movement, but less probable, when directions are opposite. When the rhythm of the periodic movement is disturbed by the discrete movement, two types of phase reset can be obtained: type 1 resets provoked at weak perturbations show a small phase shift on the ongoing rhythm, whereas type 0 resets occur at strong perturbations and cause large phase shifts.*

Keywords: coordination, dual task, periodic movements, discrete movements, phase entrainment, phase reset.

1. Introduction

A single voluntary movement superimposed upon a periodic rhythmic movement (e.g. a discrete motor reaction of a trembling patient who is suffering from Parkinson's disease) is supposed to be affected by phase entrainment; i.e. the onset of the single discrete motor response is not simply determined by the onset of the go-stimulus (independently of all other ongoing activity), but the rhythm of the ongoing "background" movement modulates the onset probability of the discrete response across the period. Thus, the response onset is more probable to occur during that phase, when the tremor movement is in the same direction as the discrete response, but less probable, when directions are opposite. This behaviour can be interpreted in the framework of the minimum energy model of Bernstein [1]. Such an entrainment was demonstrated in tremor patients performing unimanual tasks and in normals mimicking tremor in addition [2, 3].

However, bimanually executed tapping tasks are mainly discussed from the viewpoint of phase resetting [4, 5]. Studying the synchronization of repetitive tasks with external signals has a long history in experimental psychology. For example, Stevens [6] examined the regularity of repetitive finger taps with the standard finger-tapping task, which is composed of a synchronization phase and a continuation phase. In the synchronization phase, the subjects synchronize taps of the right hand index finger with auditory signals produced by a metronome (Fig.1a). After some initial signals, there is full synchronisation installed and then the metronome is stopped but the subjects are required to continue tapping at the same rate [6].

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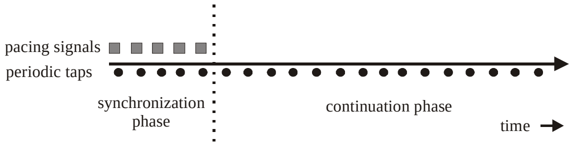

Fig. 1 a: Standard synchronization-continuation paradigm [6]. In the synchronization phase, the subject synchronizes tapping to an auditory signal, which is terminated after some period. During the continuation phase, the subject is asked to continue tapping at the same rate as before without pacing signals.

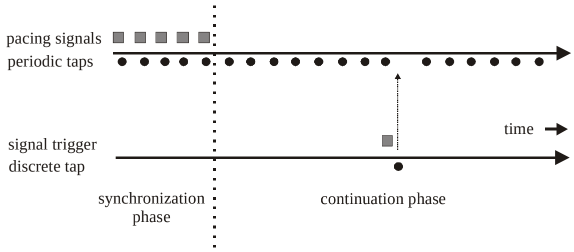

Fig. 1 b: Dual task bimanual interaction paradigm [5]. Single left-hand taps in response to an (external) auditory trigger stimulus have to be performed during the continuation phase in order to investigate the bimanual interaction.

One basic finding is the variability of intertap intervals in the continuation phase. Concerning the movement control of the taps, Wing and Kristofferson [7] suggested the existence of an internal timekeeper, which generates command pulses in self-paced tapping. Each (internal) command pulse of the timekeeper system triggers a movement (finger tap). The time between the command pulse and the onset of the corresponding motor action is called motor delay. According to this two-level timing model, the temporal precision of self-paced finger tapping depends on both the variability of the command pulse intervals of the central timekeeper and the execution timing variability introduced by the peripheral motor system. Thus both factors will contribute to the variability of the intertap intervals, too, [8]. Also, several previous studies demonstrated that the variability of finger taps increases in synchronization tasks when visual pacing signals are used instead of auditory signals [9, 10]. Vorberg and Wing [11] proposed an extension of the Wing-Kristofferson model, including a linear phase correction mechanism for synchronized tapping.

Bimanual tasks – in contrast to unimanual tasks - require interlimb coordination in addition, which also has been studied for many years. Yamanishi *et al.* [4, 12] suggested that self-paced tapping is controlled by a specific neural oscillator, and, consequently, they had to assume that coordinated bimanual movements (as in bimanual tapping) are based on a two-coupled-oscillator model. Presenting the so-called Haken-Kelso-Bunz model of rhythmic interlimb coordination, Haken *et al.* [13] demonstrated the occurrence of phase transitions in human interlimb coordination when performing self-paced tapping by both hands. The model suggests the concept of a non-linear system of coupled oscillators. Bimanual dual tasks, but now consisting of a periodic tapping by one hand and, in response to an external trigger event, a discrete (reaction time) response by the other hand, were used by Yamanishi *et al.* [4] and Yoshino *et al.* [5]; the concept of such a paradigm is shown in Fig. 1b. Yamanishi *et al*. [4] used a visual signal for triggering the taps of the left index finger in bimanual tapping, whereas Yoshino *et al*. [5] triggered the left taps by using an acoustic signal. Data were analysed under the viewpoint of phase resetting according to Winfree's definition of general limit cycle oscillators [14]. Two types of phase resetting could be obtained, following Winfree [14]: type 1 resets provoked by weak perturbations show a small phase shift of the ongoing rhythmic movement, whereas type 0 resets occur at strong perturbations and cause large phase shifts similar to a restart of the current cycle. In the Yoshino *et al*. [5] work, some subjects showed type 1 phase resetting and were able to continue the self-paced tapping rhythm nearly without any phase shift due to the left hand "perturbation", whereas other subjects typically showed a type 0 reset behaviour caused by the execution of the single movement.

While coordinating periodic movements with voluntary single movements, these earlier investigations report either phase entrainment or phase resetting to occur, probably depending on whether the movements are unimanual or bimanual. From the motor point of view, the execution of a single response in a reaction time task by a trembling patient (e.g. Parkinsonian patient, [2]) represents a dual task situation due to the ongoing tremor activity; thus this experimental situation would be comparable to a unimanual version of the Yamanishi *et al.* [4] experiment. Actually, this obviously given neighbourhood of the 'entrainment effect' and the 'limit cycle resetting theory' was not yet considered in literature. In this work, therefore, the interlimb coordination and interaction reported to occur in bimanual tapping tasks are compared to that in unimanual tapping; for this purpose, a novel experimental concept was developed. The experimental data obtained were analysed from the viewpoint of phase resetting as well as with respect to the entrainment hypothesis. A particular point of interest is the suggestion by Yamanishi *et al.* [4] that musically trained subjects are able to precisely coordinate bimanual tasks independently (which also was proposed by Klapp *et al*. [15] and Summers [16]); for this purpose, both musically trained subjects and those without such experience are tested.

2. Materials and Methods

Four right-handed young healthy subjects participated in this pilot study; another six subjects will follow. One group of subjects was musically trained (e.g. playing the piano) and the other group had no such experience (group 2). All subjects had normal or corrected-to-normal vision. None had any signs or history of any disease or neurological troubles. They were naive about the experimental hypotheses. Each subject had to take part in the following three experiments.

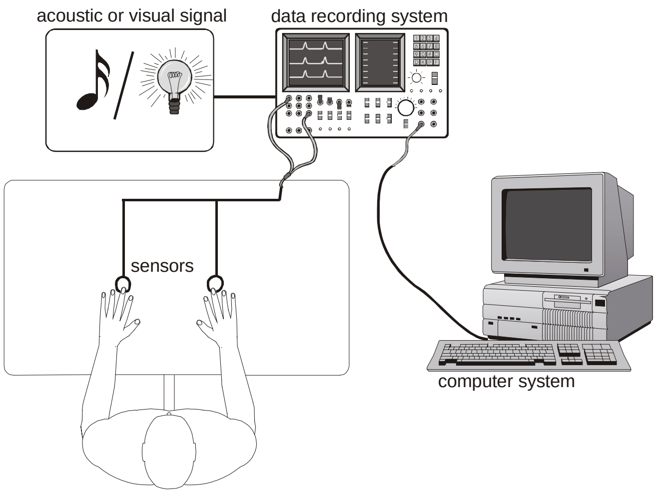

Fig. 2: Schematic illustration of the experimental setup. The subject is sitting in front of a table with two embedded force sensors for the index finger of the right and left hand, respectively. The signal for the single (discrete) finger taps is either acoustic or visual, the pacing signal for the periodic tap consists of a sequence of beeps. Data are recorded and analysed by PC.

Experiment 1:

The subject sits at a table with two embedded force transducers recording the taps of the index finger tip of the left and the right hand, respectively, (Fig.2). The experimental session consists of 24 trials, each with a synchronization phase and a continuation phase. In the synchronizing phase, a series of five acoustic pacing signals (duration 50 ms, 500 Hz tone) are presented to synchronize the periodic index finger tapping of the (dominant) right hand. The total interstimulus interval between the acoustic pacing signals amounts to N = 600 ms (i.e. 1.66 Hz). After the synchronization phase, the subjects are required to continue tapping without a pacing signal at the same rate (continuation phase). During the continuation phase, twelve **acoustic** trigger signals (duration 50 ms, 2000 Hz tone) are presented in random intervals (3000 to 5000 ms) to the subjects who are asked to react as quickly as possible by a single tap of the index finger of the left hand (bimanual tapping). The paradigm of Experiment 1 is adapted as closely as possible to the design of Yoshino *et al*. [5] (Fig. 3).

Experiment 2:

The procedure is the same as in Experiment 1; however, during the continuation phase twelve **visual** signals (bright red light, duration 50 ms) are presented instead of the acoustic trigger signals to the subjects who again are asked to react as quickly as possible by a single tap of the index finger of the left hand (bimanual tapping).

Experiment 3:

The procedure was the same as in experiment 2, however, the single tap in response to the visual trigger signal has also to be performed by the index finger of the **right hand,** in addition to the periodic tapping during the continuation phase (unimanual tapping).

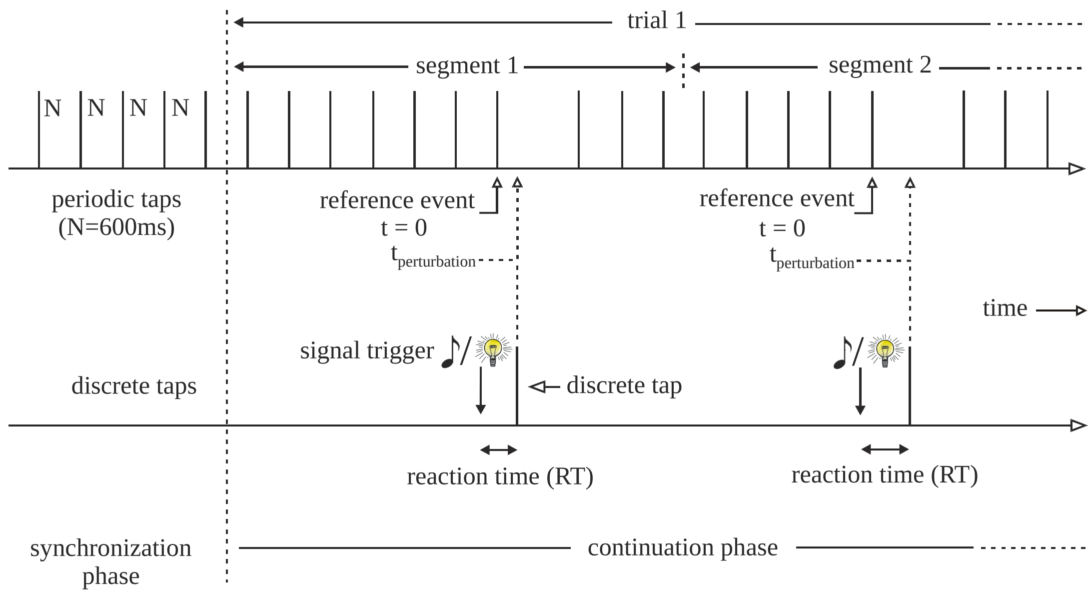

Fig. 3: Time course of the dual task interaction paradigm [5].

Data analysis:

Data at a sampling rate of 1000 Hz were recorded and evaluated by PC and subsequently checked by inspection. The trials are divided into 12 segments; each segment contains one discrete (single) tap in response to a trigger signal. Within segments, the following events (onsets of signals) are defined according to Yoshino *et al*. [5], (Fig.3):

- The left tap following the trigger signal is considered to be the single discrete response to the trigger signal (*perturbation event*); in Experiment 3, the first right tap following the trigger signal within the expected reaction time (RT) interval of 200 – 400 ms is regarded as the single discrete response tap, but in the case of two tap occurrences within this RT interval, the first one is taken. RT is defined as the time between trigger signal and onset of the corresponding response tap.

- The last right hand tap of the periodic tapping before the single discrete tap represents the reference tap (*reference event*), which defines the origin (i.e. $t = 0$ and $\varnothing = 0$) within the segment.

- For $t > 0$, the normalized phase $\varnothing$ of the periodic tapping cycle of the right index finger is defined as $\varnothing = t/N$ with N being the period of the periodic tapping; i.e. the phase of a perturbation event is $\varnothing_{perturbation} = t_{perturbation}/N$.

The principal results are illustrated by the so-called phase resetting curves (Fig. 4). They show the intertap intervals (ms) of all segments as a function of the normalized phase $\varnothing$ of the periodic tapping cycle. Every segment (an experimental session consists of 24 times 12 = 288 segments) is represented by six vertically aligned dots; their common position on the abscissa is the phase of the perturbation $\varnothing_{perturbation} = t_{perturbation}/N$, which is the single discrete tap within this segment. Due to the definitions given above, the reference taps of all segments have an ordinate value of 0 ms, but the two leading and three trailing right hand (periodic) taps are represented by the dots below and above, respectively. The dashed line above t=0 represents the occurrences of the single discrete taps (perturbation events).

3. Some Pilot Results

Experiment 1: Bimanual tapping, acoustical signal for the perturbation event

The phase resetting curves of the members of group 1 (musically trained) showed type 1 reset following Winfree's definition [14] (Fig. 4a), whereas the phase resetting curves of the members of group 2 (no experience) showed a significant type 0 reset (Fig. 4b). As mentioned above, type 1 reset means almost no influence of the perturbation event on the periodic tapping, which is recognized by the parallel (horizontal) orientation of the lines of dots. Fig. 4b with Type 0 reset, however, shows that the cycling of the trailing periodic taps is restarted at the perturbation event, resulting in the tilted orientation of the trailing tap lines parallel to the perturbation event line.

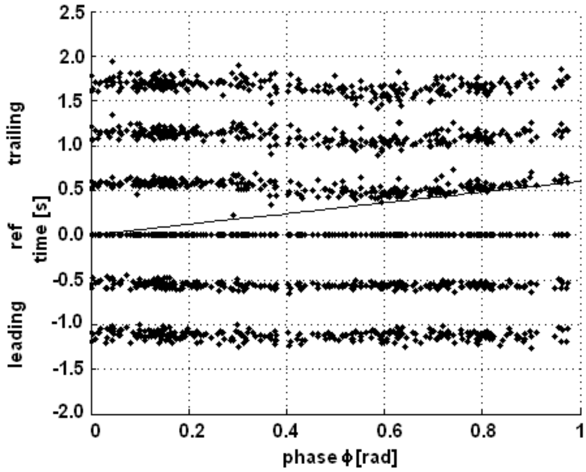

Fig. 4a: Phase resetting curve for type 1 reset. The line represents the occurrence of the perturbation event, the black dots represent the taps of the right finger.

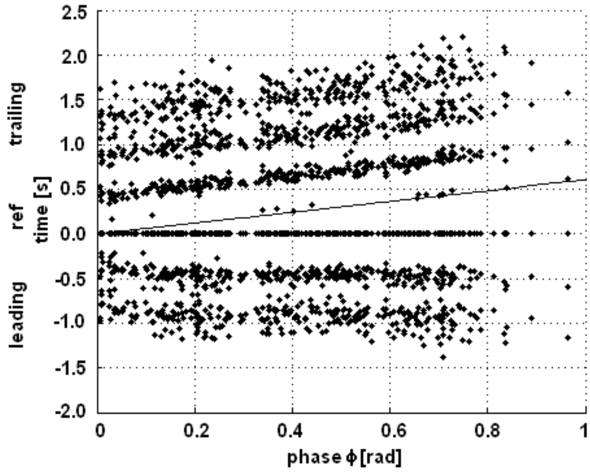

Fig. 4b: Phase resetting curve for type 0 reset. The line represents the occurrence of the perturbation event, the black dots represent the taps of the right finger.

As expected, all tested subjects showed some variance in the intertap intervals of the periodic right index finger tapping during the self-paced continuation phase of each trial, but they comply with the given rhythm (Fig. 5a). Some subjects, however, tended to shorten the intervals between the right taps within the continuation phase, and they are temporarily readjusted by the next synchronization phase (Fig. 5b).

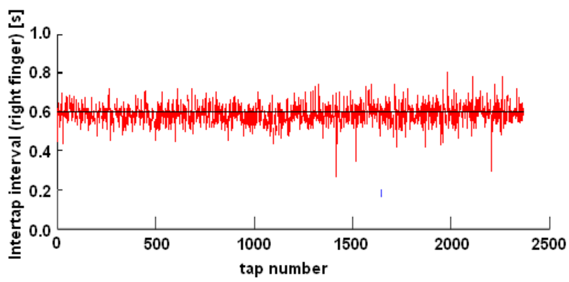

Fig. 5a: Variation of the intertap intervals of the right index finger taps. The black line represents the given rhythm.

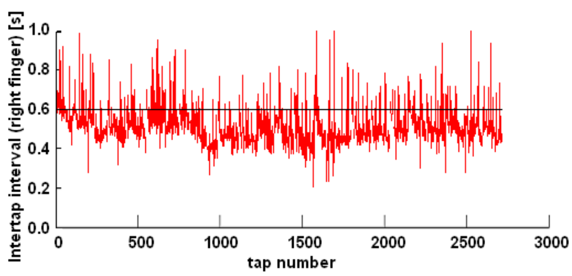

Fig. 5b: Drifting intertap intervals of the right index finger taps. The black line represents the given rhythm.

Concerning the RT between auditory signal and left tap, a variance between 0.3 and 0.5 s could be observed, some left taps even were omitted. In general, an increase of RT from the beginning of the experiment to its end could be observed .

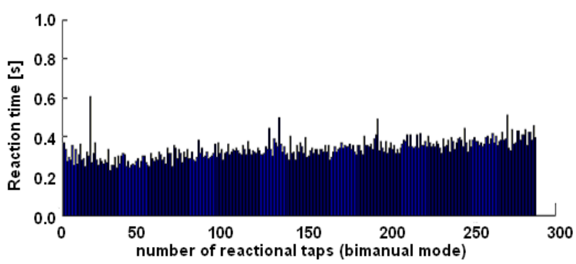

Fig. 6: RT for the perturbation event as a function of segment number.

Experiment 2: Bimanual tapping, visual signal for perturbation event

In this experiment, again the phase resetting curves of the members of group 1 (musically trained) showed type 1 reset (Fig. 7a), whereas the phase resetting curves of the members of group 2 (no experience) showed a significant type 0 reset (Fig. 7b).

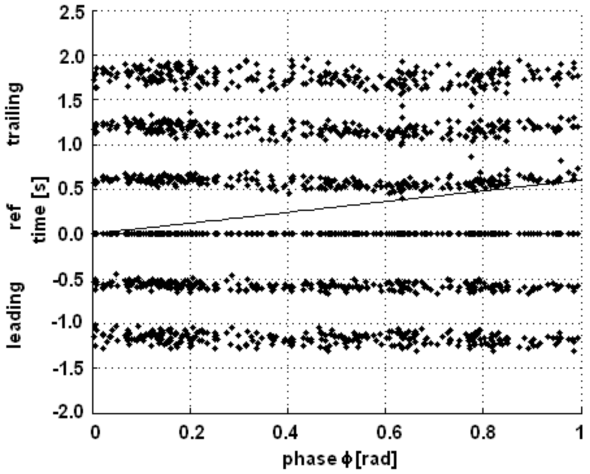

Fig. 7a: Phase resetting curve for type 1 reset. For details see Fig. 4a.

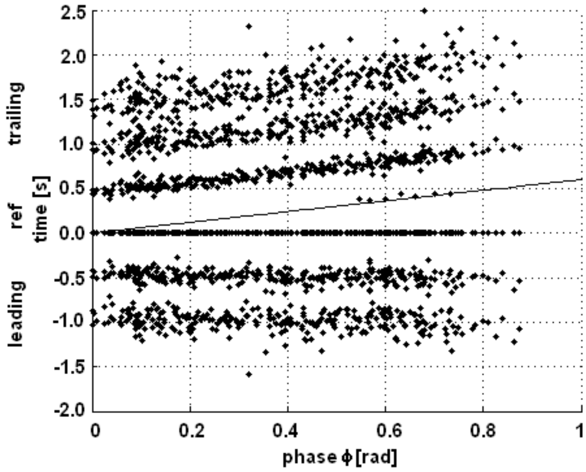

Fig. 7b: Phase resetting curve for type 0 reset. For details see Fig. 4b.

Most subjects' RTs were between 0.3 and 0.5 s, again some taps were omitted. Despite a longer reaction time was expected when using a visual signal instead of a tone, no difference could be observed when comparing the RTs in Experiment 1 and Experiment 2.

Experiment 3: Unimanual tapping, visual signal for perturbation event

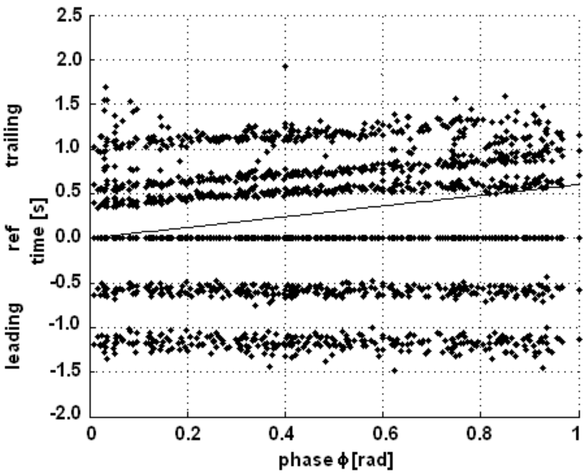

Fig. 8a: Phase resetting curve of the unimanual dual task (group 1). For details see Fig. 4a.

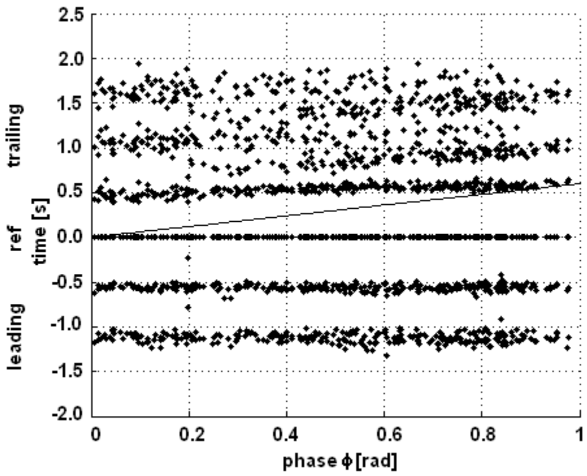

Fig. 8b: Phase resetting curve of the unimanual dual task (group 2). For details see Fig. 4b.

Comparing the bimanual tapping experiments and the unimanual one, some differences in the phase resetting curves could be observed. Most of the musically trained persons (group 1) produced type 0 reset (Fig. 8a) whereas the subjects with no experience tended to show type 1 reset (Fig. 8b).

The reaction times in the unimanual tapping experiments varied between 0.2 and 0.8 s.

4. Discussion

Comparing the results of Experiment 1 and Experiment 2, there seems to be no difference in the RTs when using either an acoustical or visual trigger signal for the perturbation tap with the left index finger. Chen *et al*. [9], however, suggested an RT increase when a visual pacing stimulus is used instead of an acoustic one; a possible explanation for this discrepancy may be the different subjective intensities of both stimuli which were not matched, but they influence the RT. The general RT increase with progression of the experiment might be caused by some fatigue and a decrease of the level of attention, introduced by the monotonous tapping.

Based on the results of previous studies reported by Yamanishi *et al.* [4], Klapp *et al*. [15] and Summers [16], it was to be expected that musically trained subjects produce type 1 phase reset. That leads to the conclusion that subjects who have experience in coordinating dual tasks with arbitrary temporal relations as they are encountered when playing the piano, are able to precisely execute two movements asynchronously.
Concerning the results of Experiment 3 with the unimanual dual task, the data obtained thus far are very complex and have not yet been adequately processed. A discussion must be postponed until the complete data set becomes available and, presumably, more sophisticated data processing methods are developed. Although the current state of the experimental results suggests the entrainment hypothesis [3, 17, 20] could be introduced to interpret the tapping results [18, 19], such a conclusion would be highly speculative at this time.

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