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A Coupled Oscillator Model of Interactive Tapping

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ABSTRACT

Background: Synchronization in music has been a popular experimental basis for studying social interactions, as musicians are required to synchronize to each other's beats and integrate abstract social information in order to coordinate their actions as part of a non-verbal communication process. A finger-tapping paradigm has been used in studies of sensorimotor synchronization as well as coordination dynamics within and between people (Repp 2005). Recent models of tapping dynamics have included two error-correction mechanisms: phase and period correction (Repp & Keller). They have generally been linear models, which are oversimplifications of these dynamics.

Aims: To model the dynamics capturing entrainment between pairs in a finger-tapping paradigm.

Method: Pairs of subjects were asked to tap on their respective keyboards following an 8-beat auditory stimulus sent through their headphones. Subjects were instructed to keep the given beat as precisely as possible as well as synchronize with the 'other'. They were in scenarios where they received auditory feedback of themselves tapping, the other, or the computer metronome.

Results: A dynamical systems approach was taken to model the tapping dynamics, using a system of two oscillators coupled in both phase and frequency, corresponding to phase and period correction. The model demonstrated that the tapping dynamics depend on the four coupling constants (phase and frequency for each oscillator), and are highly sensitive to noise.

Conclusions: Both phase and frequency coupling is required to capture the tapping dynamics of dyads. Coupling constants can be used to capture the degree of interaction.

I. INTRODUCTION

Tapping has frequently been used as an experimental paradigm in the field of music cognition and perception, and particularly for the study of sensorimotor synchronization (Repp 2005). It has also been prevalent in studies of coordination dynamics, most commonly studied within subjects (Engstrøm et al.; Keller et al. 2007). However, music is generally a social activity performed in groups, whereby musicians have to coordinate their movements with other performers in both a synchronized and complementary manner as part of a non-verbal communicational process leading to a coherent work of art. Musicians have to synchronize their movements with the auditory feedback coming from other members of the band, as well as integrate visual stimuli they may exchange with one another. The behavioural and neural mechanisms involved in 'playing together' are still fairly poorly understood, as studies of joint music production and performance have been scarce. These mechanisms are particularly interesting for the study of social cognition, as this coordination of actions may require the same mechanisms as entrainment in social situations – such as the ability to synchronize goals, intentions, and actions in order to jointly perform a goal directed task (Sebanz et al.).

Real-time, two-person exchange has not been the easiest paradigm for studying music and social cognition, as the experimental design and analysis require careful control (which usually constrains the interactive aspect) and the use of complex mathematical methods, respectively. Even in minimal interactions such as joint tapping, numerous approaches have been taken to describe the dynamics, many involving implementation of mathematical models. This behaviour has mostly been explored during self-paced tapping or tapping along with a computer metronome (Wing & Kristofferson; Repp & Keller; Repp 2005).

There have been three main approaches in computational modelling of sensorimotor synchronization studied via tapping paradigms: dynamical systems approach, control-theory, and information processing methods (Repp 2005). Dynamical systems theory treats tapping as continuous movement and is concerned with phase space trajectories, which describe the evolution of state variables over time. This approach has been taken for experiments involving other inter-personal activities, such as joint pendulum swinging (Schmidt et al. 1998), leg swinging (Schmidt et al. 1990), synchronized finger movements (Oullier et al.), and the joint rocking of chairs (Richardson et al.). Control-theory is an engineering method, which uses feedback regulation to produce the desired outputs, and combines both linear and non-linear equations to describe the system. The information processing method has been the most popular due to its simplicity and ease of implementation (Repp 2005). It treats the system as a discrete one (i.e. discrete taps), and is restricted to linear models. Vorberg implemented a discrete-time model designed to have people tapping along with it. In this paper, we have taken the dynamical systems approach to model the joint tapping data.

Joint tapping with a computer or another person requires inter-tap interval (ITI) error corrections in the attempt to synchronize with the other member of the dyad. Previous linear models have incorporated two error correction mechanisms: phase correction, which is thought to be involved in subconscious mechanisms that regulate actions, and period correction, a conscious mechanism involved in perception and planning (Repp & Keller).

In this study, we were interested in capturing the tapping dynamics of dyads in various degrees of interaction: no mutual coordination (no coupling between pairs), unidirectional (leader-follower scenario) and bidirectional coordination. These conditions were constrained by the experimenter in the degrees of auditory coupling, such that subjects found themselves in scenarios where they could hear only themselves tapping, the other, or the computer metronome. The tapping dynamics observed in each condition were modelled using non-linear differential equations. A weakly coupled oscillator model was used to capture these dynamics, where the oscillators represented each tapper coupled with the other in both phase and frequency. The phase and frequency changes over time thus represented both error-correction mechanisms: phase and period correction.

II. METHOD

A. Participants

Right-handed subjects with normal hearing were recruited from the University of Aarhus, Denmark. Thirty paid volunteers, 21 to 48 years of age, participated in the study. No musical training was required. The subjects were paired off, comprising fifteen pairs.

B. Materials and Apparatus

Two Yamaha MIDI keyboards were connected to the computer via an M-Audio 2x2 MIDISPORT interface. The MIDI outs from the interface were connected to two Roland JV-1010 sound modules, which further sent signals to two respective channels on a Phonic mixer. The stimulus used was an 8-beat metronome, which was generated using Cubase. It was sent from the computer, fed through a third channel on the mixer, sent through headphone amplifiers, and received at two sets of headphones. The output from the keyboards was recorded in real-time in Cubase. The mixer was used to adjust the auditory feedback that the subjects were receiving, namely hearing the computer-generated metronome, their own feedback from the keyboard outputs, or their partner's feedback. The elaborate set-up ensured an auditory delay (time between pressing the key and hearing the sound) of no more than 8ms, which is below the threshold of human auditory perception.

C. Procedure

The subjects of each pair were placed in separate rooms, receiving no visual contact with each other. They were asked to tap on their respective keyboards for 8 bars (32 beats) by pressing the marked key with their right index finger, following the 8-beat stimulus sent through their headphones. Notes corresponding to C3 and E3 were marked for each subject and partner, respectively. The stimulus was one of three different metronomes (tempos of 96, 120, and 150 beats per minute), which were alternated in random order. The same stimulus was sent to both subjects in each trial. Following the 8 beats, the stimulus would cease and the subjects would receive auditory feedback from one of three sources: their own tapping, their partner's tapping, or the computer metronome. The computer metronome was always precise as no noise was added. The subjects would find themselves in one of 5 different scenarios: no mutual coordination (both subjects receive only auditory feedback of themselves tapping), 2 asymmetric coordination conditions (subject 1 hears the self, subject 2 hears subject 1; and vice versa), synchronization to an external stimulus (both subjects only hear the computer metronome), and interaction (both subjects receive feedback from the other, but not the self). Each condition was carried out 4 times for each tempo, also alternated in random order, resulting in a total of 60 trials per pair.

Two instructions were given to the participants: to keep the given beat as precisely as possible, as well as to synchronize with the other subject or the computer metronome in scenarios corresponding to hearing the 'other' or the computer, respectively. The subjects were told which condition they would be in previous to each trial. Therefore, they were informed that they would be analyzed on both synchronization and drift from the metronome. They were also asked to keep their eyes closed during each trial, to not count in their heads or to tap with any other parts of their body (feet, other hand, or bopping of head). They were told by the experimenter when to cease the tapping (after 32 beats) at the end of each trial.

D. Analysis

The data was imported into MATLAB using the MIDI toolbox, and only the onset times were looked at. Plots of ITIs were generated for each trial and grouped according to condition. A dynamical system approach was taken, using non-linear differential equations to represent the pair's tapping behaviour as a system of two oscillators, weakly coupled in both phase and frequency – hence corresponding to phase and period correction. The model was implemented in MATLAB, and the differential equations were solved using the Runge-Kutta method.

III. RESULTS

E. Inter-Tap Intervals

Dyads' ITIs were plotted against the interval numbers for each trial and observed across conditions. Figure 1 shows an example of a single trial, where ITIs of both members of a pair are plotted in conditions of no mutual coordination (a. both hear only the self), unidirectional coupling (b. leader-follower), and interaction (c. both hear only the other).

The most consistent condition was the interactive one, where ITI oscillatory behaviour (Figure 1c.) was observed in all trials of every subject pair. This corresponds to the correction of tapping onsets in opposite directions, suggesting a mutual adaptation to each other's outputs. The condition where there was no auditory coupling between the subjects and they only received auditory feedback of themselves tapping showed no correlation between subjects and was the most variable across trials. Two scenarios were observed in the leader-follower condition: one showed the 'follower's' ITIs oscillating around the leader's less variable values, and the other had uncorrelated ITIs when the 'follower' chose not to cooperate with the other. The same behaviour was observed for all three tempos, 96, 120, and 150 beats per minute.

A speed up effect was observed in some conditions of interaction, such that subjects would become slightly faster than the original tempo with time.

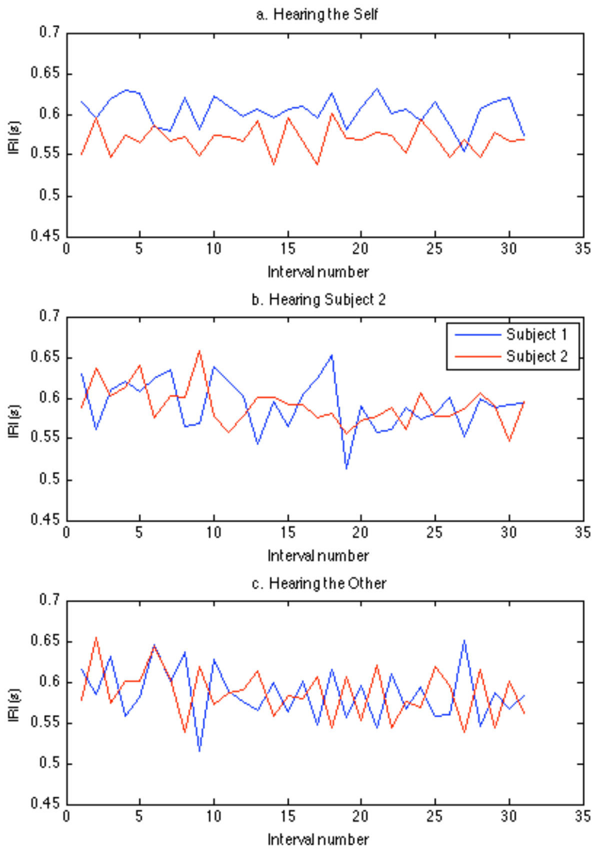


Figure 1. Inter-tap intervals of a dyad in a single trial: a) No coupling between the pair, both hear only themselves; b) Unidirectional coupling, both hear subject 2; c) Interaction condition, both hear the 'other' subject.

A. Weakly Coupled Oscillator Model

In order to capture the dynamics of this behaviour, the dynamical systems modelling approach was taken. The system was thought of as two oscillators, each with their own intrinsic frequency and some degree of coupling depending on the condition. The coupling in the raw data shows only small perturbations away from the limit cycle, and thus the weakly coupled oscillator model was chosen. Coupled oscillators have been used to model many concepts and phenomena in nature, such as the swinging of pendulum clocks, pacemaker cells, the chirping between crickets, fire-flies emitting light sequences in sync, and synchronization of clapping in large crowds after an enjoyable performance (Pikovsky et al.).

The changes in phase of the two oscillators over time were described using the following two equations:

$$\frac{d\theta_1}{dt} = \omega_1 + c_1 P_{21}(\theta_2) \cdot F_1(\theta_1) \qquad (1)$$

$$\frac{d\theta_2}{dt} = \omega_2 + c_2 P_{12}(\theta_1) \cdot F_2(\theta_2) \qquad (2)$$

Here θ_1 and θ_2 are the phases of the two oscillators, and ω_1 and ω_2 are the angular frequencies. The second term in the equations is the coupling term, where $P_{12}(\theta_1)$ and $P_{21}(\theta_2)$ are described as the pulses coming from oscillator 1 and 2, respectively. They represent the instant at which the tap of the 'other' subject is heard. Since we are working with a continuous system, they are modelled as continuous functions, namely $p(\frac{1}{2} + \frac{1}{2}\cos(\theta))^m$, where p and m are constants (Ermentrout). $F(\theta)$ is a phase response curve, set to a negative sinusoid in order to capture the error-correction in opposite directions (Ermentrout). Consequently, if the pulse is perceived as arriving after the subject's own tap, the subject would adjust by slowing down. Alternatively if the pulse is perceived as arriving before the tap, the subject would error-correct by advancing in phase (speeding up). The coupling constants c_1 and c_2 were used to adjust the coupling strengths between the two oscillators.

In order to account for the occasional speed-up effect, we decided to couple the oscillators in frequency as well. This would in turn also incorporate the 'period correction'. Therefore, two more equations were used to describe the model:

$$\frac{d\omega_1}{dt} = c_3 P_{21}(\theta_2) \cdot F_1(\theta_1) \qquad (3)$$

$$\frac{d\omega_2}{dt} = c_4 P_{12}(\theta_1) \cdot F_2(\theta_2) \qquad (4)$$

New coupling constants were assigned to adjust the frequency coupling between the oscillators. The intrinsic frequencies (memory term) of each oscillator were not included in the equation because they were part of the initial condition, which was taken from the experimental data.

Finally, Gaussian noise was added to both the frequency and phase equations, in order to capture the ITI variability seen in the behavioural data.

B. Model Fit to Data

The model was simulated in MATLAB and the coupling constants were swept for each pair of subjects to determine the best fit. In cases of unidirectional coupling, two of the coupling constants were set to zero, corresponding to the oscillator attributed to the person who could only hear their own tapping. For the interaction condition, all four coupling constants were set to non-zero values. Figure 2 shows an example model fit to the interaction condition trial data, where the frequencies (inverse of ITIs) are along the y-axis.

The system was very sensitive to noise, much like the experimental data; however the resulting phase slips have not yet been quantified.

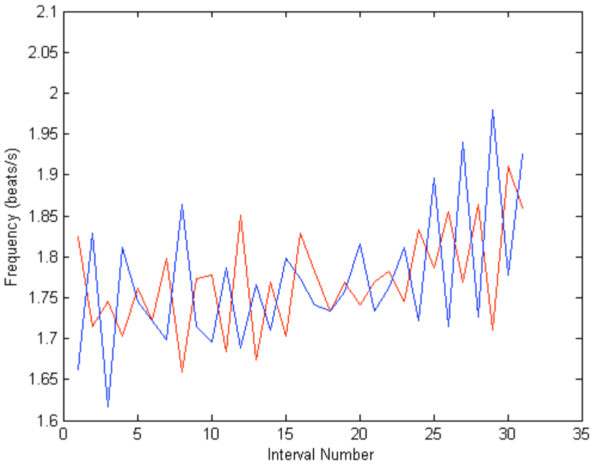
IV. DISCUSSION

The coupled oscillator model demonstrated that joint tapping dynamics depend on four coupling constants (phase and frequency for each oscillator), and are highly sensitive to noise. The model was able to qualitatively capture the dynamics of each condition of interaction by varying the degrees of phase and frequency coupling. Further characterization of phase response curves and coupling parameters is required to understand the implications of this.

The experimental data suggests that dyads attempted to lock in phase with the other in the interactive condition, thereby correcting their tapping onsets in opposite directions. This behaviour did not change over the course of the trials and appeared to be characteristic of the joint condition. This shows that the subjects were continuously adapting to each other's behaviour. Further analysis is still required to quantify this behaviour, such as cross-correlations of the ITIs.

In future research and analysis we would like to address the directionality of interaction to determine whether there are inherent leaders and followers. We also plan to study the neural processes that underlie this behaviour in an EEG version of this experiment.

a) Experimental Data



b) Model

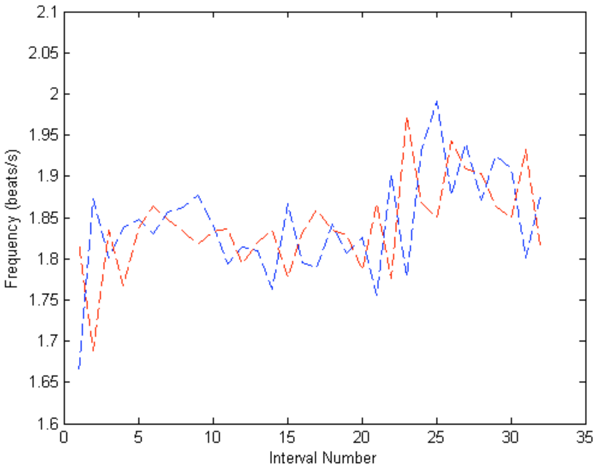


Figure 2. Model versus experimental data comparison of the interactive condition: a) Experimental Data and b) Model.

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