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Nonlinear modelling of polyrhythmic hand movements

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Abstract: An experiment on bimanual hand movements is studied. Data are analyzed by means of a symbolic transformation. It is found that there exist changes in the strategy of the performance of a polyrhythm when the speed of performance (the external control parameter) is varied. This leads to the conclusion that the relevant underlying mechanisms are nonlinear. Based on plausible assumptions a phenomenological model with a simple nonlinear correction mechanism is proposed. It is in qualitative agreement with the experimental data.

INTRODUCTION

The ability of a person to perform precise motor tasks reflects his functional state and level of training. Therefore, studies of complex movements give insight in the functionality of the central nervous system. A very interesting question is how coordinated movements are controlled by the human brain [1]. In the following we will investigate bimanual polyrhythmic movements as an example. Polyrhythms are ideally suited for studying bimanual coordination, because their performance leads to strong interactions between both hands.

EXPERIMENT

In the experiment subjects had to perform a so called 3:4 polyrhythm (see Fig. 1). It was played on an electronic piano with a weighted keyboard mechanic hooked to a computer which monitored the experiment and recorded time-stamped data with a resolution of 1 ms. Fourteen different metronome tempos ranging from 800 ms per cycle to 8200 ms per cycle were tested in a randomized order. In each trial, subjects listened to the exact rhythm generated by the computer as long as they wanted, and then played along (synchronize) with the beat for four cycles after which the computer beat stopped; participants then continued for another 12 cycles during which the time series were recorded. A single time series consists of 12 cycles. The recorded data are the intervals between successive keystrokes produced by both hands, which gives 36 values for the left hand (L_1^1, L_2^1, L_3^1, L_1^2, …, L_2^{12}, L_3^{12}) and 48 values for the right hand (R_1^1, R_2^1, R_3^1, R_4^1, R_1^2, …, R_3^{12}, R_4^{12}). Details about the experiment and the data can be found in [2].

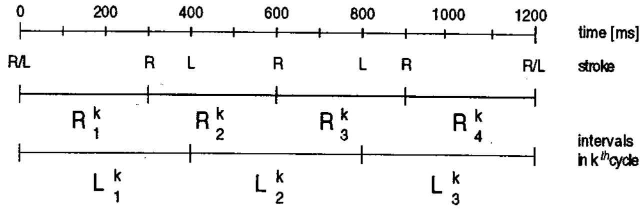

Figure 1: Schematic illustration of the 3:4 polyrhythmic task for a cycle duration of 1200 ms. "R" and "L" in the top panel denote the strokes with right and left index fingers, respectively. Each cycle starts with simultaneous strokes of the two hands. Three isochronous intervals, i.e. equidistant strokes in time, in the left hand (bottom panel) are performed against four isochronous intervals in the right hand (middle panel) within each cycle. The position of intervals within a certain cycle k is indicated by sub-indices.

DATA ANALYSIS

The procedure to analyze the data consists of two steps. Firstly, the recorded time series are transformed to a series of relative deviations in order to fulfill the requirement of stationarity to a sufficiently good approximation. Then a symbolic transformation as a powerful visualization technique is applied. The symbol sequences are also the basis for a quantitative evaluation of the performance by applying measures of complexity [3].

In the following the symbolic transformation procedure is briefly described. If a produced interval played by the right or left hand is shorter than the prescribed proportion of the actual cycle duration, we associate a '0' (black square), otherwise a '1' (white square). Using this coding scheme perfect performance results in a completely random pattern. In this case the relative deviations are randomly distributed around zero with small variance. Therefore, any type of order in Fig. 2 indicates a systematic deviation from the prescribed rhythm. Interesting transition phenomena, e.g. the one between $T = 1400$ ms and 2000 ms (approx. trial 90) in the left hand of Fig. 2, can be found for all subjects who were tested. This kind of phase transitions give strong evidence for nonlinear mechanisms in the underlying control system.

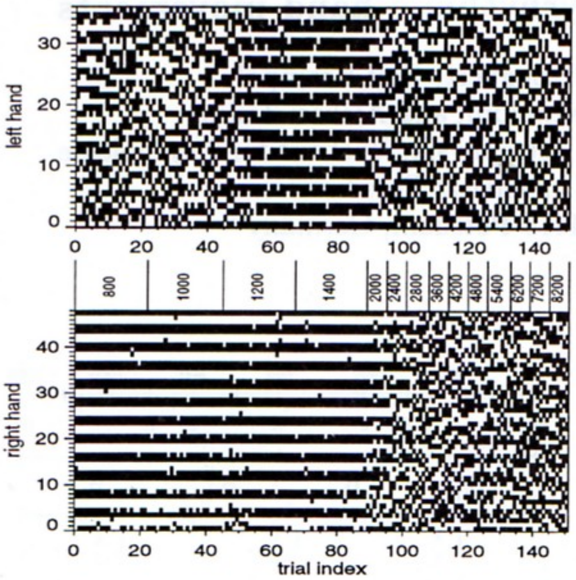

Figure 2: Symbol sequences of all trials of one subject. The time is increasing on the ordinate, where 36 symbols are plotted for left hand time series and 48 symbols for the right hand. The cycle durations are indicated by the vertical labels between the plots.

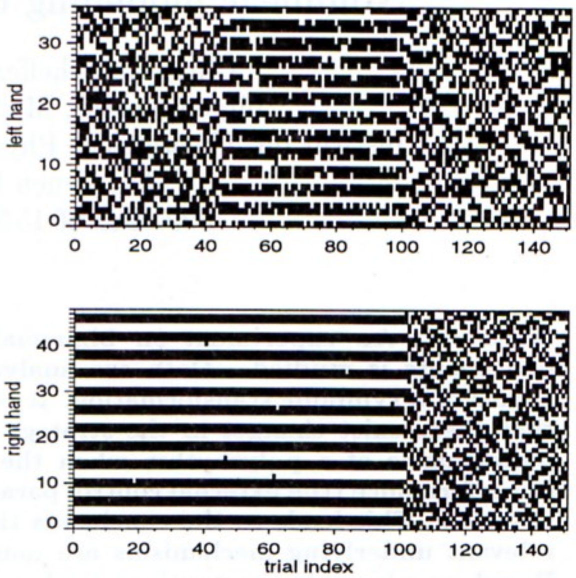

Figure 3: Result of a numerical simulation. Under proper variation of the speed dependent nonlinearity parameters k^l and k^r, the symbolic transformations of numerical and experimental data show close similarity.

MODELLING

In the following we present a dynamical model for the 3:4 polyrhythm production. The discrete time model describing the produced interval lengths is given in Eq. (1). The essential features are a nonlinear mechanism correcting deviations of the ideal speed and coupling between the hands.

$$\begin{aligned} y_{i+1}^{l,r} = \frac{\delta}{N^{l,r}} - \Delta^{l,r}(i)\, k^{l,r} \tanh(x_{i-m}^{l,r} - \frac{\delta}{N^{l,r}}) \\ - \Theta^{l,r}(i)\, k^{l,r} \tanh(\tilde{\delta}^{l,r} - \tilde{\delta}^{r,l}) \end{aligned} \quad (1)$$

with $x_i^{l,r} = y_i^{l,r} + \xi_i^{l,r}$ and $\tilde{\delta}^{l,r} = \sum_{j=0}^{N^{l,r}-2} y_{i-j} + \delta^{l,r}$. δ is the prescribed cycle length and $N^{l,r}$ are 3 and 4 respectively, corresponding to the polyrhythm investigated. $\xi_i^{l,r}$ is an uncorrelated, uniformly distributed noise term, which approximates fluctuations. The term $\Delta^{r,l}(i) = 1$, if $(i+1) \bmod N^{l,r} \neq 0$, 0 otherwise, describes the within-cycle correction, whereas $\Theta^{r,l}(i) = 1$, if $(i+1) \bmod N^{l,r} = 0$, 0 otherwise, describes the coupling between the two hands and a correction mechanism on a cycle basis. Only one mechanism is active in each time step. At the end of each cycle the coupling is switched on, whereas between the simultaneous strokes the coupling is switched off and the in-hand correction mechanism is switched on. This switching mechanism is described by the two functions $\Delta^{r,l}(i)$ and $\Theta^{r,l}(i)$. Under variation of the nonlinearity parameters $k^{l,r}$ the dynamical behaviour of the model changes which is demonstrated in Fig. 3.

CONCLUSION

We have found phase transitions in data of bimanual polyrhythm production. Based on plausible assumptions about a possible control mechanism a time discrete model for rhythm production is proposed. Numerical simulations show qualitative agreement between model and experimental data. One may conclude that human motor control mechanisms are nonlinear, at least in a certain parameter range.

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