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Predicting the biological variability of environmental rhythms: Weak or strong anticipation for sensorimotor synchronization?

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ABSTRACT

The internal processes involved in synchronizing our movements with environmental stimuli have traditionally been addressed using regular metronomic sequences. Regarding real-life environments, however, biological rhythms are known to have intrinsic variability, ubiquitously characterized as fractal long-range correlations. In our research we thus investigate to what extent the synchronization processes drawn from regular metronome paradigms can be generalized to other (biologically) variable rhythms. Participants performed synchronized finger tapping under five conditions of long-range and/or short-range correlated, randomly variable, and regular auditory sequences. Combining experimental data analysis and numerical simulation, we found that synchronizing with biologically variable rhythms involves the same internal processes as with other variable rhythms (whether totally random or comprising lawful regularities), but different from those involved with a regular metronome. This challenges both the generalizability of conclusions drawn from regular-metronome paradigms, and recent research assuming that biologically variable rhythms may trigger specific *strong anticipatory* processes to achieve synchronization.

1. Introduction

Synchronizing our movements with environmental rhythms such as a partner's walking cadence is part of our everyday sensorimotor behavior. Among the most striking examples may be our spontaneous tendency to move on the beat of music, observed since the earliest months of life (Zentner & Eerola, 2010). The sensorimotor synchronization paradigm has traditionally investigated the neuropsychological processes involved in synchronizing simple rhythmic movements, such as finger tapping, with basically regular (isochronous) auditory metronomes (Repp, 2005). Despite notable pushes towards studying synchronization with non-isochronous sequences including musical pieces (*e.g.*, Rankin, Large, & Fink, 2009; Repp, 2002), local tempo changes (*e.g.*, Schulze, Cordes, & Vorberg, 2005), and virtual adaptive partner's movements (*e.g.*, Repp & Keller, 2008), the main focus on regular metronomic sequences however contrasts with the typically variable rhythms contained in environmental stimuli. Especially, it is widely acknowledged that rhythms generated by natural bio-behavioral systems exhibit a characteristic structure of fluctuations over time, namely *long-range correlation*, or *fractal* fluctuations (*e.g.*, Bullmore et al., 2009; Gilden, 2009; Kello et al., 2010; Markowitz, Ivie, Kligler, & Gardner, 2013; West & Schlesinger, 1989). Research has shown that the human perceptual-motor system is sensitive to the temporal structure of biologically variable stimuli (Wark, Lundstrom, & Fairhall, 2007), and synchronizing with fractal signals has recently been assumed to involve a very specific synchronization process, namely *Strong Anticipation* (Marmelat & Delignières, 2012; Stephen, Stepp, Dixon, & Turvey, 2008; Stepp & Turvey, 2010).

The strong anticipation hypothesis has been formulated in contrast to more classical conceptions of *weak* anticipatory processes (Dubois, 2003), involving internal models for short-term prediction and correction of the periods and/or asynchronies produced to achieve synchronization (*e.g.*, Madison & Delignières, 2009; Mates, 1994a, 1994b; Semjen, Schulze, & Vorberg, 2000; Thaut, Miller, & Schauer, 1998; Vorberg & Schulze, 2002; Vorberg & Wing, 1996; for a review see Repp, 2005; Repp & Su, 2013). In contrast to such local adaptations, strong anticipation is assumed to involve a global tuning of behavior to the statistical properties of environmental fluctuations. This attunement relies on the existence of lawful regularities in environmental fluctuations, hence the role of long-range correlations in the stimuli presented. In this way, the temporal structure of environmental stimuli determines the structure of behavior, leading to the matching of environmental and behavioral fluctuation structures (Stephen et al., 2008).

The Strong Anticipation framework thus questions the generalizability of results from classical synchronization paradigms to ecological, *i.e.* fractal – or long-range correlated – conditions. In

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particular it raises the following issues: First, are synchronization processes to be differentiated between long-range correlated stimuli and other variable/regular stimuli, or between any kind of variable (including long-range correlated) stimuli and regular stimuli? Second, to what extent can alternative models, based on local short-term adaptations, account for the matching of fluctuation structures attributed to strong anticipation? These issues have potentially important implications for optimizing human/artificial-environment interaction, like the use of rhythmic auditory stimulation for gait rehabilitation in Parkinson's patients (*e.g.*, Hove, Suzuki, Uchitomi, Orimo, & Miyake, 2012).

To answer these issues we used a synchronized finger tapping paradigm under five different conditions of variable (long-range and/or short-range correlated, uncorrelated) and regular metronomes. In view of the above mentioned elements we formulated the following working hypotheses:

1. Strong anticipation should only be involved in conditions where inter-stimuli intervals comprise long-range correlations, and be unaffected by the presence of other forms of lawful regularities.
2. The matching of behavioral and environmental structures of fluctuations should be observed only in conditions where inter-stimuli intervals comprise long-range correlations.
3. The structure matching should not be accounted for by simple models implementing local short-term synchronization processes.

2. Methods

2.1. Participants and device

Eleven young adults (9 males and 2 females; mean age 30.2 years, ±8) volunteered to participate. Nine declared themselves right-handed, and two left-handed. They had no extensive practice in music, and none of them declared neurological or recent upper-limb injury which might affect finger tapping performance. Informed consent was obtained from participants, and the study protocol was approved by the local institutional review board (Montpellier-1 University).

Participants were seated comfortably with their dominant-side forearm, hand palm and fingers resting on a table so that only the index finger moved. Finger taps were performed on a flat rectangular (4 cm × 4 cm × 2 mm) pressure sensor, in synchronization with PC-driven sequences of auditory metronomes implemented in the *Matlab Psychtoolbox*. Pressure data and auditory signals were recorded using *LabJack U12* device (sampling frequency 300 Hz).

2.2. Auditory sequences, task and procedure

The experiment included a single session comprising five experimental conditions assigned in random order. Conditions differed only in the structure of fluctuations of the metronome inter-onset intervals (IOI) presented: (1) LRC condition: IOI series exhibited persistent Long-Range Correlations. Lag 1 autocorrelation was 0.6, and the autocorrelation function showed the typical asymptotic power-law decay over increasing lags, meaning that statistical memory between IOI persisted even for a large number of intervening IOI (Beran, 1994). (2) SRC condition: IOI series exhibited positive Short-Range Correlations generated by a first-order autoregressive process. Lag 1 autocorrelation was 0.6, and the autocorrelation function showed a rapid exponential decay, meaning that statistical memory between IOI extinguished within a few intervening IOI. (3) WN condition: IOI series were random. (4) CONTRA condition: IOI series exhibited a contradictory combination of negative short-range correlations, generated by a first-order autoregressive process, and positive correlations persisting over the long range. (5) REGULAR condition: Successive IOI were isochronous.

For each condition, a pool of 50 series with similar statistical properties was generated before the experiment using the ARFIMA (Auto-Regressive, Fractionally Integrated, Moving Average) modeling method (*fracdiff* software package in R). The method allows for simulation, estimation and forecasting of mixed short-term and long-term memory series. The mean of IOI series was 800 ms for all conditions, and chosen so as to fall within the most comfortable frequencies for finger tapping (*e.g.*, Gilden, Thornton, & Mallon, 1995). The coefficient of variation of IOI series was set at 6% for all variable metronome conditions, corresponding to the natural coefficient of variation of self-paced tapping performance (*e.g.*, Torre & Delignières, 2008a). Table 1 summarizes the statistical properties of IOI series generated for each experimental condition.

Trial duration was about 3 min 30 s, designed to record series of 262 taps and corresponding auditory signals. Participants were instructed to synchronize finger taps with the auditory signals (finger flexion on the beat) as accurately as possible over the whole trial.

2.3. Data analysis

Inter-tap intervals were defined as the time between two successive taps: $ITI_n = T_{n+1} - T_n$. Asynchronies were defined as the time interval between the performed tap and the corresponding metronome onset: $ASYN_n = T_n - O_n$, so that negative asynchronies mean that taps preceded the metronome onsets. To assess synchronization performance, a one-way repeated measures ANOVA 5(Conditions) was applied to mean and standard deviation of ASYN series.

For a quantitative and qualitative assessment of the structure of fluctuations over the short and long terms in IOI, ITI and ASYN series, we computed the autocorrelation functions from lag 1 to lag 15. For sake of homogeneity of analyses and proper comparison across experimental conditions, we limited ourselves to the assessment of autocorrelation functions. Indeed, classical fractal methods (*e.g.* Detrended Fluctuations Analysis, spectral analysis, etc.) would be of limited relevance for non-fractal series as in the present SRC or CONTRA conditions (*e.g.*, Wagenmakers, Farrell, & Ratcliff, 2004). To quantify the matching of the structures of fluctuations we assessed for each participant and each condition the correlation between the autocorrelation function of the IOI series and the autocorrelation function of the corresponding ITI series: First, the autocorrelation coefficients of IOI and ITI series were transformed into Fisher's z scores. Second, linear correlation was computed between the z-transformed autocorrelation coefficients of IOIs and corresponding ITIs.

In addition, cross-correlation analysis was performed to assess the interdependence of fluctuations in IOI and ITI series, from lag −10 to lag 0 (current ITI are correlated with previous IOI), and from lag 0 to lag +10 (current ITI are correlated with subsequent IOI). Significant cross-correlation at lag 0 would show that current ITI and IOI have similar lengths. Significant cross-correlation at negative lags would mean that ITI tend to reproduce the length of previous IOI, and inversely (see also Rankin et al., 2009; Repp, 2002).

3. Results

3.1. Synchronization performance

Fig. 1 displays an example of IOI and the corresponding ITI series produced in a single experimental trial. Participants showed similar synchronization performance in all variable and regular metronome conditions. In particular, results demonstrated the