Human Movement Science 62 (2018) 81–104

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Exploring complexity matching and asynchrony dynamics in synchronized and syncopated task performances

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ARTICLE INFO

Keywords:
Complexity matching
Fractal scaling
Syncopation
Interpersonal coordination
Finger tapping

ABSTRACT

When two people synchronize their rhythmic behaviors (e.g., finger tapping; walking) they match one another not only at a local scale of beat-to-beat intervals, but also at a global scale of the complex (fractal) patterns of variation in their interval series. This "complexity matching" had been demonstrated in a variety of timing behaviors, but the current study was designed to address two important gaps in previous research. First, very little was known about complexity matching outside of synchronization tasks. This was important because different modes are associated with differences in the strength of coordination and the fractal scaling of the task performance. Second, very little was known about the dynamics of the asynchrony series. This was important because asynchrony is a variable directly quantifying the coordination between the two timing behaviors and the task goal. So, the current study explored complexity matching in both synchronized and syncopated finger tapping tasks, and included analyses of the fractal scaling of the asynchrony series. Participants completed an interpersonal finger tapping task, in both synchronization and syncopation conditions. The magnitude of variation and the exact power law scaling of the tapping intervals were manipulated by having one participant tap in time with a metronome. Complexity matching was most stable when there was sufficient variation in the task behavior and when a persistent scaling dynamic was presented. There were, however, several interesting differences between the two coordination modes, in terms of the heterogeneity of the complexity matching effect and the scaling of the asynchronies. These findings raised a number of important points concerning how to approach and understand the interaction of inherently complex systems.

1. Introduction

Whether the question is how the nervous system regulates behavior within a changing environment, how a child learns to speak from engaging with her parents, or how a stigmatized person addresses his difficulties within society, human behavior inherently involves the interaction of complex, dynamical systems. These interactions involve patterns of co-regulation and co-evolution, making it difficult to understand these systems outside the context of their interactions with one another. For instance, the child's pattern of speaking changes with linguistic feedback from her parents, but her parents' patterns of feedback also change according to the patterns in her developing speech (Kavanaugh & Jirkovsky, 1982). So, there is a need to better understand the basic principles underlying these kind of multiscale, interdependent relationships between systems. One avenue of research that offers some insight

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https://doi.org/10.1016/j.humov.2018.09.006
Received 18 September 2017; Received in revised form 8 September 2018; Accepted 10 September 2018
0167-9457/

into this issue involves how interacting people tend to match one another's complex patterns of variation in task performance.

Research has demonstrated that many different kinds of human performances display fractal scaling (Bassingthwaighte, Liebovitch, & West, 1994; Diniz et al., 2011; Van Orden, Kloos, & Wallot, 2009). That is, the pattern of variation across many performances of a task is not random, but instead obeys a power-law scaling relationship, such that small fluctuations in performance show the same basic pattern as large fluctuations (Eke et al., 2000; Holden, 2005). For instance, when someone rhythmically taps their finger, some taps fall below the average tapping interval and some fall above. Importantly, the *pattern of deviations* shows coherent trends in which the participant speeds up for a short while, and then slows down again. More importantly, these trends obey a fractal pattern, sometimes called "1/*f*" or "pink" noise, where the relationship between the size of the deviation and how many taps are involved in that trend is the same across all scales. These kind of fractal scaling relationships are characteristic of natural systems (Mandelbrot, 1983; West & Deering, 1995), and many studies have shown fractal scaling in a variety of human physiological and behavioral signals (e.g., Linkenkaer-Hansen, Nikouline, Palva, & Ilmoniemi, 2001; Schenkel, Zhang, & Zhang, 1993; Van Orden, Holden, & Turvey, 2003; 2005). Although there is debate concerning the origin and meaning of fractal scaling (see Diniz et al., 2011; Van Orden et al., 2009), finding pink noise in a behavior has generally become accepted as a signature of system complexity (Diniz et al., 2011).

More recent research has shown that the degree of fractal scaling in a behavior also tends to be closely matched to the scaling in the behavior of coupled systems (Delignières & Marmelat, 2014; Fine, Likens, Amazeen, & Amazeen, 2015; Hennig, 2014; Stephen, Stepp, Dixon, & Turvey, 2008). This "complexity matching" is typically assessed by correlating the fractal scaling exponents between interacting systems. That is, the degree of fractal scaling can be quantified by certain time series analyses, which yield a scaling exponent (α). A time series of task performances (e.g., inter-tap intervals) are said to show fractal scaling when the scaling exponent is near $\alpha = 1$, and are said to show a random pattern when the exponent is near $\alpha = 0$. So, the bivariate correlation of scaling exponents can show that the degree of fractal scaling of one system is dependent on that of another, with greater correlations indicating stronger complexity matching between the interacting systems. Complexity matching has been observed in several kinds of simplified laboratory tasks, such as participants tapping their fingers in time with chaotic metronomes (Stephen et al., 2008) or two participants swinging pendulums in time with one another (Marmelat & Delignières, 2012). Importantly, research also suggests that similar phenomena are present in more naturalistic and complicated forms of behavior. This includes rhythmic behaviors similar to the laboratory tasks (e.g., team rowing; Den Hartigh, Marmelat, & Cox, 2018) and non-rhythmic behaviors, such as the actions of two partners interacting in a virtual reality task (Zapata-Fonseca, Dotov, Fossion, & Froese, 2016). Complexity matching, and more broadly multiscale coordination, has also been demonstrated in the bodily movements of two people interacting verbally (Schmidt, Nie, Franco, & Richardson, 2014), as well as in the timing (Abney, Paxton, Dale, & Kello, 2014) and syntactic complexity (Xu & Reitter, 2016) of the speech itself. In fact, research supports that complexity matching might play a critical role in the kind of language development processes in the example above (Abney, Warlaumont, Oller, Wallot, & Kello, 2017).

One of the central questions in this field of research regards the nature of coordination underlying the complexity matching effect. Paralleling the debates about fractal scaling in human behavior more broadly (Diniz et al., 2011), some researchers proposed that complexity matching reflects a more general property of system interdependence, while others argued for localizable, mechanistic dynamics. Several of early studies supported that complexity matching resulted from a "global" coordinative process (e.g., Marmelat & Delignières, 2012; Stephen et al., 2008). These studies found that although there was a strong correlation between the scaling exponents defining the two interval time series, there was considerably weaker correlation between the time series themselves, on a beat-to-beat basis. That is, one system's behavior at any particular time did not strongly predict the other system's behavior at that time, but the overall structure of one system's behavior, across all timescales, was strongly predictive of the other system's overall structure. These findings lead some researchers to consider some "global" coordinative process that operated across many timescales, without producing any strong "local" coordination.

Other researchers have argued that a local, or "short-term", coordinative process is sufficient to create complexity matching (Hennig, 2014; Konvalinka, Vuust, Roepstorff, & Frith, 2010). For instance, Torre, Varlet, and Marmelat (2013) demonstrated that a mechanistic model, based exclusively on a short-term error-correction process, could produce both the strong complexity matching and the relatively weak cross-correlation between series. Similarly, Coey, Washburn, Hassebrock and Richardson (2016) demonstrated that although the cross-correlation between series was relatively weak overall, the strength of the peak cross-correlation was significantly related to the strength of the complexity matching observed.

One way to better understand the coordination involved in complexity matching is to explore experimental manipulations, which are known to affect coordination dynamics generally, but have yet to be implemented in complexity matching research. Notably, the existing literature was almost exclusively focused on synchronization tasks (but see Abney et al., 2014, Coey et al., 2016). This was an important limitation because different modes of coordination can be more or less stable. Ample research has shown that synchronized (or inphase) modes are more stable than syncopated (or antiphase) modes of coordination (see Repp, 2005; Schmidt & Richardson, 2008; for reviews). The difference in stability between these modes can be demonstrated by increasing the movement frequency. When in the syncopated mode, increasing movement frequency past a critical value produces a spontaneous transition to the synchronized mode, in both continuous and discrete timing tasks (e.g., Schmidt & Turvey, 1994; Volman & Geuze, 2000). The opposite transition, from synchronization to syncopation does not occur spontaneously, even when the frequency is decreased to a point where stable syncopated, antiphase behavior is possible (Haken, Kelso, & Bunz, 1985). So, as a manipulation of the strength of coordination, comparing syncopation to synchronization might help clarify the coordinative dynamics underlying complexity matching. This specific manipulation complements an earlier complex matching study (Marmelat & Delignières, 2012), which manipulated the strength of the coordination within a synchronization task by varying the perceptual coupling between participants. It also