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Original article

Multi-scale interactions in interpersonal coordination

Tehran J. Davis *, Thomas R. Brooks, James A. Dixon

Center for the Ecological Study of Perception and Action and Department of Psychological Sciences, University of Connecticut, Storrs, CT 06260-1020, USA

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Abstract

Background: Interpersonal coordination is an essential aspect of daily life, and crucial to performance in cooperative and competitive team sports. While empirical research has investigated interpersonal coordination using a wide variety of analytical tools and frameworks, to date very few studies have employed multifractal techniques to study the nature of interpersonal coordination across multiple spatiotemporal scales. In the present study we address this gap.
Methods: We investigated the dynamics of a simple dyadic interpersonal coordination task where each participant manually controlled a virtual object in relation to that of his or her partner. We tested whether the resulting hand-movement time series exhibits multi-scale properties and whether those properties are associated with successful performance.
Results: Using the formalism of multifractals, we show that the performance on the coordination task is strongly multi-scale, and that the multi-scale properties appear to arise from interaction-dominant dynamics. Further, we find that the measure of across-scale interactions, multifractal spectrum width, predicts successful performance at the level of the dyad.
Conclusion: The results are discussed with respect to the implications of multifractals and interaction-dominance for understanding control in an interpersonal context.

Keywords: Component-dominant dynamics; Interaction-dominant dynamics; Interpersonal coordination; Multifractal; Time series analysis

1. Introduction

To be successful in sports, players must coordinate their actions with others across many different spatial and temporal scales. For example, soccer teammates on an offensive attack must coordinate their more immediate movements in order to complete a pass, while on a longer scale adjust their position and heading to create opportunities to score a goal. On the other side of the coin, defenders must anticipate and match the offense's strikes and movements, while at the same time making subtle adjustments to steer their opponents to unfavorable positions, thereby reducing the threat of a score. While these cooperation and competition dynamics play out most dramatically in sports, they are present in even the most common of human actions. Indeed, many actions in our work, leisure, and play are similarly best understood as dynamic interactions with others.

An especially fruitful framework for addressing interpersonal or multi-agent coordination of this sort has employed tools and concepts from dynamical systems theory (DST). DST approaches focus on modeling how co-actors may become coupled when performing a shared task—from small-scale interpersonal interactions as when two people rhythmically coordinate their limb movements,[1–4] to the types of large-scale coordination dynamics that are present in an attacking side of football players.[5] Much of this research has appealed to principles of self-organization to explain how multiple interacting agents may become functionally coordinated without a need for a centralized controller—a significant issue when "control" is spread out among different actors—and how patterns of coordination may spontaneously re-organize to meet changing task demands for both individuals and collectives.

To this end, recent studies have focused on the interpersonal coordination of limb movements when two people engage in a joint supra-postural manual task, one that demands a high degree of manual precision and postural alignment (such as when mutually handling or passing an object). For example, Ramenzoni and colleagues[6] asked pairs of co-actors to perform an aiming task where one held a pointer (small rod) inside the bounds of a target ring held by the other. Participants stood facing one another, arms outstretched, and were instructed to

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* Corresponding author.
E-mail address: tehran.davis@uconn.edu (T.J. Davis).

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never allow the objects to come in physical contact with one another. The difficulty of the task was manipulated by varying the size of the ring. Increasing task difficulty (trials with a smaller diameter ring) resulted in increases in interpersonal coordination of hand and postural adjustments, as measured by the number and duration of shared configurations between the two actors. In a follow-up experiment, an additional manipulation was used to challenge the postural stability of each actor. Participants stood either with their feet apart (as before) or with their feet in a tandem stance that reduced postural stability, thereby making the supra-postural aiming task more demanding. This additional task demand resulted in a reorganization of intra-personal coordination at the individual level (between the hand and postural alignments of each individual actor) to preserve the necessary interpersonal coordination required to meet the task. Similar patterns of coordination emerge even in instances where information about the movements of co-actors is limited, and one cannot see their co-actor, but only the movement of the object they are manipulating;[7] suggesting that the emergent coordination may be closely tied to the detection of information related to the task demands rather than an incidental product of visual entrainment.[8]

These studies demonstrate how a nested hierarchy of synergistic intra-personal and inter-personal activity may emerge to meet and adapt to the evolving joint task demands. However, several important questions are left open. First, and perhaps more obviously, we may ask what role (if any) do the individual task demands have on each actor's relative contribution to achieving the shared goal? For example, in the aforementioned studies the manual (holding ring, holding pointer) or postural (feet apart, feet tandem) demands of the alignment task were different for each actor. As is often the case in cooperative action, co-actors may have adopted complementary roles influenced by their individual constraints in order to meet this shared goal.[9,10] For example, using a similar paradigm, Nguyen et al.[11] recently demonstrated that coordination between co-actors' hand movements systematically exhibit a leader–follower dynamic when facing different postural demands (where the person in the stable stance "leads"), indicating that co-actors in this task may spontaneously (without explicit direction) transition into distinct roles provided by their individual constraints.

Second, interpersonal coordination involves the combined activity of multiple agents across multiple, nested spatiotemporal scales—a pass between teammates is nested within an evolving attack and a volley in tennis is one part of an extended rally. A better understanding of interpersonal coordination requires that we are able to capture the nested structure of coordination across these multiple scales. However, it is often the case that analyses of interpersonal coordination dynamics focus on a single scale, or address the nested structure of coordination in a piecemeal fashion, one scale at a time. While relationships between patterns of short- and long-term activity have been often explored within single actors, only recently has research begun to directly address multi-scale coordination in joint tasks.[12–15]

In the present study, we address these issues using the interpersonal supra-postural manual task paradigm and characterizing the coordination between actors with a complementary form of analysis that has been explicitly designed to address the possibility of multiply nested, contingent structures: multifractal analysis. A number of accessible tutorials on multifractal methods are available, so we do not present another tutorial here.[16,17] Rather, we first introduce some basic concepts and related measures from multifractal analysis. Then, we present a short description of multifractal detrended fluctuation analysis (MFDFA),[18] the multifractal method we employ here. Finally, we show how these measures may be profitably applied to the study of relatively complex, joint action, such as the interpersonal supra-postural manual task. Specifically, we test: a) whether the hand-motion time series were multifractals; b) if that multifractal structure was indeed indicative of interactions across scales; and c) whether the multifractal index of across-scale interactions, multifractal spectrum width, predicts performance in the dyadic task.

1.1. A brief introduction to multifractal analysis

Multifractal analysis provides a method for quantifying complex distributions that have non-uniform properties across (usually spatial or temporal) scales.[19,20] A natural starting place for understanding multifractals is to contrast them with mono-fractals (also, just called fractals). Mono-fractals can be considered a special case of multifractals in which a single power-law is sufficient to describe the relationship between the measured quantity (e.g., movement) and the dimension (e.g., time), where a power-law is a particular type of one-parameter model expressing a non-linear function. Fig. 1A and B shows a canonical example, diffusion of a particle in a heterogeneous medium,[21] which follows the power-law relationship $x^2 \sim t^{\alpha}$, where x^2 is the mean squared displacement, t is time, and α is the power-law exponent ($\alpha = 1.4$, in our current example). The

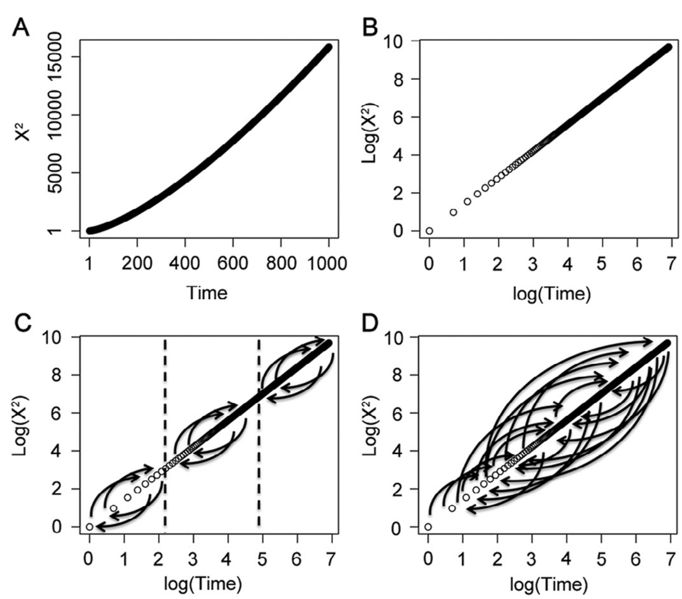

Fig. 1. A and B show a canonical power-law relationship between average displacement, X^2, and time, using natural (A) and double-log (B) plots. C and D show schematically how effects might be distributed under component-dominant (C) and interaction-dominant (D) dynamics.