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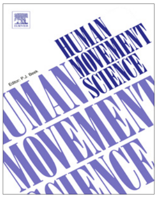

Multifractal formalisms of human behavior

Espen A.F. Ihlen [a,*], Beatrix Vereijken [b]

[a] Department of Neuroscience, Norwegian University of Science and Technology, Trondheim, Norway
[b] Department of Human Movement Science, Norwegian University of Science and Technology, Trondheim, Norway

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ABSTRACT

With the mounting realization that variability is an inevitable part of human behavior comes the need to integrate this phenomenon in concomitant models and theories of motor control. Among other things, this has resulted in a debate throughout the last decades about the origin of variability in behavior, the outcome of which has important implications for motor control theories. To date, a monofractal formalism of variability has been used as the basis for arguing for component- versus interaction-oriented theories of motor control. However, monofractal formalism alone cannot decide between the opposing sides of the debate. The present theoretical overview introduces multifractal formalisms as a necessary extension of the conventional monofractal formalism. In multifractal formalisms, the scale invariance of behavior is numerically defined as a spectrum of scaling exponents, rather than a single average exponent as in the monofractal formalism. Several methods to estimate the multifractal spectrum of scaling exponents – all within two multifractal formalisms called *large deviation* and *Legendre formalism* – are introduced and briefly discussed. Furthermore, the multifractal analyses within these two formalisms are applied to several performance tasks to illustrate how explanations of motor control vary with the methods used. The main section of the theoretical overview discusses the implications of multifractal extensions of the component- and interaction-oriented models for existing theories of motor control.

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* Corresponding author. Address: Department of Neuroscience, Norwegian University of Science and Technology, N-7489 Trondheim, Norway.

E-mail address: espen.ihlen@ntnu.no (E.A.F. Ihlen).

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1. Introduction

Variability in the temporal dynamics of a multitude of phenomena in psychology, biology, and human movement science has gained considerable interest during the last decades (e.g., Astumian, 1997; Goldberger, 1996; Howard, 1997; Kelso, 1995; Turvey, 2007). Variability seems omnipresent across behavioral patterns and across experimental setups, but how to account for variability in motor control theories, particularly the origins of variability, is still heavily debated. Component-oriented theories consider variability as a result from specific sources and underlying mechanisms of the motor control system. These sources and mechanisms are considered to be specific for both the movement pattern and the environmental context in which the movement appears. In contrast, interaction-oriented theories consider variability to be evidence of a self-organized and meta-stable motor control system that is common across all movement patterns and environmental contexts.

Several methodological frameworks within time series analyses have been developed to provide numerical evidence for the component- and interaction-oriented theories. One of the most frequently employed methods is the numerical identification of fractal variation in performance variables (e.g., Gilden, 2001; Goldberger, 1996; Hausdorff et al., 1996; Torre & Wagenmakers, 2009; Van Orden, Holden, & Turvey, 2003). Formally, a performance variable is considered to be *fractal* and *scale invariant* when its spectral density S_f satisfies a power law relation $S_f \sim 1/f^{\zeta}$. The fast variations in the performance variable over a few data samples are represented as oscillations with high frequencies f and the slow variations over hundreds or even thousands of data samples are represented as low frequencies f. The particular kind of scale invariance is defined by the spectral exponent $\zeta = 2H - 1$ or by the related Hurst exponent H (Hurst, 1951; Mandelbrot & Van Ness, 1968). Both the component- and the interaction-oriented theories of motor control try to explain the origin of the omnipresent $1/f^{\zeta}$ fluctuations in biological systems in general and human movement in particular (cf. Diniz et al., 2011).

Almost every study that investigates the presence of $1/f^{\zeta}$ fluctuations in human movement and behavior, assumes that the scale-invariant structure of variability can be described by the monofractal formalism where a single scaling exponent ζ or H summarizes the fractal structure of the performance variable. However, these exponents can vary in time just like the performance variable themselves, reflecting a temporal evolution in the scale-invariant structure of the performance variable. Structural changes in performance variables have been suggested as central tenets in motor control theories, for example phase shifts in bimanual coordination reflected in abrupt changes in the magnitude of variability and critical slowing down (Kelso, 1995). Furthermore, structural changes in performance variables can also be generated by multiplicative interactions between temporal scales, which is the main concept in interaction-oriented theories of motor control (cf. Ihlen & Vereijken, 2010). The variation of scale-invariant structures is numerically defined in multifractal formalisms by the entire spectrum of exponents. However, in contrast to the monofractal formalism, the application and interpretation of multifractal formalisms has received little attention outside the literature of mathematics and physics, and there is a general lack of information about how and why to apply multifractal analyses in the behavioral sciences. Nevertheless, recent studies indicate that the dynamics of stimulus–response intervals have multifractal fluctuations across a range of experimental contexts, indicating multiplicative interactions between temporal scales (Ihlen & Vereijken, 2010; Kuznetsov & Wallot, 2011; Stephen & Dixon, 2011). Furthermore, the multifractal spectrum has also been able to differentiate between healthy and pathological heart rate variability and between different pathologies not possible by single exponents or by other non-conventional analyses (e.g., Ivanov et al., 1999; Wang, Huang, Xie, Wang, & Hu, 2007). The multifractal formalism thus extends the monofractal formalism and has the potential to shed new light on the debate between component- and interaction-oriented theories of motor control. It is therefore opportune to illustrate how the multifractal formalism can be applied to the field of human behavior and discuss how its results can extend current theories of motor control.

The main aim of the present theoretical overview is to introduce the multifractal formalism to theories of variability in human behavior. The theoretical overview will discuss multifractal extensions of