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INTRODUCTION

Representational Models and Nonlinear Dynamics: Irreconcilable Approaches to Human Movement Timing and Coordination or Two Sides of the Same Coin? Introduction to the Special Issue on Movement Timing and Coordination

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For several years research on human movement timing and coordination has been dominated by two different frameworks, namely representational models on the one hand and dynamical systems theory on the other. Numerous publications in recent years reflect both frameworks' potentials to motivate original empirical research and to foster methodological progress. Unfortunately the progress that has undoubtedly been made occurred largely *within* frameworks. Until more recently few attempts have been made to develop complementary or even integrative perspectives. Therefore, it is not uncommon to find issues of *Journal of Experimental Psychology: Human Perception and Performance, Journal of Motor Behavior,* or *Brain and Cognition* where the tables of content promise articles on similar topics; closer reading reveals little overlap in theoretical perspective, methods used, or even the cited references.

This state of affairs partly stems from historical developments and limited exchange among disciplines. Timing research within experimental psychology gained much of its momentum from the two-level timing model proposed by Wing and Kristofferson (1973a, 1973b). The two-level conception refers to the distinction between a central, unitary clock or timer and temporal delays caused by a second level, peripheral motor implementation. The stochastic properties of central timing and peripheral motor components (notably the assumed independence of the two levels) allow the estimation of the variances contributed by each model component through linear methods. The empirical basis for this estimation are the covariances in the time series obtained from discrete intervals in repetitive tapping tasks. In its original form the two-level model is open-loop; that is, it has no feedback or error correction mechanism.

Its capability to explain critical empirical phenomena observed in simple tapping studies, its conceptual parsimony, and its mathematical elegance made the two-level

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timing model one key reference for the discussion of timing in simple as well as more complex tasks ever since. Several authors proposed models for the synchronization of tapping with a metronome that combine the two-levels concept with linear error correction mechanisms (Mates, 1994; Schulze, 1992; Schulze & Vorberg, 2001; Semjen, Vorberg, & Schulze, 1998; Vorberg & Wing, 1996). Extended versions of the two-level timing model (Vorberg & Hambuch, 1978, 1984) successfully accounted for timing performance in synchronized bimanual tapping or alternate tapping tasks (Semjen, 2001; Wing, Church, & Gentner, 1989). More recently, the notion of a single, central clock was challenged by studies illustrating variance reduction in synchronized, bimanual tapping (Helmuth & Ivry, 1996) or demonstrations of parallel, partly hand-independent timing in bimanual rhythm tasks (Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Pressing, Summers, & Magill, 1996). With respect to rhythmic timing, investigations of the covariance structures in time series obtained from rhythmic tasks revealed strong limitations of the original Wing–Kristofferson model. Based on these findings Vorberg and Hambuch (1978, 1984), proposed a different concept centered on the notion of timekeepers. The timekeeper concept maintains the idea of stochastic timing mechanisms operating at two independent levels and the modeling of covariances as a critical test of underlying control structures, but gives up the notion of a central, unitary clock as the single mechanism responsible for the observed timing behavior. Timekeepers are programmable, single-usage representations of interval durations that control time periods between successive events. More recently, Vorberg and Wing (1996) elaborated the timekeeper approach into a framework explicitly designed to account for rhythmic timing, the rhythm program hypothesis. This model assumes that higher-level representations of rhythmic patterns (namely rhythm programs) are transformed into executable timekeepers during performance by a hierarchical parameter specification process. So conceived, the rhythm program hypothesis combines the stochastic properties of the two-level model with a notion typical of cognitive models, the relevance of abstract mental representations.

The assumption of timing and coordination being under the control of abstract (although not necessarily conscious) mental representations is the most critical difference between representational models and models originating from dynamical systems theory. One important implication in representational models is that there exists a certain level of control at which it is irrelevant which effectors (muscles, joints, or tendants) ultimately implement (execute) the movement under consideration. It is this implication that dynamical models of timing and coordination take strong issue with. According to dynamical systems theory the critical observable phenomena in human timing and coordination must be viewed as properties emerging from nonlinear, oscillatory processes in the brain and the motor system and their interactions (Haken, 1996; Kelso, 1995; Kelso, Holt, Rubin, & Kugler, 1981; Turvey, 1990). Rather than assuming abstract representations, proponents of the dynamical systems approach focus on spontaneous pattern formation and self-organization (Haken, 1988; Kugler & Turvey, 1987; Schöner & Kelso, 1988). It is this black-box approach that has irritated cognitive psychologists. At the same time the reemphasis of motor processes attracted researchers in Movement Sciences and Motor Behavior to the dynamical systems framework. This historical development is best exemplified by a comparison of the articles collected in the original and the more recent editions of G. E. Stelmach's famous ‘‘Tutorials in Motor Behavior.’’

The research on human timing and coordination motivated from the dynamical systems perspective focuses on the stability and qualitative changes (phase transitions or bifurcations) during movement production and phenomena like coupling between limbs or the entrainment of oscillating systems with other internal or external signals. Within psychology and movement sciences, related research had its classics in two studies demonstrating tempo-induced phase transitions from anti-phase to in-phase movements in bimanual finger tapping (Yamanishi, Kawato, & Suzuki, 1979; Yamanishi, Kawato, & Suzuki, 1980) or finger wiggling tasks (Haken, Kelso, & Bunz, 1985). The observed qualitative changes in the coordination pattern of the hands cannot be explained by extant linear models; they were however, successfully accounted for by models of coupled, nonlinear oscillators. One critical variable in dynamical models is the control parameter (movement frequency in the above examples) that governs the momentary stability state and transitions to other states in a complex dynamical system. Experiments in the dynamical systems tradition typically apply induced variations in tempo during or introduce perturbations to stable systems. As an example, Peper, Beek, and van Wieringen (1995a) and Peper, Beek, and van Wieringen (1995b) had drummers produce a complex polyrhythmic pattern (3:8) while the auditory pacing signal increased its frequency. The authors found systematic transitions from more complex to increasingly simpler frequency ratios that could be accounted for by Farey–Tree principles characterizing their nonlinear oscillator model. Related phenomena are beyond the scope of linear models because their data analysis tools make relatively strong assumptions regarding the stationarity of time-series. At the same time, nonlinear models resist analytical solution (which is always possible for linear models) such that simulation or surrogate data approaches became important methodological tools in the dynamical systems tradition.

Linearity is not per se a constituent property of representational models. From a dynamical systems perspective linear models describe special, stable states within complex systems that typically have nonlinear properties. This is to say that nonlinear models assuming mental representations are perfectly feasible, as it is true of linear models that come without mental representations. Likewise representational models and dynamical system theory are not irreconcilable with respect to their preferred clock metaphors (i.e., stochastic timekeepers vs nonlinear oscillators). Any clock mechanism has to live up to the accumulated evidence for certain phenomena, like the negative lag-1 autocorrelation, the Weber-type increase of variance with interval duration, or the phase transitions in bimanual performance (see Gregor Schöner's discussion in this issue). From this perspective, extant models in both frameworks have some way to go. More recently there have indeed been attempts to reconcile stochastic properties of timekeeping with nonlinear error correction or coupling mechanisms (Beek, Peper, & Daffertshofer, this issue; Daffertshofer, 1998; Engbert, Krampe, Kurths, & Kliegl, this issue; Engbert et al., 1997; Turvey, Schmidt, & Rosenblum, 1989).

It seems fair to say that representational models have for too long abstracted from the critical contribution of processes and structures in the motor system in their explanations. At the same time it seems questionable whether physical reductionism will be successful in accounting for performance in tasks with explicit timing or coordination requirements that individuals manage to deliberately control, like in musical performance. At the level of much simpler tasks this point is elaborated in two recent articles by Semjen (this issue; Semjen & Ivry, 2001). At this stage a closer convergence of theoretical perspectives inherent to the two frameworks appears at least a promising route to models that have a broader explanatory scope.

The collection of articles in this special issue were authored by researchers who were critically involved in the investigation of timing and synchronization of repetitive movements, rhythm production, bimanual coordination, and the neuropsychology of timing. Initially the authors were brought together by a conference staged in Potsdam, Germany, in September 1999 (funded by Deutsche Forschungsgemeinschaft). In organizing that conference we deliberately invited researchers who represent either the representational or the dynamical systems framework for each of the above topics. Not surprisingly the talks at the conference elicited heated, controversial discussions about central theoretical tenets. At the same time it became evident that there was more common ground than previously thought and that there exist many open questions of mutual interest that require complementing methods of data analyses. In this spirit the attendants decided to transform the presentations of their own concepts and empirical findings into articles that explicitly address related research motivated by the other framework. All contributors made significant attempts to go beyond their own theoretical commitments and put the accumulating findings into a broader perspective, and pointed out directions for integrative approaches. The results of these efforts are the articles assembled in this special issue.

The articles in this special issue are grouped into four sections. The first section contains three articles that introduce and discuss representational and dynamical systems approaches at a conceptual level. Alan Wing argues for an information processing perspective on movement timing by linking findings from neuropsychological and neurophysiological studies to the two-level distinction into central timekeeping and peripheral motor implementation processes. Gregor Schöner gives a detailed introduction to the basic concepts and modeling approaches in the dynamical systems framework. In this context he also addresses the conceptual and formal requirements of the clock metaphor which is inherent in any model of timing. David Rosenbaum presents an extended version of his broadcast theory of timing that demonstrates that critical phenomena in human movement timing and rhythm production can be likewise explained by representational and dynamical systems models.

The second section combines articles that address the empirical study of sensorimotor synchronization during simple, repetitive movements. Gisa Aschersleben reviews evidence for the role of different feedback systems (i.e., auditory, tactile) that contribute to error correction and systematic distortions of asynchronies in tapping to a metronome. Her results highlight the necessity to consider the role of nerve conduction as well as strategic aspects in synchronization tapping. Hans-Henning Schulze and Dirk Vorberg describe linear models of phase correction in synchronized tapping. Using Monte-Carlo simulations they demonstrate that even apparently simple, linear models face serious problems of parameter identifiability and estimation. Mingzhou Ding, Yanqing Chen, and Scott Kelso describe the use of autocorrelation and spectral density functions to identify component ‘‘memory’’ processes in very long (10 min) tapping trials. Their approach amounts to using scaling exponents for these functions as a method to separate out task-specific processes. The approach proposed by Engbert, Krampe, Kurths, and Kliegl also involves longer time series from synchronization tapping tasks. They introduce the method of identifying unstable periodic orbits to test a model that combines a stochastic timekeeper component with nonlinear error correction.

The articles in the third section address bimanual timing tasks and rhythm production. Richard Ivry and Thomas Richardson propose a multiple timer model with a gating mechanism that can account for specific phenomena in bimanual tapping tasks that were outside the scope of the original central timer model. Andras Semjen compares timing performance in discrete and continuous tasks. He concludes that dynamical models are more tuned to the timing phenomena observed in continuous task performance. With regard to discrete tapping tasks, Semjen argues for the existence of timing goals, a concept that, in his view, speaks for the assumption of mental representations at some level. Peter Beek, Lieke Peper, and Andreas Daffertshofer discuss past extensions of the original Haken–Kelso–Bunz model (Haken et al., 1985) to bimanual and polyrhythmic tapping. To overcome some of the apparent limitations of these earlier models they propose a new two-level oscillator structure that may not only be viewed as the dynamical analog of the two-level timing model

(Wing & Kristofferson, 1973a), but also opens up the possibility of incorporating this and related timekeeper models within the dynamical systems approach. The article by Jeff Summers addresses the microgenesis of rhythmic skill, especially the changes in performance when participants encounter and adapt to the constraints inherent in multifrequency tapping. The adaptation to performance constraints in bimanual rhythm production is also the topic of the last article in this section. Ralf Krampe, Ralf Engbert, and Reinhold Kliegl propose to view observed interindividual differences in performance as the result of adaptive changes occurring in the course of aging or the long-term acquisition of high-level expertise.

The final section of this special issue consists of two articles that focus on the neural substrates of timing and perceptuo-motor coordination. Warren Meck and Aimee Benson describe how the frontal–striatal circuitry can implement the internal clock and also regulate the attentional aspects of time estimation and production. Chris Miall and G. Z. Reckess focus on the role of the cerebellum in coordinating the visual input in guiding the timing of hand movements during a continuous tracking task.

Many of the articles in this special issue point out directions for integrating or at least complementing the hitherto almost irreconcilable theoretical perspectives expressed in the dynamical systems view on the one hand, and representational approaches on the other. It is too early to tell whether such integrative attempts will provide the answers to those questions that none of the two frameworks has sufficiently addressed so far. However, we think that this collection of articles preserved some of the spirit of open-mindedness prevailing at the conference. We believe that this spirit has all the potential to motivate the necessary future research and collaborative efforts.

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