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The organization of action: Contemporary relevance of Turvey's approach to motor behavior

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ABBREVIATIONS

DFs	Degrees of freedom
HKB	Haken-Kelso-Bunz
ϕ	Relative phase
$\Delta\omega$	

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ABSTRACT
In this article, I will list the major contributions that Michael Turvey has made to the field of motor control from the perspective of my own research in the area. There are multiple research programs that I have carried out over the last twenty-five years that have all been influenced by the ecological and dynamical systems accounts that were pioneered by Michael Turvey. In this article I will highlight significant developments in 1) contribution of movement to timing and time perception 2) the contribution of the motor system in beat perception in music 3) postural sway dynamics 4) the role of detuning in bimanual coordination and finally 5) the control of unstable objects. In all these lines of work, I will specifically provide instances of how Michael Turvey's ideas inspired subsequent research in my lab and elsewhere.

KEYWORDS: Ecological psychology | Motor control | Dynamical systems

INTRODUCTION: THE TURVEY APPROACH

Michael Turvey (1942-2023) was a pioneer in ecological psychology and movement control. While he also made several significant contributions to research in cognition (memory, reading, and cognitive dynamics), I will focus on his work on motor control and learning in this article. I had the pleasure of working with Michael Turvey from 1995-2000 as a graduate student at the University of Connecticut. During this period, I was profoundly influenced by his quest for a representation-free motor control theory, one that promoted heterodox views that were a welcome contrast to the leading information processing theories of the day. In his early career, Turvey was best known for introducing the work of Nikolai Bernstein to the west and in particular the problems of degrees of freedom and dimensionality. Along with Peter Kugler, Turvey also introduced the idea that a synergy or a coordinative structure can be studied from the lens of thermodynamics, thereby developing a physics-based approach to movement and its stability.

Turvey argued that the total number of available degrees of freedom (DFs) of the body is typically greater than that required to reach the motor goal. The number of muscles per degree of freedom is much greater than two and due to remote compensation processes, very hard to identify. The major argument that Turvey put forth was that the nervous system takes advantage of neuromuscular redundancies to control actions in a flexible way so that, for example, the same motor goal can be reached differently depending on our intentions, external environmental (e.g. obstacles) or intrinsic (neural) constraints [1]. Despite this flexibility, the central control of actions is unambiguous: each time the body moves, a unique action is produced despite the possibility of using other actions leading to the same goal. Turvey was particularly interested in how movements can be so flexible and adaptable at the same time, while being in service of the task goal [2]. Following Bernstein's work [3], Turvey concluded that the relation between neural activity, muscular activity, and movement is equivocal [1]. Given constantly changing interactions among neural and muscular components, a pattern of muscular activity might give rise to different movements, and different patterns of muscular activity might give rise to the same movement. Likewise, different movement kinematics of the body can have the same or different kinetic consequences. When the number of states of each of these components is considered, there are, arguably, too many DF in any given movement to make executive control possible. Thus, a complete theory of motor control cannot just be based on neural activation states and muscle level control.

The dynamical systems approach assumes that general principles of coordination emerge when the movements are treated as the solutions of a self-organizing dynamical system [1,4,5]. Turvey and his followers argued that during the performance of any given act, the large number of components are combined into functional units called coordinative structures or synergies. Contrary to the mainstream approaches, in the dynamical perspective, the term synergy or a coordinative structure refers to a temporarily assembled functional unit.

This collective variable or synergy is expressed in dynamical terms rather than anatomical or biomechanical terms; it is a collective, task-specific organizational state achieved by the system. Kugler and Turvey went further to argue that this coordinative structure is best studied as an open thermodynamical system. This approach that Michael Turvey pioneered has been deeply influential in my own intellectual growth as a scientist. And using these general principles, I have extended these ideas into a few domains of research both the center and periphery of human motor control research.

In the subsequent sections, I will provide a few examples of how Michael Turvey's approach has influenced my research programs spanning many areas from posture control to rhythmic coordination.

HOW MOVEMENT TRAJECTORIES CONTRIBUTE TO MOVEMENT TIMING

Turvey's major claim was that the body is a complex system that takes in environmental information and acts lawfully upon this information. To entrain to a stimulus train, this complexity needs to converge on the necessary dimensions in order to produce synchronized and controlled movement, taking into account motor delay and variability. A leading model of motor timing, the Wing-Kristofferson model tackles this problem as a process that involves a central timekeeper, or clock, that controls the timing intervals and the peripheral motor system that implements the signals from the timekeeper [6]. Within this model, time is represented centrally, independent of the motor system. According to this model and its underlying assumptions, timekeeping does not rely on feedback from the effectors and is relatively independent of the movements themselves.

However, work from our group [7,8,9] indicates that movement trajectories directly contribute to movement timing. Finger movement trajectories when moving to a metronome demonstrate asymmetry, and this asymmetry is negatively correlated with timing accuracy, and decreases at higher tapping frequencies [7]. Specifically, higher velocity movements occur in the flexion cycle before each tap (to aid in synchronization with the beat) and lower velocity movements occur in the extension cycle after each tap (as a correction to maintain period accuracy). Further analysis has revealed that the movement trajectories contribute to the achievement of synchronized movement timing by using proprioceptive information about the position of the hand that is made available through movement. Thus, it is possible to have steady, synchronized movements without invoking a central timekeeper. We have further extended this paradigm to even deal with issues of anticipatory timing [10].

MUSIC PERCEPTION: HOW MOTOR SYSTEM AIDS BEAT PERCEPTION

A tight relationship between movement and auditory rhythm perception is evident in how the human motor system responds to auditory stimulation and is evidenced by strong motor involvement during music listening and rhythm tasks [11,12]. How we move to music has by itself become a systematic subfield of inquiry [13] that often focuses on body synchronization with music. My work in this area has been strongly inspired by Turvey's idea that perception involves the motor system.

Music often makes us to move in time with a perceived pulse or beat, implying a forward connection between auditory and motor systems that enables sound to guide movement planning and execution. Interestingly, motor planning regions are active even when merely listening to music with a beat and not moving along. This raises the question: is the motor system necessary for beat perception, or is such motor activity a consequence of beat perception, reflecting unexecuted movement or spread of neural activation? We have argued that this perception–action relationship goes beyond the idea that sensory perception informs motor planning and contends that the motor system may influence active perceptual processes. This bidirectional or circular causality is a characteristic of the models and theories that we have since developed [14,15]. In this body of work, we show that downregulating motor regions of the brain (posterior parietal cortex and premotor areas) has a strong effect on auditory beat perception [15,16]. Although this idea is reminiscent of the Gibsonian connection between action and perception, it also ties in very well with the inspiration Turvey drew from the motor theory of speech perception [17] developed by Alvin Lieberman at Haskins Laboratories.

POSTURE CONTROL, SENSORY INFORMATION AND STOCHASTIC RESONANCE

The control and coordination of posture is a very complex task that involves several distributed muscles, joints, and sensory receptors [18]. Over two decades ago, Michael Turvey and I worked on how such a smart complex system can be assembled in a task-specific way [19]. Although I never got around to doing experiments on this topic at that time, Turvey was always fascinated by the power of stochastic resonance on sensory receptors, inspired by the work by Priplata, Collins, and others [20]. In my laboratory we have extended this interest by showing that subthreshold auditory noise has the same effect on postural fluctuations in healthy young adults [21] and in healthy older adults [22]. In recent years we have used this line of thinking to show auditory and somatosensory white noise can stabilize standing balance together, another mark of stochastic resonance. Postural sway of healthy young adults who were presented with continuous white noise through the auditory or tactile modalities and through a combination of both (using a wearable device) showed that auditory or tactile noise reduces sway variability with and without vision. More recently, we have also shown that auditory noise also reduces the variability of sway in multiple time scales and frequencies [23]. In ongoing work in my laboratory, these parameters of acoustic/tactile manipulation are being optimized for the most effective balance stabilization, especially in individuals with postural instabilities.

DETUNING AND BIMANUAL COORDINATION

One of Turvey’s major contributions has been in bimanual rhythmic coordination. In particular, he was a key figure in extending the predictions of the germinal Haken-Kelso-Bunz (HKB) model of motor coordination4. In this model bimanual in-phase and anti-phase coordination modes represent two basic movement patterns with distinct characteristics, with the former being more stable and preferred mode of coordination for the nervous system. At high speeds, anti-phase movements show a phase transition to in-phase movements. Turvey pioneered a method to understand the contribution of each limb to the overall coordination pattern involves detuning ($\Delta\omega$) the natural eigenfrequency of each limb [24]. In my laboratory have we experimentally broke the symmetry between the two upper limbs by adding elastic and viscous force fields using a Kinarm™ robot exoskeleton [25]. By measuring the symmetry breaking on coordination stability as participants performed bimanual in-phase and anti-phase movements using their left and right hand in 1:1 frequency locking mode, we showed the effect of detuning on bimanual coordination as predicted by Michael Turvey. We applied viscous & elastic force fields and manipulated the asymmetry between the limbs as measured through the mean and variability of relative phase (φ) from the intended modes of 0 ° or 180 °. Our results showed that when force fields were mismatched participants exhibited a larger deviation from the intended phase and exhibited higher variability in relative phase in mismatched force conditions compared to matched force conditions, with overall higher variability during anti-phase coordination mode. This result was made possible by use of modern robotics to extend a phenomenon that Michael Turvey experimented with using handheld old-fashioned pendulums [1].

UNSTABLE OBJECT DYNAMICS

Humans often control and interact with objects that are unstable. Common examples of this include riding a bicycle, balancing a tray of food, writing with a handheld object, maintaining the oscillations of a hula-hoop, and stick balancing. Unstable objects require carefully assembled synergies since the object must be stabilized through the interaction between the human control and physical dynamics of the object itself. Such tasks require so much precision that small changes in state can produce catastrophic changes in stability. Michael Turvey and I won an Ig Nobel prize for characterizing the dynamics of hula hooping, where organized motions of the body keep the hoop in stable oscillatory motion parallel to the ground. Yet again, we followed Turvey’s theory that multiple degrees of freedom (DF) of the lower limbs in producing the oscillations are resolved into a few control DFs. Using complex dimensionality reduction techniques [25], we have shown that kinematic variance of the lower limbs during hula hooping was accommodated by two modes whose relative contributions varied with task parameters. Analysis of the joints of the lower limb and their phase relationships suggested a lower-limb organization into a vertical suspension mode and an oscillatory fore-aft mode. In my laboratory, we have obsessed over this control problem ever since. We have looked at inverse problems in hula hooping [26], and then migrated to the study of human stick balancing which revealed motor learning as a function of mastering Levy distributions [27].

CONCLUDING REMARKS ABOUT MICHAEL TURVEY

Turvey was a thought leader in motor control whose work and mentorship have inspired and benefited so many aspects of my various research programs. In the preceding sections, I have shown his influence on my work across many diverse areas of motor control. Although I have found maintaining a commitment to representation-free approaches very difficult, I have always tried to stay focused on Turvey’s advice to all scientists to take out minimal loans of intelligence. Turvey’s approach has not only inspired scientists in motor control, but also in various aspects of cognitive dynamics. My home department at the University of California, Merced has taken some of Turvey’s work in motor control and has extended it to the study of cognitive systems at large.

I consider working with Michael Turvey as one of the greatest scientific privileges I have enjoyed. I also had the unusual honor of receiving the Ig Nobel prize in physics along with Michael Turvey for our joint work on hula hooping. I sincerely hope that we continue to celebrate his legacy by moving forward with taking his approach to many scientific domains. As Turvey often used to remark, we need to go forth and continue to make discoveries.

REFERENCES

1. Turvey MT. Coordination. *Am Psychol.* 1990 Aug;45(8):938-53. doi: 10.1037//0003-066x.45.8.938.

2. Torre K, Balasubramaniam R. Disentangling stability, variability and adaptability in human performance: focus on the interplay between local variance and serial correlation. *J Exp Psychol Hum Percept Perform*. 2011 Apr;37(2):539-50. doi: 10.1037/a0020556.
3. Bernstein N. The coordination and regulation of movements. Oxford: Pergamon Press; 1967.
4. Kelso JAS. Dynamic patterns: The self-organization of brain and behavior. Cambridge, MA: The MIT Press; 1995.
5. Kugler PN, Turvey MT. Information, natural law, and the self-assembly of rhythmic movement. Mahwah NJ: Lawrence Erlbaum Associates; 1987.
6. Wing AM. Voluntary timing and brain function: an information processing approach. *Brain Cogn*. 2002 Feb;48(1):7-30. doi: 10.1006/brcg.2001.1301.
7. Balasubramaniam R, Wing AM, Daffertshofer A. Keeping with the beat: movement trajectories contribute to movement timing. *Exp Brain Res*. 2004 Nov;159(1):129-34. doi: 10.1007/s00221-004-2066-z.
8. Torre K, Balasubramaniam R. Two different processes for sensorimotor synchronization in continuous and discontinuous rhythmic movements. *Exp Brain Res*. 2009 Nov;199(2):157-66. doi: 10.1007/s00221-009-1991-2.
9. Pabst A, Balasubramaniam R. Trajectory formation during sensorimotor synchronization and syncopation to auditory and visual metronomes. *Exp Brain Res.* 2018 Nov;236(11):2847-2856. doi: 10.1007/s00221-018-5343-y.
10. Balasubramaniam R, Haegens S, Jazayeri M, Merchant H, Sternad D, Song JH. Neural Encoding and Representation of Time for Sensorimotor Control and Learning. *J Neurosci*. 2021 Feb 3;41(5):866-872. doi: 10.1523/JNEUROSCI.1652-20.2020.
11. Iversen JR, Balasubramaniam R. Synchronization and temporal processing. *Curr Opinion in Behav Sci*, 8, 175-180. doi: 10.1016/j.cobeha.2016.02.027
12. Ross JM, Warlaumont AS, Abney DH, Rigoli LM, Balasubramaniam R. Influence of musical groove on postural sway. *J Exp Psychol Hum Percept Perform*. 2016 Mar;42(3):308-19. doi: 10.1037/xhp0000198.
13. Ross JM, Iversen JR, Balasubramaniam R. Motor simulation theories of musical beat perception. *Neurocase*. 2016 Dec;22(6):558-565. doi: 10.1080/13554794.2016.124275
14. Proksch S, Comstock DC, Médé B, Pabst A, Balasubramaniam R. Motor and Predictive Processes in Auditory Beat and Rhythm Perception. *Front Hum Neurosci*. 2020 Sep 11;14:578546. doi: 10.3389/fnhum.2020.578546.
15. Ross JM, Iversen JR, Balasubramaniam R. The Role of Posterior Parietal Cortex in Beat-based Timing Perception: A Continuous Theta Burst Stimulation Study. *J Cogn Neurosci*. 2018 May;30(5):634-643. doi: 10.1162/jocn_a_01237.
16. Gordon CL, Cobb PR, Balasubramaniam R. Recruitment of the motor system during music listening: An ALE meta-analysis of fMRI data. *PLoS One*. 2018 Nov 19;13(11):e0207213. doi: 10.1371/journal.pone.0207213.
17. Galantucci B, Fowler CA, Turvey MT. The motor theory of speech perception reviewed. *Psychon Bull Rev*. 2006 Jun;13(3):361-77. doi: 10.3758/bf03193857.
18. Balasubramaniam R, Wing AM. The dynamics of standing balance. *Trends Cogn Sci*. 2002 Dec 1;6(12):531-536. doi: 10.1016/s1364-6613(02)02021-1.
19. Balasubramaniam R, Riley MA, Turvey MT. Specificity of postural sway to the demands of a precision task. *Gait Posture*. 2000 Feb;11(1):12-24. doi: 10.1016/s0966-6362(99)00051-x.
20. Priplata AA, Niemi JB, Harry JD, Lipsitz LA, Collins JJ. Vibrating insoles and balance control in elderly people. *Lancet*. 2003 Oct 4;362(9390):1123-4. doi: 10.1016/S0140-6736(03)14470-4.
21. Ross JM, Balasubramaniam R. Auditory white noise reduces postural fluctuations even in the absence of vision. *Exp Brain Res*. 2015 Aug;233(8):2357-63. doi: 10.1007/s00221-015-4304-y.
22. Ross JM, Will OJ, McGann Z, Balasubramaniam R. Auditory white noise reduces age-related fluctuations in balance. *Neurosci Lett*. 2016 Sep 6;630:216-221. doi: 10.1016/j.neulet.2016.07.060.
23. Carey S, Ross JM, Balasubramaniam R. Auditory, tactile, and multimodal noise reduce balance variability. *Exp Brain Res*. 2023 May;241(5):1241-1249. doi: 10.1007/s00221-023-06598-6.
24. Schmidt RC, Turvey MT. Models of interlimb coordination--equilibria, local analyses, and spectral patterning: comment on Fuchs and Kelso (1994). *J Exp Psychol Hum Percept Perform*. 1995 Apr;21(2):432-43. doi: 10.1037//0096-1523.21.2.432.
25. Kaur J, Proksch S, Balasubramaniam R. The effect of elastic and viscous force fields on bimanual coordination. *Exp Brain Res*. 2023 Apr;241(4):1117-1130. doi: 10.1007/s00221-023-06589-7.
26. Cluff T, Robertson DG, Balasubramaniam R. Kinetics of hula hooping: an inverse dynamics analysis. *Hum Mov Sci*. 2008 Aug;27(4):622-35. doi: 10.1016/j.humov.2008.02.018.
27. Cluff T, Balasubramaniam R. Motor learning characterized by changing Lévy distributions. *PLoS One*. 2009 Jun 22;4(6):e5998. doi: 10.1371/journal.pone.0005998.

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