AVANT, Vol. III, No. 2/2012
ISSN: 2082-6710 avant.edu.pl/en

From Physical Education to Physical Intelligence:
50 years of Perception-Action by Michael T. Turvey

Michael T. Turvey
Center for the Ecological Study of Perception and Action,
University of Connecticut, Storrs, CT, USA
& Haskins Laboratories, New Haven, CT, USA
michael.turvey[]uconn.edu

Received 7 June 2012; accepted 16 July 2012; published online 24 December 2012.
Editor of the Comments: Witold Wachowski

Editorial Abstract
Author comments on the changes in his approach to questions concerning action and perception, current and future status of ecological psychology, as well as specificity of human nature.

Keywords: Michael T. Turvey; perception; action; ecological psychology; affordance.

From "A note on the relation between action and perception" to…

From "A note on the relation between action and perception" to "Ecological perspective on perception-action: What kind of science does it entail?" what has changed in Michael T. Turvey's approach to questions concerning action and perception?

I am happy to be asked this question. It gives me an opportunity to reminisce (more than a little) and to underscore what I see as the broad theoretical significance of the ecological perspective for psychology and philosophy, but, perhaps more importantly, for science in the large.

At the meeting of the North American Society for the Psychology of Sport and Physical Activity (NASPSPA) held at the University of Illinois in May 14-16, 1973, I presented a short paper that focused on the potentially deep similarities between perceiving a letter of the alphabet (e.g., A) and the act of writing that same letter. That one could perceive as "same" the indefinitely many variants (in sizes, orientation, and script) of the letter A, and that one could write the "same" variant (more or less) of the letter A using indefinitely many combinations of muscles, muscular contractions, joints, and joint motions, suggested that the principles of A-perception and A-action were (a) extremely abstract, and (b) of like kind. The published paper (Turvey, 1974, *A note on the relation between action and perception*) promoted the idea of mathematical symmetry groups related through an isomorphism.

The 1974 paper was not strictly ecological. It was my first foray into what I then termed "action theory." It was an opportunity to begin thinking about action in ways that I had been exploring perception, ways that were motivated by the style of inquiry expressed in James Gibson's writings, most notably (for me) his 1959 chapter *Perception as a function of stimulation* and his 1966 book *The senses considered as perceptual systems*. Shortly after the NASPSPA meeting I took advantage of a Guggenheim Fellowship (1973-1974) to fully acquaint myself with the Russian literature on movement published in the journal *Biofizika* (translated and published in English as *Biophysics*), particularly the literature inspired by the ideas of Nicolai Bernstein. His primary works had been made available in English in the 1967 publication of *The coordination and regulation of movements*. In significant degree, it was Bernstein's emphasis upon the topological rather than the metrical properties of movements that had encouraged me to think more abstractly about the grounding of the human ability to write the letter A.

At this juncture I should make clear the origins of my interests in perception-action. My undergraduate and Master's degrees were in physical education. I often puzzled over matters such as how to teach a 14-year-old the technique of discus throwing. Or how is it possible for a midfielder in football (I am English born) to hit a 40 m pass on the run to the right winger who, in seemingly one motion, chests the ball down to his feet and sends the ball on an inward curving trajectory to the far post where it is intercepted by the on-rushing striker who directs it by his head into the goal?

My Ph.D. degree (received from Ohio State University in 1967) is in Experimental and Physiological Psychology. As a doctoral student I investigated the pre-perceptual visual information store (later called iconic memory) and short-term verbal memory, and I examined the effects of cortical and limbic system lesions on learning and memory functions in rats. My course work was heavy on learning theory, sensory systems, higher brain functions, embryo- and neurogenesis, and comparative psychology. In the latter course I encountered the concept of "higher-order stimulus" and the name of its author, James Gibson. I was intrigued. That encounter, though fleeting, was pivotal in my career. Some months after, while studying in the stacks at the main library of Ohio State University, and seeking a brief respite from assigned readings, the Sigmund Koch volumes on *Psychology: A study of a science* caught my eye, particularly the volume entitled *Perception*. What next caught my eye was the name James Gibson in the list of contributing authors. I read his chapter (already identified above): *Perception as a function of stimulation*. I read it there and then. My immediate reaction: So that's *why it is possible* for football players to do what they do!

I should also remark on the significance of my study of embryo- and neurogenesis. That material introduced me to Paul Weiss and the unconventional possibility that order is not an *a priori* fact of a biological system (not program-driven, or other-generated) but an *a posteriori* fact (execution-driven, or self-generated).

From 1967 to 1974, at the University of Connecticut and the Haskins Laboratories, I dedicated myself to the parallel challenges of (a) acquiring the skills of scientific experimentation, and (b) abiding Michael Faraday's admonition of "Work. Finish. Publish." I did so as a practitioner and expositor of the information processing approach while struggling with the relentless rethinking of psychological theory demanded by Gibson's overhaul of the field's foundational concepts. My major accomplishment in this period, I should note, was a body of research on peripheral and central processes in vision (*Psychological Review* 1973) that, along with my experiments on primary and iconic memory ,earned me the American Psychology Association's Early Career Award, the first major award, I believe, to be given in (what was then) the relatively new field of Cognition.

Two papers were written during my Guggenheim year. One linked the ideas of Gibson and Bernstein (*Preliminaries to a theory of action with reference to vision*); the other contrasted Gibson's approach to vision with that of the "seeing machines" of an emerging artificial intelligence (*Perspectives in vision: Conception or perception?*). The Gibson-Bernstein paper was completed early in 1974. The book it was intended for, as a chapter, was not published until 1977. Fortunately, the paper was made publicly available two years earlier in the widely distributed *Haskins Laboratories Status Report*, the same year the conception-or-perception chapter was published. In combination, these two papers became the springboard for a radical rethinking of the scientific status of perception and action.

What was at issue? Gibson's growing insistence in the 1960s and 1970s for an objective conception of information—required in no small part by the universal success of controlled locomotion by foot, wing, and fin—placed novel demands on philosophy, biology, and physics, as duly noted by Robert Shaw (my long-term, and most important colleague), William Mace, Ed Reed, and others. Information in Gibson's specificational sense, rather than Shannon's uncertainty-based sense, is *information about*.

Claude Shannon pursued the concept of information on the working premise that "meaning is irrelevant," adjudging that the concept was more approachable if treated as a mathematical abstraction independent of meaning. It could then also be treated as independent of coding systems, since differences among codes would only be differences in number of coding elements. The successes of Shannon's formulation for machine intelligence and communication are obvious. James Gibson, in sharp contrast, pursued the concept of information on the working premise that "meaning is relevant." As the basis for steering oneself through cluttered surroundings, information must be about whether a surface affords stepping on and bounding from by you, an opening affords passage for you, a brink in a surface affords leaping over by you, and so on. Locomotion is conducted in terms of a practical semantics, in terms of meanings that are activity-relevant. In contrast to Shannon's information carried by code, Gibson sought information as carried by invariants of energy distributions (e.g., multiply reflected light, hydrodynamic flows) structured by environmental layouts and sources relative to a stationary or moving point of observation.

Information in the sense of *information about* ties down the definition of perception as *direct*: To perceive x is to detect information about x. "Perceiving x" and "detecting information about x" are simply two ways of referring to the same, single state of affairs. The identity implies that perception is resonance-like and, thereby, a matter of laws and principles. The identity also implies (as Shaw and colleagues would eventually argue in 1979 and 1982) that perception is a fact of existence: It is necessarily what it is and not something that can be either right or wrong. A primary implication of the latter is that whatever success is achieved by the epistemic functions of organism-environment systems, it is achieved on the basis of satisfying existential criteria, not logical criteria.

All classical definitions and explanations of perception are shaped by the belief that light to the eye, sound to the ear, and so on are nonspecific (impoverished, ambiguous) in respect to the environmental states of affairs responsible for them. Accordingly, perception must be *indirect*. Alhazen in the 10th century and Helmholtz in the 19th century expressed the nature of perceiving as follows: Given a proximal stimulus (e.g., retinal image, sensations), one must both ask and answer (albeit unconsciously) “what distal stimulus would normally have produced it?”

The implied central role of inference, common to almost all past and present formulations of perception, is not assumed by the familiar modes of induction and/or deduction but, rather, by the mode of “abduction”, as Charles Peirce (see Harris and Hoover 1983) chose to name it: an inference from observation to explaining hypothesis. Perception understood as indirect is the (unconscious) making of inferences from effect to cause. Unconscious inference is paradoxical. It presumes knowing (a) the causes (having mental representations of them) and (b) the relations between effects and their causes, both of which can only be acquired on the basis of unconscious inferences. As an important aside, indirectness marks the Gestalt alternative to Alhazen and Helmholtz despite its dismissal of sense data and inference. To paraphrase Koffka, the world does not look as it does because the conditions of stimulation are what they are but because the brain states are what they are. Solipsism is (at the very least) equally as unsatisfying as the paradox of unconscious inference.

Expanding upon the question above of “what was at issue?” if perception is to be understood in terms of laws and principles, then what of action? In the mid-1970s we studied action as a separate enterprise, with Bernstein’s ideas as the focus. In the latter part of the 1970s the action question became more pressing to my colleagues and me as the limitations of the major approaches to the coordination and control of movement (those deriving from cybernetics, neurophysiology, information processing, and artificial intelligence) became more apparent. There was considerable intelligence borrowing conducted (a) from an *a priori* stance toward the orderliness of movement (the prescribing of causally involved architectures and algorithms), and (b) coordinate with a *sui generis* attitude to individual action phenomena (treating them as unique and not explainable through general principles).

At some juncture we realized that, for a fully consistent ecological theory of perception-action, addressing the problems of coordination and control required the kind of generality typically associated with physics. But what kind of physics might that be? It certainly could not be Newton’s, the physics of machines, but it could be that which Kant (1790/2000) saw expressed in organisms, a physics of self-organization involving “nothing analogous to any causality we know” (Section 69: 279).

Two developments of the 1970s helped our quest—the awarding of the Nobel Prize in Chemistry to Ilya Prigogine for his work on nonequilibrium thermodynamics, and the rapidly developing mathematics of nonlinear, dynamical systems. Prigogine's physics underscored that both biological and nonbiological order of varied degrees of complexity are *a posteriori* facts, the lawful consequences of irreversible (dissipative) processes. The developing mathematics highlighted the evolution of stable, unstable, and metastable states shaping the trajectories of systems of high dimensionality, an evolution that followed from changes in one or a few control variables. A third development should not go unstated, a fortuitous link between ecological psychologists at the University of Connecticut and the founders of homeokinetic physics (a physics for all systems) authored by Iberall, Soodak, and Yates. By 1980 we had made sufficient progress for Peter Kugler, Scott Kelso, and me to publish seminal papers with the title *On the concept of coordinative structures as dissipative structures*.

The experimental base for the early conceptions and their evaluation has been amplified considerably in the intervening 30+ years. Perception experiments have addressed the grounding of perception in ecological optics, acoustics, and mechanics (the patterns of mechanical forces that support the multiple achievements of haptic perception). The action experiments have addressed the grounding of rhythmic limb movements, postural organization, and inter-person coordination in the principles of self-organizing systems. Underpinning the experiments in both perception and action were new procedures and analytic methods, either adopted from or based upon advances in the burgeoning physics and mathematics of complexity. Many were summarized in Warren's2006 *Psychological Review* paper on *The dynamics of perception and action*.

In order to address the next part of the Editor's charge, the transition to 2012, I need to highlight two additional publications. The book that Peter Kugler and I published in 1987 on *Information, natural law and the self-assembly of rhythmic movement* provided a primary theoretical backdrop, what might be termed a strategic physics: a universal set of organizing physical strategies, most particularly thermodynamic, that apply with equal emphasis across the various scales and disciplines of the natural sciences. The motivation was Gibson's information and Iberall's homeokinetics (Iberall and Soodak 1987). The larger purpose, one might say, was dissolving the dualism of animate and inanimate—bringing both under the purview of law in equal degree. It could be viewed as a new kind of reductionism, a strategic reductionism (to common physical strategies) instead of a morphological reductionism (to common material properties). (An immediate benefit was its use as a springboard for the conception of *Ecological mechanics: A physical geometry for intentional constraints* published by Robert Shaw and his son in 1987.)

This theorizing was taken a step further in the 1991 publication with Rod Swenson on *Thermodynamic reasons for perception-action cycles*. An argument for a direct and deep connection of perception-action to thermodynamic principles was built on the cornerstones of (1) maximum entropy production, (2) inexorability of order production (because order produces entropy faster than disorder), (3) evolution as a global phenomenon (the system "Earth" at its highest level evolves as a single global entity), and (4) Gibson information. Perception-action cycles arise from the opportunistic coordination of (4) with self-organizing dynamics. Their significance is amplifying opportunities to produce ordered flow and consequent dissipation of potentials at a faster rate. The argument itself was that the progressive emergence of perception-action cycles (the nonergodicity of species) in Earth's evolution is a lawful consequence of opportunistic physics. It was (and is) how (1) is satisfied. In a 1995 publication, *Toward an ecological physics and a physical psychology,* my colleague Shaw and I suggested that the metaphysical hypothesis of organism-environment dualism that has tended to dominate psychological theory (implicitly or explicitly) can be, and should be, replaced by the scientific fact of organism-environment mutuality and reciprocity. This latter scientific fact nests Gibson's affordance.

So, now, how has my approach to action and perception changed between the early foray in 1974-1980 and 2012, with the latter captured in the chapter *Ecological perspective on perception-action: What kind of science does it entail?* and its companion piece (written with my wife, Claudia Carello) *On intelligence from first principles: Guidelines for inquiry into the hypothesis of physical intelligence (PI)*?

Ideally, given my remarks above, it should come as no surprise that ecological psychology can be considered as a psychology for all organisms, the 96 phyla that comprise the Five Kingdoms—Bacteria, Protoctista, Animalia, Fungi, and Plantae (Margulis and Schwartz 1982/1998). It can be considered as a psychology that aims to understand how all organisms "make their way in the world" (see Reed 1996)—how they perceive and act. It should also be evident that ecological psychology, at least as interpreted by my closest colleagues and me, pursues the desired understanding in terms of identifying conceptions, theory and methods up to the charge of delivering a law-based account of the phenomena characteristic of nature's ecological or mesoscopic scale. In this regard, note that the expansion (signaled by the colon) of *Ecological perspective on perception-action* is *What kind of science does it entail?*

The science currently in force in the study of perception-action, and cognition in general, focuses primarily on Animalia in the phylum Craniata, and on explanation derivative of nervous-system properties and expressed in a language of artifacts that compute (in language-like symbols, or neural-like states). While all members of Animalia other than sponges are endowed with nervous systems, the size of the endowment is not a straightforward index of perception-action competence (see McCrone's 2006 appraisal of the jumping spider *Portia labiata*). That nervous systems are absent in the four other kingdoms means that the vast majority of perceiving-acting systems lie outside the explanatory scope of a science that gives primacy to the nervous system.

In reviewing the lineage of *Ecological perspective on perception-action* (scheduled for a 2013 publication) I have presented both explicit examples and subtle clues as to the look of the entailed science. Here, I add (with minimal but ideally sufficient detail) two further examples, that of affordance and that of prospectivity.

A primary desideratum is ecological ontology, organism-specific descriptions of the surrounding surfaces, substances, and media that clarify how any given habitat (*where* an organism lives) is partitioned into distinct niches (*how* an organism lives). The ecological furnishings, Gibson suggested, are affordances. In respect to all five kingdoms, an affordance is an invariant combination of properties of surface and substance taken with reference to an organism and specific to an action performable by the organism. The niches of organisms comprise possibilities for action, and are perceived as such .As an organism moves (like an animal, or a bacterium), or grows (like a plant), or ramifies (like a fungus), or spreads (like a mold), relative to its surroundings, some action possibilities persist, some newly arise, and some dissolve, even though the surroundings, analyzed classically as objects in Euclidean relationships, are unchanging. Gibson in his 1979 book summarized an affordance thusly: It exists whether or not it is perceived or realized, it cuts across the subjective-objective dichotomy, and it is equally a fact of environment and behavior. What kind of science does affordance entail? The answer, I suggest (and present in *Ecological perspective on perception-action*), is a science of objective relational properties that includes among its fundamental notions *compatibility* (in the quantum sense of other relations remaining potential when one is actualized) and *impredicativity* (defining properties in terms of the system they constitute). In several publications, Anthony Chemero and I have explored the relevance to ecological psychology of non-well-founded set theory and the impredicative definitions that it supports (e.g., in *Biological Theory* 2007).

Eleanor Gibson (1994; see also Reed 1996) singled out *agency* as the core phenomenon to be explained by psychology. Its three defining properties are prospectivity, retrospectivity, and flexibility. In approximate terms, prospectivity and retrospectivity are the abilities to coordinate current behavior with emerging and prior states of affairs, respectively. In similarly approximate terms, flexibility is the ability to vary the means to achieve an end. Agency, I would argue, is characteristic of all phyla to greater or lesser degree. If such is the case, then each of the defining properties must be based in a generic principle. For example, rather than asking how the future is produced from an internal model, one should ask about the coupling (between organism and environment) that results in coordination with the future.

Prospectivity relying on systemic lawfulness can be termed *strong anticipation*, following a suggestion by Dubois in 2001. Voss (2000) has identified a general framework for the anticipation of a "master" system (e.g., light-dark cycle) by a "slave" system (e.g., organism) with delays, namely, $dx/dt = g(x)$, $dy/dt = f(y) + k(x - y_\tau)$. The term y_τ identifies a past state of y delayed by τ. The effect of the coupling term $k(x - y_\tau)$ is to minimize the difference between the state of x at the current time, and the state of y at a past time. If this difference is successfully minimized, then the difference between the present state of y and the future state of x is also minimized. The effect of this minimization is the synchronization of y with the future of x (for physical and biological examples see papers by Nigel Stepp and colleagues 2010, 2011). The basic coupling dynamics can be extended in two ways: by including multiple x values delayed relative to a given y value, or by including multiple y values relative to which a given x value is delayed. As suggested by Stepp in his 2012 dissertation, there may be a universal equation encompassing all variants of strong anticipation—all variants of lawful prospectivity.

The capstone of the line of inquiry from the 1974 paper (which first paired the terms perception and action) to the present is the focusing of my efforts and those of several of my colleagues on the so-called hypothesis of physical intelligence (PI), alias intelligence-from-first-principles. The overarching concern of avoiding loans of intelligence, or "self-actional explanatory terms," as Dewey and Bentley would have said in 1948, puts a premium on understanding the ill-defined but intuitive notion of intelligence through the strategies that collectively define the ecological approach to perception-action. In a paper in the first of several planned special issues on PI in *Ecological Psychology*, Claudia Carello and I identified 24 guidelines for seeking intelligence from first principles.

The Present and Future of Ecological Psychology

What is the current status of ecological psychology?
What dangers or misunderstandings do you see?
What will be the role of ecological approach in the future?

The final chapter of Ed Reed's portrayal of the life and science of James Gibson summarizes the status of ecological psychology within the field *circa* 1988. I would say that much has remained the same since that summary. The mentalistic and mechanical models that we associate with Descartes and Helmholtz and Sherrington continue to dominate, buttressed by the versatile current instantiations of Turing machines and Turing's mechanization of mathematics and thinking. The contemporary satisfaction obtained from tying hypothesized mental functions to anatomical networks revealed by fMRI and other modern technologies is creating a deepening sense of comfort with the theoretical status quo. From the latter perspective, the critical reexamination of the base concepts demanded by ecological psychology is seen as largely unnecessary and irrelevant—as just so much heterodoxy.

Also conforming to Reed's 1988 summary is the continuing tendency for select theoretical and methodological advances within the ecological perspective on perception-action to be incorporated into the old language of standard theories of sensory processes and motor control. Especially bothersome is the co-opting of terms (e.g., affordance and optic flow) for uses in cognitive science, human factors, and education that are conceptually at some remove from their definitions and usage in ecological psychology.

What makes the ecological approach to perception-action challenging is that it requires honest recognition of the obvious: Physics is not done yet! In our 1995 paper *Toward an ecological physics and a physical psychology*, Shaw and I set the stage with the statement (inspired by Robert Rosen, 1991) that "Material systems that express 'knowing about' are more general in respect to the principles that underlie them than the material systems that physics currently addresses." The sections of this paper are (i) organism-environment mutuality and reciprocity, (ii) toward a functional semantics, (iii) controlled locomotion as the paradigmatic form of "knowing about," (iv) physicalizing and intentionalizing information, (v) intentional behavior as a symmetry of the ecological scale, and (vi) direct perception: symmetry again. Only by recognizing and addressing the incompleteness of physics can we hope to reverse the historical tendency of treating perceiving, acting, and knowing as necessitating special explanation outside the purview of universal physical principles.

For an appreciation of my expectation for the future role of ecological psychology I recommend Turvey and Shaw (1995) and suggest special attention to their inserts entitled "Psychology on the cusps between the past, present and next centuries" and "Direct perception."

On Human Nature

Does human nature pose an important challenge? Is there any mystery to it?
Are these questions too trivial in the 21st century?

My answer to this question paraphrases Reed's *Conclusion* to his 1996 book.

Ecological psychology is the study of how organisms encounter their world (precisely, their habitat—where they live, and their niche—how they live). Ecological psychology has plenty of room for appreciating the specialness of human life but as a scientific stance it does not hold human life separate from the rest of the planet's life forms nor the encounters of other life forms less real than those of humans. The specialness of human life is the richness and non-ergodic nature of human encounters (occupying niches that did not exist previously) necessitated by the great and volatile diversity of human surroundings. Its study is far from trivial, and we should expect it to place significant demands on scientific inquiry in the 21st century.

References

Bernstein, N. 1967. *The coordination and regulation of movements*. London, UK: Pergamon Press.

Chemero, A., Turvey, M.T. 2007. Complexity, hypersets, and the ecological approach to perception-action. *Biological Theory*, 2: 23-36.

Dubois, D.M. 2001. Incursive and hyperincursive systems, fractal machine and anticipatory logic. *American Institute of Physics Conference Proceedings*, 573: 437-451.

Dewey, J., Bentley, A.F. 1948. *Knowing and the known*. Boston MA: Beacon Press.

Gibson, E. J. 1994. Has psychology a future? *Psychological Science*, 5: 69-76.

Gibson, J. J. 1959. Perception as a function of stimulation. S. Koch, eds. *Psychology: A study of a science, I*: 457-501. New York: McGraw-Hill.

Gibson, J.J. 1966. *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Gibson, J.J. 1979/1986. *The ecological approach to visual perception*. Mahwah, NJ: Lawrence Erlbaum Associates.

Harris, J.F., Hoover, K.D. 1983. Abduction and the new riddle of induction. E. Freeman. eds. *The relevance of Charles Peirce*: 132-144. La Salle, IL: Monist Library of Philosophy.

Iberall, A.S., Soodak, H. 1987. A physics for complex systems. F. E. Yates. eds. *Self-organizing systems: The emergence of order*: 499-520. New York: Plenum.

Kant, I. 2000. *The Critique of Judgment*. trans. J.H. Bernard , Amherst, New York: Promethius Press. (German original 1790).

Kelso, J.A.S., Holt, K., Kugler, P.N., Turvey, M.T. 1980. On the concept of coordinative structures as dissipative structures. II. Empirical lines of convergence. G.E. Stelmach, J. Requin, eds. *Tutorials in motor behavior*. Amsterdam: North Holland.

Kugler, P.N., Kelso, J.A.S., Turvey, M.T. 1980. Coordinative structures as dissipative structures I. Theoretical lines of convergence. G.E. Stelmach, J. Requin, eds. *Tutorials in Motor Behavior*: 1-47. Amsterdam: North Holland.

Kugler, P.N., Turvey, M.T. 1987. *Information, natural law and the self-assembly of rhythmic movement.* Hillsdale, NJ: Lawrence Erlbaum Associates.

McCrone, J. 2006. Smarter than the average bug. *New Scientist*, 190: 37-39.

Margulis, L., Schwartz, K.V. 1982/1998. *Five kingdoms*. New York: Freeman.

Reed, E.S. 1988. *James J. Gibson and the psychology of perception*. New Haven CT: Yale University Press.

Reed, E.S. 1996. *Encountering the world*. Oxford: Oxford University Press.

Rosen, R. 1991. *Life itself.* New York: Columbia University Press.

Shaw, R.E., Kinsella-Shaw, J.M. 1988. Ecological mechanics: A physical geometry for intentional constraints. *Human Movement Science*, 7: 135-200.

Shaw, R.E., Turvey, M.T., Mace, W.M. 1982. Ecological psychology: The consequence of a commitment to realism. W. Weimer, D. Palermo, eds. *Cognition and the symbolic processes II*: 159-226. Hillsdale, NJ: Lawrence Erlbaum Associates.

Stepp, N. 2012. *Emergence of anticipation at multiple time scales*. Unpublished doctoral dissertation. University of Connecticut, Storrs, Connecticut, USA.

Stepp, N., Chemero, A., Turvey, M.T. 2011. Philosophy for the rest of cognitive science. *Topics in Cognitive Science*, 3: 425-437.

Stepp, N., Turvey, M.T. 2010. On strong anticipation. *Cognitive Systems Research*, 11: 148-164.

Swenson, R. 1989. Emergent attractors and the law of maximum entropy production: Foundations to a theory of general evolution. *Systems Research*, 6: 187-197.

Swenson, R. 2010. Selection is entailed by self-organization and natural selection is a special case. *Biological Theory*, 5: 67–181.

Swenson, R., Turvey, M.T. 1991. Thermodynamic reasons for perception-action cycles. *Ecological Psychology*, 3: 317–348.

Turvey, M.T. 1974. A note on the relation between action and perception. M.G. Wade, R. Martens, eds. *Psychology of motor behavior and sports*. Urbana, IL: Human Kinetics.

Turvey, M.T. 1975. Perspectives in vision: Conception or perception? M. Rawson, D.D. Duane, eds. *Language, perception and reading*: 131-194. Baltimore: York.

Turvey, M.T. 1977. Preliminaries to a theory of action with reference to vision. R. Shaw, J. Bransford, eds. *Perceiving, acting and knowing: Toward an ecological psychology*: 211-265. Hillsdale, NJ: Erlbaum.

Turvey, M.T., Carello, C. 2012. On intelligence from first principles: Guidelines for inquiry into the hypothesis of physical intelligence (PI). *Ecological Psychology*, 24: 3-32.

Turvey, M.T., Shaw, R. 1979. The primacy of perceiving: An ecological reformulation of perception for understanding memory. L-G Nilssen, eds. *Perspectives on memory research: In honor of Uppsala University's 500th anniversary*: 167-222. Hillsdale, NJ: Erlbaum.

Turvey, M.T. (in press, 2013). Ecological perspective on perception-action: What kind of science does it entail? W. Prinz, M. Bessard, A. Herwig, eds. *Action science: Foundations of an emerging discipline.* Cambridge MA: MIT Press.

Turvey, M.T., Shaw, R.E. 1995. Toward an ecological physics and a physical psychology. R. Solso, D. Massaro, eds. *The science of the mind: 2001 and beyond*: 144-169. Oxford: Oxford University Press.

Voss, H.U. 2000. Anticipating chaotic synchronization. *Physics Review E,* 61: 5115-5119.

Warren, W.H. 2006. The dynamics of perception and action. *Psychological Review,* 113: 358-389.