APA CENTENNIAL FEATURE

Theoretical Concepts and Strategies for Understanding Perceptual-Motor Skill: From Information Capacity in Closed Systems to Self-Organization in Open, Nonequilibrium Systems

J. A. S. Kelso
Program in Complex Systems & Brain Sciences
Center for Complex Systems, Florida Atlantic University

The editor has asked me for a brief impression of Fitts's (1954) article and how it fits into the history of research in perceptual-motor skills.[1] There is little doubt that Fitts's work was a seminal article in the field: It was the first to apply Shannon and Weaver's (1949) theory of information to the motor system and to quantify task difficulty in terms of information units. In particular, the relation between amplitude, movement time, and precision (or tolerance) has come to be known as Fitts's Law because of its wide applicability to different perceptual-motor tasks. Fitts was clearly committed to finding empirical relations that reflect limits of human capabilities, and the relation he identified has stood the test of time. On the other hand, it is not appropriate to confirm the status of law on the basis of the relation identified by Fitts, at least if one means a law for the motor system itself rather than a law linking experimentally manipulable quantities. As Kerr (1978) pointed out some years ago, task-defined variables like amplitude and movement time are not necessarily the essential internal parameters used by the motor system to control movement. Indeed, on hindsight, it is now quite clear that they are not (see later). I would say, nevertheless, that Fitts's empirical relation has been and continues to be an enormous stimulus to research in the field: There have been many contemporary efforts to refine it, if not explain it from other, perhaps more fundamental, underpinnings. The work throughout the 1980s of Richard Schmidt, Howard Zelaznik, and colleagues in California, Karl Newell and Les Carlton at Illinois, and David Meyer et al. at Michigan in this direction stands out. With the increasing sophistication of modeling by biophysicists, it is now possible to write equations of motion for system-relevant variables that reproduce empirically observed trajectories in Fitts-type tasks. Artificial neural networks can also simulate the predicted effects, as well as, one is tempted to add mischievously, everything else.

Preparation of this article was supported by the National Institute of Mental Health Grant MH42900 and Contract N00014-88-J119 from the U.S. Office of Naval Research. I thank Betty Tuller for comments.

Correspondence concerning this article should be addressed to J. A. S. Kelso, Program in Complex Systems & Brain Sciences, Center for Complex Systems, Florida Atlantic University, Boca Raton, Florida 33431.

Fitts (1954) treated the motor system, after Shannon, in terms of the capacity of a communication channel to transfer information in the presence of noise. His view in 1954 differed somewhat from that later expressed by Fitts and Posner (1967) in their wonderful little book *Human Performance* (my first exposure by Posner's student Jerry Ells to "information processing"). Although Fitts believed he could infer "the information capacity of the motor system . . . from measures of the variability of successive responses" (p. 381), later Fitts and Posner (1967) pointed out that "the concept of channel capacity as employed in information theory should not be confused with concepts regarding man's capacities and limitations" (p. 92). I agree with this latter assessment, published after Fitts's death, but probably for different reasons than Fitts and Posner (1967). Some of my reasons might be helpful in placing this article in historical context (i.e., with 20-20 hindsight!) and might also draw attention to conceptual limitations of Fitts's work (and maybe the role of information-theoretic approaches in cognitive psychology).

On reflection, it must have been tempting in the 1950s to take the machinery of information theory into psychomotor behavior and other aspects of psychology, just as in the early 1970s we accepted, hook, line and sinker, closed-loop cybernetic ideas. The fact that the central nervous system is not a channel simply sending out orders from a central controller has become clear, if it was not then. The fact that Shannonian information carries no semantic content also makes it a poor candidate for communication in biological and physiological systems. In addition, information theory refers only to closed systems; this might not alter one's views of the significance of Fitts's Law too much (at least in the way movement experiments are performed), but it should cause one to pause and question the assumptions behind the law, especially now, when there is a much better understanding of the creative pattern-forming capabilities of open, nonequilibrium systems.

If there is a striking feature about biological systems, it is that they are coordinated. Fitts (1964) himself defined skill as a highly organized behavior in both space and time and

[1] My charge is not to review the literature, so references are kept to an absolute minimum. I ask the reader's forbearance on this point, particularly those whose work is mentioned.

Journal of Experimental Psychology: General, 1992, Vol. 121, No. 3, 260-261

defined the central problem of skill learning as how such organization or patterning comes about. Information-theoretic approaches, with their arbitrary metrics, are not going to reveal much about that. The fact that enormously complex nervous systems synergize their elements for specific biological functions suggests information compression in the semantic sense, not informational complexity in the Shannonian sense used by Fitts. In such complex systems, we cannot speculate a priori, as did Fitts (1954, pp. 389–390), that tasks that use the hand will have higher information capacity than tasks that use the arm. Identified synergies or coordinative structures are known to be spatially and temporally distributed among many interacting elements. This does not necessarily mean informational complexity as found in the Shannonian view, which stems from the statistical mechanics of closed systems. Rather, the existence of synergies in open, nonequilibrium systems implies a smaller set of informationally simple but functionally meaningful chunks. Their representational structure may be said to correspond to attractive collective states of a dissipative dynamical system. Semantic information appears to be created in dynamical systems by a cooperativity among participating elements.

The equation of variability in a subject's responses with noise in the channel requires extension, if not revision. Not everything about movement variability, 40 years of work since Fitts (1954) notwithstanding, should be labeled in the *error* category. Rather, in the context of modern theories of self-organization, fluctuations have been demonstrated, by myself and others (e.g., see contributions in Newell & Corcos, in press), to play a formative or constructive role in sensorimotor coordination, perception, learning, and even the brain itself, probing the stability of system states and enabling the discovery of new patterns. Without variability, the motor system, in this view, would lack an important source of flexibility. Moreover, instability—a fundamental generator of change in open systems—is revealed by parametrically induced enhancement of variance. Without variability in this sense, new forms of behavioral organization would be severely limited.

How might Fitts (1954) see the field now, nearly 40 years after his seminal paper? On the information-theoretic side, he would see several important developments. Among these are efforts to extend information theory into nonequilibrium systems by Haken (1988) in Stuttgart[2] and explicit attempts along similar lines to incorporate semantic information into computational theory and computer design by Shimizu's group in Tokyo. Also, proponents of James Gibson's perceptual theory have always wanted information to be more than a stimulus, that is, to somehow carry its own semantics. Newer measure-theoretic quantities derived from information theory and the ergodic theory of dynamical systems (including symbolic dynamics) are being used to good effect to distinguish drug effects in animal exploratory and locomotory behavior by Martin Paulus and colleagues at San Diego and may have applications elsewhere. More germane to motor systems, Fitts would now find (a) explicit models of coordination dynamics on several levels of description; (b) geometric-kinematic invariants for movement trajectories; (c) proposed variational principles for skilled movement such as jerk minimization; and (d) various equilibrium-seeking models of motor control. Although it would be wrong to say that all these developments stem from Fitts, his ghost is present in all of them, whether it be the theoretical context of his work (which is much broader than motor systems per se) or his famous empirical relation among the amplitude, direction, and precision of goal-oriented movement.

So why then, after all these years, does Fitts's Law seem to work so well? Some years ago, following extensive kinematic studies of Fitts-type tasks for both limb and speech movements, I suggested that the reason for the *lawfulness*, or regularity, evident in Fitts's Law was because the surface relation between movement time and amplitude emerges from harmonic basis functions (e.g., mass-spring dynamics) tailored by boundary or task conditions (e.g., spatial accuracy requirements). Guiard (in press) has recently produced quite compelling evidence along this line. In particular, he observed deviations from linearity (simple harmonic motion) in a cyclical aiming task as the tolerance or accuracy requirements were systematically increased. The relation identified by Fitts is lawlike, one assumes, because of the ubiquity of periodic motion (regular and irregular) in nature and the corresponding role of the (nonlinear) oscillator as an archetype of time-varying behavior. It is important to note that whether such a dynamical system exhibits postural states or discrete, rhythmical (or even chaotic) behavior depends solely on its parameters. In this view, Fitts's Law itself arises as a consequence of applying parameters to an underlying dynamical law created by the nervous system for a specific goal-directed action.

---

[2] Haken (1988) developed the maximum entropy principle of Jaynes. The latter has a nice ring to it for psychologists: "If any macrophenomenon is found to be reproducible, then it follows that all microscopic details that were not under the experimenter's control must be irrelevant for understanding and predicting it" (Jaynes, 1985, p. 256).

References

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381–391.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 243–285). San Diego, CA: Academic Press.

Fitts, P. M., & Posner, M. I. (1967). *Human performance.* Brooks/Cole: Monterey, CA.

Guiard, Y. (in press). Information and energy constraints in cyclical aiming. *Acta Psychologia.*

Haken, H. (1988). *Information and self-organization.* Berlin: Springer-Verlag.

Jaynes, E. T. (1985). Macroscopic prediction. In H. Haken (Ed.), *Complex systems: Operational approaches in neurobiology, physics and computers* (pp. 254–269). Berlin: Springer-Verlag.

Kerr, B. (1978). Task factors that influence selection and preparation for voluntary movements. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 55–69). San Diego, CA: Academic Press.

Newell, K. M., & Corcos, D. M. (Eds.) (in press). *Variability and motor control.* Champaign, IL: Human Kinetics.

Shannon, C., & Weaver, W. (1949). *The mathematical theory of communication.* Urbana, IL: University of Illinois.