Since the middle of the nineteenth century, movement scientists have been challenged to explain processes underlying the control, coordination, and acquisition of skill. Information processing and constraints-based approaches represent two distinct, often perceived as opposing, views of skill acquisition. The purpose of this article is to compare information processing and constraints-based approaches through the lens of Fitts’ three-stage model and Newell’s constraints-based model, respectively. In essence, both models can be identified, at least in spirit, with ideas about skill described by Bernstein (1967, 1996). Given that the product of “skill acquisition” is the same, although the explanation of the processes might differ, it is perhaps not surprising that similarities between the models appear greater than the differences. In continuing to meet the challenge to explain skill acquisition, neural-based models provide a glimpse of the cutting edge where behavior and biological mechanisms underpinning processes of control, coordination, and acquisition of skill might meet.

**Key Words:** control, coordination, learning, development, dynamical systems, Fitts

The dimensions of skill are frequently and easily recognized in movement. Performances that evoke in us a spine-tingling reaction emerge from a vast array of movements; the elegant finesse of the concert flautist, a deft side-step from a rugby three-quarter, the perfect tone and pitch of an operatic diva or the speed and the immaculate precision of a Formula 1 driver’s passing maneuver. Without exception these are examples of skills derived from experience and ability expressed through coordination and control of human movement. In the context of this article “skill” refers to coordinated, accurate, and relatively error-free perceptual motor
performance and not to skill as the term might be applied generally to the inclusion of nonmotoric tasks. Movement scientists have become highly proficient at measuring the coordination and control of movements described as skilled but as yet they have not provided a unified or unifying theory, eminently testable, that can explain how such skills are acquired or learned. Perhaps the approach advanced by Bernstein (1967) would have offered an opportunity for unification, if selective interpretations of his writings (Requin, Semjen, & Bonnet, 1984) had not prevailed. In the absence of selective interpretation, textbooks might have presented a better-integrated approach to describing the study of coordination, control, and skill. But, such has not been the case and as exemplified by Bongaardt (2001), continental as well as ideological divisions have occurred:

“In the West, Bernstein is often quoted for his ground-laying work on movement coordination qua observable performance (e.g., Turvey, 1990). Eastern European and Russian researchers often refer to him as a neuroscientist, stressing the relevance of planning action and taking the initiative (e.g., Feigenberg and Latash, 1996) … for Bernstein, the two approaches were complementary…” (Bongaardt, 2001, p. 64)

Contemporary textbook accounts of motor control and motor learning typically offer two theoretical perspectives of motor learning and also include separate specific chapters on the related topics of memory, practice, and feedback (e.g., Rose, 1997; Schmidt & Lee, 1999). In general, two theoretical perspectives of motor learning emerged separately from the domains of experimental/cognitive psychology and ecological psychology/dynamical systems theory, respectively. An information processing approach was derived from cognitive and experimental psychology and an ecological approach to skill acquisition emerged from ecological psychology and dynamical systems theory.\footnote{Information processing approaches are sometimes appraised critically as “prescriptive approaches” (e.g., see Newell, 1986, 1991). In our view, information processing, derived from experimental and cognitive psychology, includes schema and closed-loop theories, and stages/phases models like that proposed by Fitts (1962). The constraints-based approaches, derived from ecological psychology, have been associated with dynamical systems, coordinative structures, coordination dynamics, and action–perception pattern formation. It is taken as read that in the motor control field many dynamicists are not ecological psychologists and likewise many ecological psychologists are not dynamicists.}

In our view, the relationship between information processing and ecological approaches as described in many contemporary textbooks is not presented as a complementary one. That is, the qualities of each theoretical perspective of skill acquisition are not discussed or presented such that in combination they could easily be perceived to form a complete whole by enhancing each other’s characteristics.\footnote{The separation between the information processing and ecological approaches to skill acquisition might, in a small way, be viewed as analogous to the modernist–postmodernist views of science and “not-science,” respectively (Devine, 2004). A similar separation in motor control between motor systems and action systems approaches resulted in the “motor-action controversy” (see, for example, van Wieringen, 1988).}

Within the motor control literature, two frequently cited exemplars of information processing are closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975). From an ecological approach, major concepts are perception-action coupling, coordinative structures, and constraints (Kugler, Kelso, & Turvey, 1980). Through “constraints” Newell proposed a solution to the discrepancies in explanations of
coordination associated with the historically separate domains of motor learning and motor development (Newell, 1985, 1986, 1991). Incidentally, we think that the study and teaching of motor development and motor learning would benefit greatly from an integrative approach but that debate is beyond the scope of this article.

Interestingly, the contrasting perspectives of information processing and the ecological approach as applied to motor learning can be intrinsically linked to parallel theoretical perspectives in motor control represented by the motor systems view (information processing) (Schmidt, 1975) and the action systems view (dynamical systems) (Reed, 1982). In a broader context, the debate between information processing approaches and ecological approaches to studying motor behavior could be viewed as an emergent property of the more general debate about behavior, conducted between proponents of the cognitive and ecological approaches to psychology (Neisser, 1976).

Within motor behavior generally, individual researchers, while recognizing the diversity of explanations for skill acquisition, often adhere (sometimes with tenacity analogous to “Super Glue”) to a particular view. As coauthors of this article we felt a collective responsibility to attempt to provide a cohesive account, yet not surprisingly each of us holds a distinctly different perspective of how motor skill is acquired. One of us (Davids) would stoutly defend a view perhaps best described as “ecological psychology/dynamical systems theory.” Another (Elliott) would identify with a strong association through an information processing approach to optimizing goal-directed performance, and one (Anson) unashamedly holds a mechanistic neural systems structure and function information processing view. In our attempt to achieve cohesion (collegiality and friendship were retained throughout this adventure) we will use the terms “information processing approach” and “constraints-based approach” to capture the main cognitive and ecological perspectives of the processes underpinning skill acquisition.

In this article, we examine whether two models of skill acquisition represented by a constraints-based approach and an information processing approach are as widely divergent as might be inferred from many textbook accounts. From an information processing approach, we assess the impact of, in our view, the under-cited Fitts’ three-stage model of motor skill learning (Fitts, 1962, 1964) and from a constraints-based perspective we examine the influence of Newell’s constraints-based model (Newell, 1981, 1985, 1986, 1991). We also briefly discuss the extent to which ideas about perceptual-motor skill acquisition have altered during the last 20 years since the constraints-based approach to explain motor learning was proposed (Newell, 1985, 1986). Finally, we suggest that integration of knowledge from theories of brain function along the lines suggested by Wolpert, Kawato, and colleagues (Haruno, Wolpert, & Kawato, 2001; Wolpert, Doya, & Kawato, 2003) could be indicative of the future development of the theoretical base underpinning skill acquisition, control, and coordination.

**Perceptual-Motor Skill Acquisition: An Information Processing Approach**

The information processing approach to understanding perceptual-motor skill is steeped in history marked by iconic figures like Donders (Donders, 1969 [1868]) and Woodworth (Woodworth, 1899). In modernist times Paul Fitts (1962, 1964)
led the post-World War II explosion of human factors research that contributed information processing legacies including Fitts’ Law for speed/accuracy relations. Although, as we shall see, Fitts proposed an extensively researched three-stage model of motor skill learning, the model is seldom cited as a pillar of information processing-based theory. Ironically, the apparent lack of recognition of Fitts’ model could have inadvertently contributed to the rise in popularity of the constraints-based approach to explaining perceptual-motor skill.

From a behavioral perspective, it is likely that a constraints-based approach to theorizing about skill acquisition was proposed for two reasons: Information processing approaches, for example, see Adams (1971) and Schmidt (1975), were perceived to lack generalizability to real-world motor skills, and second, in the early 1980s the ecological approach to motor control was seen by some (Reed, 1982) to be ripe as a source of replacement, not only for motor control theory but also through cross-pollination for motor learning. Not surprisingly, the acquisition of skilled movement, like the origin of the universe, is associated with more than one possible explanation. Before considering information processing and constraints-based theories, it is perhaps helpful to recall what is needed to establish a theory. The New Oxford Dictionary of English (Pearsall, 1998, p. 1922) defines theory as “a supposition or a system of ideas intended to explain something, especially one based on general principles independent of the thing to be explained.”

Within these guidelines, the proposals for a constraints-based approach to coordination and development formulated by Newell (1985, 1986, 1991) qualify as theory. In part, the constraints-based approach to coordination, control, and skill was, according to Newell, intended to bridge the perceived gap between motor control and motor learning principles and between biological and behavioral levels of analysis (Newell, 1985). Certainly a common explanatory basis to account for coordination, control, and skill is desirable. But the parallel inference that this had not, or could not, be accomplished under an information processing approach is not necessarily accurate. True, closed-loop theory (Adams, 1971) and schema theory (Schmidt, 1975), both information processing in nature, were frequently criticized for their inability to serve as general theories of coordination, control, and skill but this lack of generalizability might have had more to do with the specific nature of each theory and less to do with the information processing approach per se. We will return to discuss the constraints-based approach later in this article.

It is of interest to note that alternative information processing-related notions to explain skill acquisition not previously cast as theories might contain substantial explanatory strength. For example, many textbooks include descriptions of Fitts’ three-stage model of motor learning (Fitts, 1962, 1964) but seldom indicate that it was derived from several theoretical models—communication, control system, and adaptive system, respectively. Communication models were derived from the general concept of information processing in which the operations of translation, transmission, reduction, collation, generation, and storage of information were conducted (Crossman, 1959; Fitts, 1954; Fitts & Peterson, 1964). Control system models emerged from the study of feedback and servomechanisms associated with the interface between human operators and complex machinery. The development of such models accelerated following World War II with intense interest from the
military (Taylor, 1957). Adaptive system models recognized the dynamic nature of learning, and, implicitly, of skill acquisition. Their proponents (e.g., Gibson, 1960; Miller, Galanter, & Pribram, 1960; Newell, Shaw, & Simon, 1958) argued, according to Fitts, for recognition of hierarchical processes and “programs” that carried out routine functions as well as higher level programs or plans. Adaptive systems models were associated with three kinds of processes: “(a) one that insures variability in input or system parameters, (b) one that provides a criterion measure, and (c) one that results in the system changing or maintaining its program or parameters so that over time it will tend to achieve a performance level which is closer to the optimal.” (Fitts, 1964, p. 251)

In two papers; “Factors in complex skill training” and “Perceptual-motor skill learning,” Fitts (1962, 1964) presented a robust, empirically-based proposition that the acquisition of skill could be accommodated in a three-stage model. On closer examination, the content of the two papers seems to identify as important much of what proponents of the constraints-based approach claimed to be missing from the information processing perspective, i.e., a bridge between behavior and biology and continuity between control and learning in the perceptual-motor skill literature. Yet, few contemporary accounts would locate these two papers anywhere other than within an information processing perspective. Fitts’ contributions should, although seldom do, serve as a significant part of the bulwark of information processing theory specifically and human performance theory generally (Posner, 1967). Here we briefly describe the three-stage model of skill learning proposed by Fitts and suggest that the content and structure of this information processing-based model is consistent with, rather than antagonistic toward, contemporary views of skill acquisition.

**Fitts’ Three-Stage Model of Motor Learning**

Lieutenant Colonel Paul M. Fitts, PhD, was Chief of the Psychology Branch of the Aero Medical Laboratory, Wright-Patterson Air Force Base from 1945-1949. His contributions to the development of the field of human engineering and human factors were immense as recognized in the naming of the Paul M. Fitts Human Engineering Division at Wright-Patterson Air Force Base, in Dayton, Ohio (Summers, 1995). Fitts later held the position of Professor of Psychology and was head of the Human Performance Center at the University of Michigan until his untimely death in May, 1965. In addition to being an innovator in ergonomics and human engineering, Fitts’ interest in perceptual-motor skill learning and acquisition comprised a background of breadth and depth well beyond the constraints of a fighter plane cockpit.

This description of Fitts’ three-stage model is based substantially on two primary sources (Fitts, 1962, 1964). The intellectual merits of these primary resources is substantiated by the continuing interest and publication of contemporary work on the scheduling of feedback, practice structure, task difficulty, and the processing procedures associated with skill acquisition (Guadagnoli & Lee, 2004; Swinnen, 1996). In the post-World War II era of technological development, interest in the interaction between human performance and machines grew exponentially. Scientific pursuits resulted in new categories of knowledge that included human factors, cybernetics, and information processing. The blooming of knowledge in these
“new” areas created both risk and opportunity in the pursuit of knowledge about motor learning. One of the risks identified by Fitts was that the potential splintering of knowledge would threaten the coherence represented by the important holistic category of “learning” in two ways:

“First, the theoretical framework within which skilled performance is now being viewed by most students of this topic is such that sharp distinctions between verbal and motor processes, or between cognitive and motor processes serve no useful purpose. Second, because the processes which underlie skilled perceptual-motor performance are very similar to those which underlie language behavior as well as those which are involved in problem solving and concept formation, we should expect to find that the laws of learning are also similar, and that no advantage would result from treating motor and verbal learning as separate topics.” (Fitts, 1964, p. 243)

Certainly there is a great deal of laboratory work on practice structure and cognitive effort that highlights many of the similarities between verbal and motor processes, as well as the role of higher-order cognitive processes in perceptual-motor learning. For example, research on knowledge of results (Salmoni, Schmidt, & Walter, 1984) and contextual interference (Lee & Magill, 1983) indicates that practice regimes structured to encourage active problem solving facilitate motor learning to a greater extent than more passive protocols. The same principles surrounding cognitive effort apply to verbal learning (e.g., Battig & Shea, 1980) and are not dissimilar to the notions of implicit and explicit learning associated with Bernstein (1967, 1996) as described by Beek (2000). In the area of expertise, the development of excellence in domains as diverse as dance, juggling, bridge, and physics all seem to depend on similar practice histories structured to develop domain-specific planning, reasoning, and evaluation capabilities (Ericsson & Lehmann, 1996); see also Battig & Shea, (1980). Although Ericsson’s work on expertise is definitely conducted within the theoretical perspective of information processing, it is interesting that he equates the development of expertise to “maximal adaptation to task constraints” (Ericsson & Lehmann, 1996, p. 273), a point with which few constraints-based theorists would disagree.

In identifying perceptual-motor skill, Fitts nominated three characteristics: spatial-temporal patterning, continuous interaction of response processes with input and feedback processes, and learning. These aspects of perceptual-motor skill performance are contemporary topics of study in a constraints-based dynamical systems approach where the focus has been on intra- and inter-limb coordination (Jirsa & Kelso, 2004), coordination of action with respect to the environment exemplified by prospective control models (Beek, Dessing, Peper, & Bullock, 2003), and changes in motor behavior over timescales related to learning and development (Newell, Liu, & Mayer-Kress, 2001). Fitts described the emergence of skill occurring through three stages or phases—hence the frequent reference in the literature to “Fitts’ three-stage model.” While the stages are considered to occur serially, the borders overlap, acknowledging the existence or at least the likelihood of parallel processing: “It must be emphasized, however, that these phases clearly overlap and that the progression from one to the other is a continuous rather than a discontinuous process.” (Fitts, 1962, p.186-187)
The three stages in order of progression are cognitive, fixation (later described as the associative stage), and autonomous. Incidentally, the later paper (Fitts, 1964) refers to the stages as “early, intermediate and late” but the content and features of each remained the same. Although provision is made for overlap between the phases, unique characteristics categorize each. The cognitive stage of skill acquisition is marked by a dependence on intellectual ability, acquiring specialized knowledge with the scores on tests of intellect and specialized knowledge being good predictors of the rate of learning in this stage. It is true that much of the laboratory work in which changes in performance have been examined over three or four practice days, or even in a single session, is limited to this initial stage of learning (Mowbray & Rhoades, 1959), a criticism of current research that remains valid.

Performance in the second stage—the fixation stage—is identified with correct movement patterns, increased speed, and a reduction in errors to less than 1%. One example of the likely duration of this stage in the context of pilot training was that it was equivalent to about 100 hours of flying in preparation for an initial solo and private pilot’s license. The third stage or autonomous phase, in addition to improvement in speed, accuracy, and diminished errors (approaching 0%), was characterized by increased resistance to stress, increased resistance to interference from other activities (Beilock, Carr, MacMahon, & Starkes, 2002), and a decrease in cortical association involvement that was interpreted as leading to greater control from lower brain centers. In this context, it is interesting that studies using the latest neural imaging technology indicate that both sensory and motor areas of the brain reveal a high degree of plasticity (Blake, Byl, & Merzenich, 2002; Mogilner et al., 1993) even just a few weeks following reconstructive surgery for syndactyly (Mogilner et al., 1993). Moreover, there is recent evidence using a “startle paradigm” that indicates subcortical structures are capable of storing and, under the right circumstances, eliciting complex motor responses (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004).

Three additional observations about the emergence of the three-stage model deserve comment. First, the development of, and access to, computers was very much in its embryonic stage in the early 1960s but Fitts had already applied the computer analogy to complex skill learning and was developing a view of components of skills such as those of running and swimming as analogous to subroutines, “… a sequence of operations that are called up on the basis of a single cue, once the subroutine itself has been established.” (Fitts, 1962, p. 190)

While Fitts identified subroutines as evolving through the process of acquisition of skill, Franklin Henry (Henry, 1981; Henry & Rogers, 1960) employed the computer analogy in reference to a “memory drum” associated with the storage of innate neuromotor-coordination patterns related to the advance preparation of well-learned simple and complex responses. The computer analogy for human behavior has been a dominant theme in philosophy and cognitive science for some time, in which the functionalist position models cognitive functions as “software” running on central nervous system hardware (e.g., Fodor, 1974, as cited by Churchland, 2002, p. 309; and see also Lachman, Lachman, & Butterfield, 1979). In more recent times, efforts have been made to understand the biophysical basis of brain and behavior and there have been increasing attempts to interpret
views of skill acquisition concepts like “representations” from the perspective of neural networks and intrinsic brain dynamics (e.g., Jirsa & Kelso, 2004). This is not unlike the theoretical developments that have taken place within an information-processing framework of motor skill acquisition where recent emphasis has been placed more on the acquisition of specific processing procedures (Elliott, Chua, Pollock, & Lyons, 1995) than on the development of task-specific representations (Proteau, 1992).

In one contemporary biological view, the subroutines and “memory drum” might be replaced by the collective behavior of cortical cell assemblies that might represent the processes underpinning skilled movements (Anson, Hyland, Kotter, & Wickens, 2000; Churchland, 2002; Wickens, Hyland, & Anson, 1994). Consistent with this view but from a different theoretical perspective it could be argued that the resulting dominant coordination patterns can be elegantly described by intrinsic attractor states characteristic of stable states of organization in dynamical movement systems (Kelso, 2002). To return to Fitts’ three-stage model, it is possible that adhering to the computer analogy in the 1960s inhibited rather than facilitated the elaboration of a parallel processing approach, resulting in a stronger “serial” perspective than might have been intended.

The second observation is the close proximity that the previous quote from Fitts has to the motor program concept advanced in the late 1960s (Keele, 1968). Given the academic lineage shared by Keele, Posner, and Fitts perhaps this is not so surprising. Third, although seldom acknowledged in textbook reviews, Fitts’ three-stage model of motor learning was built on three essential platforms of science and the generation of knowledge: theory, experiment, and experience. The influence of theory has been mentioned. Experimental evidence was drawn from numerous empirical sources including studies of “intellectualization” and early skill learning using a pilot simulation trainer. Several important learning principles were captured, including: motivation, knowledge of results, anticipatory set (readiness), part and whole learning, verbal instruction, over-learning, spaced practice, and intellectual knowledge of the task. These principles, which emerged from numerous empirical sources (Bahrick, 1984; Bahrick, Noble, & Fitts, 1954; Bahrick & Shelly, 1958; Flexman, Matheny, & Brown, 1950; Williams & Flexman, 1949) continue to provide the vanguard to topics of contemporary information about motor learning and skill acquisition (Magill, 2001; Schmidt & Wrisberg, 2004).

To construct the third platform for his model, Fitts consulted research that used survey techniques to: “tap the experiences of men and women who devote their working lives to the training of young people in various skills.” (Fitts, 1962, p. 184)

From a contemporary point of view, this research approach is best characterized by the work of researchers on expertise who often use survey techniques to chart the practice history of highly skilled artists, scientists, and athletes over many years of domain-specific practice (see, for example, Ericsson & Lehmann, 1996; Starkes & Ericsson, 2003, for a collection of papers on various skill domains). It has been claimed that, regardless of skill domain, world-class performers require in the neighborhood of 10,000 hr of dedicated practice to achieve the pinnacle of either cognitive or perceptual-motor performance. It is probably not coincidental that many skilled trades require a 3–5 year (6,000 – 10,000 hr) apprenticeship before
professional certification can be acquired. For example, in New Zealand, under the Electricity Act 1992, to become registered as an electrician required a minimum of 8,000 hr (4 years) of work (Electrical Workers Registration Board, 2002).

The studies originally reviewed by Fitts captured data from skills that ranged from piloting an aircraft to sports including “swimming, diving, tennis, football, baseball, basketball, fencing and soccer” (Fitts, 1962, p. 185). The validity of the three-stage model for the broad domain of motor skill acquisition was increased by the assessment of: “…skilled activities that were quite different from those required of pilots and the tracking tasks so often studied in the laboratory.” (Fitts, 1962, p.185)

Four characteristics of skill acquisition were distilled from the “experience-based” research: cognitive aspects, perceptual aspects, coordination, and tension-relaxation. Coordination involved two principal elements, integration and timing. Integration was identified with distal body parts (e.g., hand and foot for pilots); systems (e.g., breathing, stroking, and kicking in swimming) and body segments (e.g., torso, shoulder, arm, and wrist in golf). The timing element of coordination contained internal (intra limb), external (externally paced), and rhythmic components. It is interesting to note how harmonious these descriptions of coordination are with the definitions of coordination from an ecological perspective provided by Turvey (1990) in later years. Fitts (1962) recognized the influence of different task constraints on coordination including the need to cohere different systems and parts of the body during action as well as the need to coordinate the body or a limb with an external object or surface.

We think there is a substantial case for considering the three-stage model more broadly in relation to the acquisition of coordination and control of motor skill beyond the confines of closed-loop or schema theory. There is, however, more to the rationale for the three-stage model than the primarily information processing context in which it is frequently presented and which it serves as an exemplar. Indeed, the model’s emphasis is congruent with contemporary dynamical systems modeling of cognition, perception, and action in an integrated account of human behavior (see, Clark, 1997; van Gelder & Port, 1995). Fitts (e.g., 1962) argued that consideration of the characteristics of skill should include the dimensions of thinking, perception, and dynamic behavior. In devising a classification system for skilled performance (that could have deflected his attention from an elaboration of skill as a generic movement phenomenon) Fitts identified a number of dynamic processes essential for what in contemporary parlance would be viewed as the “control of movement”; or, in Newell’s terms, “the process by which values are assigned to the variables in the [coordination] function” (Newell, 1985, p. 297).

These dynamic processes (summarized in a figure in the original work—Fitts, 1962, p. 180) had both structural and functional features, for example, receptor nodes to handle sensory interactions; effector nodes to deal with response interactions; central nervous system processes (CNS dynamics); environmental processes including social influences and influence of environment on skill; and control processes representing control dynamics.

It is suggested that the contributions of Fitts’ three-stage model to the knowledge base underpinning movement skill acquisition, control, and coordination have
been undervalued to a significant degree. This might have occurred because Fitts’ ideas were presented as a model, rather than a theory. Whether the instantiation of the model as a theory would have thwarted or altered the critiques of the information processing view as an appropriate explanation for motor learning/skill acquisition, control, and coordination lies as much in the realm of speculation and philosophy as it does in the ignorance of pre-existing empirical evidence. As it stands, the last 20 years have seen a growth of interest in the constraints-based perspectives of the acquisition of skill, control, and coordination. In the presence of this increased interest and growth in support for constraints-based approaches to motor learning are we able to provide a more coherent, better informed account of the processes and mechanisms underlying movement skill, or are we faced simply with a different description of the same movement outcomes? There is likely no single or simple answer to this question, but a review of the empirical support for the constraints-based approach could help us provide a better-informed response.

Fitts’ contributions to knowledge about coordination, control, and skill are unabashedly distinguished in their alliance with an information processing approach as represented in popular accounts of his three-stage model. In our view, the ideas and concepts of skill acquisition, particularly as presented in the original papers (Fitts, 1962, 1964) were very much in tune with Bernstein’s perspective (Bernstein, 1935, 1967, 1996) although we can find no evidence that either individual knew of the other’s existence. It is also intriguing, to us, that the dissatisfaction with the stalwart theories (e.g., Adams, 1971; Schmidt, 1975) of the information processing perspective on motor learning (Newell, 1981, 1985, 1991) led to an alternative proposal using the constraints-based approach (Newell, 1986) which was grounded in ecological and dynamical systems theories (Kugler et al., 1980; Turvey, 1977) that in turn regarded Bernstein’s ideas as pivotal to concepts of skill acquisition. Does the same alliance (i.e., Bernstein and the dynamical systems approach) provide a rationale for such different models of skill acquisition, or are the perceived differences between information processing and constraints-based views perhaps a consequence of an overly selective interpretation of both the information processing (if Fitts’ view is included) and Bernstein’s perspective of coordination, control, and skill?

Perceptual Motor Skill Acquisition and Constraints-Based Approach

A constraints-based approach draws heavily on dynamical systems and ecological theories. By definition “ecological” refers to “the branch of biology that deals with relations of organisms to one another and to their physical surroundings” (Pearsall, 1998, p. 586). Within the ecological approach the nature of the relations among organisms (usually humans) and their environment are described as dynamical systems characterized by constant change, activity, or progress. Ecological science was defined by Turvey and colleagues as “…the study of the inclusion relations, i.e., properties, of evolved things” (Turvey, Shaw, Reed, & Mace, 1981, p. 261). Later this definition was elaborated to include a more comprehensive definition of an ecological approach to studying the behavior of biological movement systems, emphasizing processes of cognition, perception, and action: “Ecological Science,
in its broadest sense, is a multidisciplinary approach to the study of living systems, their environments and the reciprocity that has evolved between the two...Ecological Psychology...[emphasizes] the study of information transactions between living systems and their environments, especially as they pertain to perceiving situations of significance to planning and executing of purposes activated in an environment” (Kugler & Turvey, 1987, p. xii)

Within psychology, J.J. Gibson proposed an ecological theory of perception that instantiated a direct relationship between the perceiver and the environment, a relationship described by some as devoid of mental events (Neisser, 1976). The constraints-based approach to skill acquisition had at least some of its origins in the Gibsonian view.

There are parallels between Fitts’ ideas on the qualities of movement skill, and theories on the acquisition of movement coordination and control from a constraints-based perspective, especially those inspired by Bernstein’s insights (Bernstein, 1935, 1967, 1996). Prominent ideas from the ecological approach that are frequently couched in a dynamical systems perspective (Davids, Shuttleworth, Button, Renshaw, & Glazier, 2004; Newell et al., 2001; Newell & Vaillancourt, 2001) including the related framework of coordination dynamics (e.g., Jirsa & Kelso, 2004; Carson & Kelso, 2004) have led to a focus on how movements are coordinated with respect to complex and dynamic environments. Karl Newell has commented frequently (Newell, 1985, 1986, 1989, 1991) on the problems of explaining, in a uniform way, perceptual-motor skill acquisition because of the fractionation within inter- and intra-domain definitions of, for example, motor development and motor learning; motor learning and motor control, and within motor development between phylogenetic (survival driven) and ontogenetic (socially driven) perspectives. In addressing the discrepancies brought about by fractionation, Newell proposed a constraints-based model in which he argued: “the ubiquity of order and regularity in the developmental progression of children’s fundamental movement patterns is determined in large part by the constraints imposed on action” (Newell, 1986, p. 342).

Newell’s Constraints-Based Model of Coordination and Development

The constraints-based model appears to have grown from a principally descriptive account of the perceived limitations of previous explanations of motor behavior that failed to distinguish between processes of coordination, control, and skill (Newell, 1985). In his account, Newell suggested that clarification of the relationship between processes of coordination, control, and skill could be achieved by an interpretation grounded in a dynamical systems conceptual framework. This view embraced the theory of direct perception advanced by Gibson in its effort to explain how information constrains actions (Fitch, Tuller, & Turvey, 1982; Tuller, Turvey, & Fitch, 1982; Turvey, Fitch, & Tuller, 1982; Turvey et al., 1981). Thus the resulting constraints-based model rests on clearly identified ideas, linked strongly to the notion of coordinative structures and dynamical systems.

Dynamical systems theory has distinguished between processes of coordination and control with an emphasis on explaining how the many interacting parts, or
degrees of freedom, are integrated into functional, goal-directed movement solutions in dynamic environments (e.g., Kugler & Turvey, 1987; Bernstein, 1967). Dynamical systems approaches have been aimed, in part, at understanding how the number of biomechanical degrees of freedom\(^4\) of the motor system that need to be regulated by the central nervous system can be dramatically changed through the development of temporary assemblages of muscle-joint linkages (coordinative structures). Dynamical systems theory captures how muscle collectives are organized into emergent and dynamic functional units, the behavior of which is constrained by immediate environmental demands. As a result, each coordinative structure has a task-specific function, with sets of coordinative structures being combined to provide action sequences.

Newell’s constraints-based model grew, it seems, principally from a concern with how the development of coordination was described in, and inferred from, the extant literature (Newell, 1986). Understanding of perceptual-motor skill development, Newell argued, was greatly hindered by views that highlighted the debate between phylogenetic and ontogenetic perspectives of development. Furthermore, because that debate focused on development in children it was excommunicated from the domain of motor learning as that domain’s research was typically adult-centered and regarded as a separate entity. Against this backdrop, Newell suggested that a constraints-based approach to understanding coordination and control could be seen to serve two purposes: (a) to examine coordination as a general theoretical problem independent of activity class and developmental stage, and (b) to provide opportunities for comparative tests of the predictions of “prescriptive orientations to motor development” and the “coordinative structures perspective” (Newell, 1986, p. 242). The issue of independence of developmental stage and activity class is handled neatly in Fitts’ three-stage model within the progression of learning through the cognitive, associative, and autonomous stages and is not constrained by academic domain boundaries or ontogenetic or phylogenetic delimitations.

In brief, the constraints-based model of coordination indicates that coordination is an emergent pattern shaped by the interaction among three categories of constraint: organismic, environment, and task. Diagrammatically, each category appears on one point of a triangle and coordination emerges as a product of contributions from the three elements of constraint. Organismic constraints can be time independent (structural, e.g., body shape, height, weight) or time dependent (functional, e.g., synaptic connections). Environmental constraints are said to be external to the organism and can be general or task-specific and not necessarily mutually exclusive. Task constraints are linked to the goal of the activity and are influenced by the goal, rules affecting goal achievement, and whether implements or machines and presumably other organisms are involved.

\(^3\)Bernstein indicated that coordination and control were related hierarchically — coordination precedes control, (Meijer, 2001).

\(^4\)“Degrees of freedom” can be interpreted in different ways. In this article, we interpret degrees of freedom consistent with Latash’s description, that is: “the number of available control variables (degrees of freedom)” (Latash, 1993, p. 206)
While the initial part of the proposal for a constraints-based model targeted “coordination” as its explanatory goal, it is interesting to note that the figure illustrating the model (Newell, 1986, p. 348) and nearby text, specify “coordination” and “control” as the predicted output of the model. This is of interest because the primary justification, from a domain perspective, was constrained to issues embedded in motor development and motor learning but not motor control. From a historical perspective it could be argued that the inclusion of “control” as an output of the model diminished its uniqueness because alternative accounts such as those of Bernstein (1967) and Fitts (1962) provided robust explanations embracing motor control.

How does the constraints-based model work? Once the coordination function has been integrated from components of the body, performers need to learn how to control it with respect to dynamic environments because coordinative structures are tuned by environmental information to function specifically in each unique situation. This distinction between coordination and control is equivalent to Fitts’ (1962) differentiation between integration and timing as key characteristics of skilled performance. Information constrains movements5 and can be used to prospectively control actions in complex environments (Chardenon, Montagne, Laurent, & Bootsma, 2004).

The juxtaposition of theoretical ideas from dynamical systems theory and coordination dynamics with those of ecological psychology inform our understanding of how coordination functions are controlled with respect to dynamic environments. Gibson emphasized the need to understand the nature of the information that constrains movement as tight couplings emerging between perceptual and action systems with increasing task experience (Gibson, 1979). Learning involves the attunement to and construction of successful functional relations between movement and information in specific contexts, so-called information-movement couplings. Learners become attuned to relevant properties that produce unique patterns of information flow in specific environments (e.g., different sport contexts).

Jacobs and Michaels (2002) have argued that there are two processes involved when learners assemble information-movement couplings. First, learners educate attention by becoming better at detecting the key information variables that specify movements from the myriad of variables that do not. During practice, they minimize the information needed to regulate movement from the enormous amount available in the environment (Jacobs & Michaels, 2002). This process of information reduction and synthesis appears similar to the cognitive stage in Fitts’ model. Second, learners calibrate actions by tuning movement to a critical information source and, through practice, institute and sustain information-movement couplings to regulate behavior. The calibration process and accompanying practice is not dissimilar to the characteristics of the associative stage in Fitts’ three-stage model. The education of attention and calibration ideas have been empirically supported with data from a number of movement models in sports such as soccer and volleyball (Davids, 2002).

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5This is a good example of the “Western” view of Bernstein being separated from the “Eastern” view—i.e., movement is also constrained by numerous biophysical variables like muscle mass, muscle fiber type, body mass, thermal conditions, and anatomical structure, not just information.
Anson et al. (1999; Davids, Lees, & Burwitz, 2000). For example, in serving a volleyball it has been shown that individuals acquire a tight coupling between the hip and the striking arm, the timing of which is controlled by perception of optical information from the ball at the zenith of the toss (Davids et al., 1999).

It is notable that Fitts (1962) viewed variability in movement outputs primarily as a description of the characteristics, the noise if you like, inherent in the performance from trial to trial of the same or similar tasks. In a similar vein it has been shown that at least some of the trial-to-trial variability reflects the performer’s attempt to reduce error or increase efficiency of the movement under consideration (Elliott, Hansen, Mendoza, & Tremblay, 2004). From a dynamical systems perspective, variability in movement structure, exemplified by fluctuations indexing stability, permits flexible and adaptive motor system behavior, encouraging free exploration of performance contexts. This paradox between stability and variability illustrates how performers learn to control their actions in dynamic environments, a point emphasized by Bernstein (1967) in his analysis of the simple repetitive movements in hammering a nail (Davids, Glazier, D., & Bartlett, 2003; Newell & Corcos, 1993).

To us, there seem to be two features of the constraints-based approach to explaining skill acquisition that add to, or supplement, the information processing approach. One is the utilization of movement variability, the intrinsic “natural” variability characteristic of repeated performances of the same task, as an independent variable in the constraints-based perspective (Davids, Savelsbergh, Bennett, & Van der Kamp, 2002). The second is an increased emphasis on the patterns of interaction between “real-world” (as distinct from “laboratory-based”) activities and the dynamic environments in which these activities are performed. While there are naturally more similarities than differences in the products (the skilled outcomes) described by Fitts’ three-stage model and Newell’s constraints-based model, the dual explanations of the processes underlying skill acquisition coordination and control of movement provided by these two models are short of being complementary. Neither model adequately addresses coordination, control, and skill collectively; the three-stage model focused on motor learning and skill while the constraints-based model was predicated on issues associated with motor development. Perhaps the confrontational rationale for the constraints-based model (pitting it in opposition to information processing approaches and against domain differences in motor development) inhibited the emergence or expression of a complementarity.

Historically, the groundwork for a complementary association between information processing-based approaches and constraints-based approaches existed well before either approach was separately broached. Before the end of the first half of the twentieth century, Nikolai Bernstein had provided an explanation for the “coordination and regulation of movement” that would (should?) have made the “motor” (program/information processing) versus “action” (ecological/constraints-

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6 The view of variability proposed by researchers is likely the result of the nature of the task constraints facing performers and learners, in that some tasks require reduction of error as a measure of increased performance effectiveness (e.g., tracking an object), whereas other tasks favor variability as a measure of the adaptive behavior of the individual (adjusting actions to environmental changes).
based) controversy null and void. In an excellent account of Bernstein’s theory of movement behavior, Bongaardt and Meijer suggest that Bernstein’s view would not have supported a “motor-action” dichotomy: “Whereas ecological and program approaches to movement behavior have been represented as being mutually exclusive, to Bernstein there was no conflict between programs and organism-environment relationships.” (Bongaardt & Meijer, 2000, p. 58)

**Skill Acquisition, Coordination, and Control: A Bernsteinian Integration**

Much of the similarity associated with the constraints-based and three-stage models is consistent with the architecture underpinning skill acquisition, coordination, and control embraced by Bernstein (1967). Bernstein’s view cannot easily be deduced from one or two critical papers as it evolved through numerous publications over a period of more than 30 years. The papers comprising the iconic book “Coordination and Regulation of Movements” represent just eight of Bernstein’s published papers, only a third of those that were published or translated into English or German and less than 6% of his total of more than 140 publications. That a book representing such a small proportion of an individual’s total work has attained iconic status is, in a word, impressive. That his overall perspective on coordination, control, and acquisition of skill might be misinterpreted, was a real possibility (Bongaardt & Meijer, 2000). To extract a broader and deeper understanding of Bernstein’s theory, Bongaardt and Meijer’s insight was drawn from an examination of the 24 papers published/translated in English or German and from wide-ranging interviews with colleagues or “descendents” of Bernstein. We cannot do justice to the extent of that review here. In brief, Bernstein’s thinking, his “zeitgeist,” progressed from technically descriptive (biomechanically focused) in the 1920s to “coordination,” initially viewed as the “global structure of movement” and later (late 1930s) as co-opting the degrees of freedom. The notion that control followed coordination featured later not only in historical terms in writings of the 1950s and 60s but also by inference in a hierarchical form—the idea of coordination preceding control. Detailed accounts and extensive references are contained in Bongaardt and Meijer’s paper.

According to Beek (2000), in his book “On Dexterity and its Development,” Bernstein focused attention on the phylogenetic development of the central nervous system as a function of the nature of new task constraints facing the human species, e.g., as environments changed and technology developed (Bernstein, 1996). For Bernstein, adaptive pressures to perform increasingly different types of motor tasks (e.g., hunting alone with objects picked up from the surrounding environment compared to hunting in groups with pre-manufactured tools) led to the appearance of four basic levels of control in the human action system: tone, synergies, space, and action, that differed in the need for cortical control. Bernstein proposed that the four basic levels of control could be further subdivided into action planning and movement construction levels. Like Fitts’ (1962) model of skill learning, Bernstein’s model emphasized a functional organization between higher and lower levels of the central nervous system. Bernstein’s notions of “exercisability” (increased reliability resulting from increased practice) and “dexterity” (the ability to find a motor solution for any external situation) captured the relationship between cognitive activity and
exploratory practice in constructing successful and adaptive coordination solutions in dynamic environments. Depending on task constraints, it was proposed that any one of the four levels could lead the control of action with consequences for the amount of adaptation and disruption that could take place during performance. Beek also argued that because only the highest form of control proposed in Bernstein’s ideas required an explicit, deautomatized form of learning, implicit learning was the rule, explicit learning the exception (Beek, 2000). This argument is consistent with the theorized transitions from the associative to autonomous stages of learning hypothesized by Fitts (e.g., 1962).

According to Bernstein’s influence, with regard to motor skill acquisition, implicit learning is most typical of human behavior (Bernstein, 1996). Explicit learning is possible, but necessarily involves an intervention by the highest levels of control in the hierarchically organized nervous system. There might also be some strategic benefits to engaging in explicit learning so that more automatized modes of control can be flexibly overridden by the performer when required. It is worth noting that explicit learning could permit greater flexibility in transferring general control principles between different tasks, whereas implicit learning allows performers to form dependable information-movement couplings in relatively stable environments. Which type of learning is likely to be most beneficial to the performer depends on the nature and constraints of the skill being acquired (e.g., cultural, interpretative, and predominantly cognitive skills compared to basic interceptive actions such as reaching to grasp an object or an implement or refined versus gross motor skills).

**Contemporary and Future Perspectives**

Neither a constraints-based view nor an information processing perspective currently appears to adequately solve the challenge of explaining the biological and behavioral processes underlying the coordination, control, and acquisition of perceptual-motor skill. Bernstein’s view expressed in “Dexterity and its Development” (Bernstein, 1996) is perhaps the most robust in that it provides a strong account of the potential mapping of the interaction between environment, neurobiology, and movement behavior. There is little doubt that increased understanding will depend on the applications and thoughts of scholars who have depth and breadth of knowledge in both cognitive and ecological psychology and in neurobiology and physics. Contemporary views continue to focus on domain-specific characteristics. For example, a constraints-based perspective of development and learning (Rosengren, Savelsbergh, & Van der Kamp, 2003) extends the proposals advanced by Newell (1986) regarding the absurdity of a dichotomy between development and learning but provides no indication of how the TASC (Tasks, Adaptation, Selection, Constraints) model is connected to the neurobiology of the organism. Newell and colleagues examined time scales in motor learning and development incorporating a dynamical systems perspective in which organizational levels are considered as chronological rather than hierarchical structures (Newell et al., 2001). Three observational domains include physiology, coordination, and performance with allowance for the development of cell assemblies and self-organization at the physiological level. One can almost envisage Fitts smiling as his cognitive,
associative, and autonomous stages seem to map onto Newell et al.’s physiology, coordination, and performance levels that in turn are associated with the dynamical systems properties of self organization and pattern formation, convergence to attracting fixed points, and evolution of an attractor landscape, respectively. This strongly descriptive dynamical schema, although affording at first glance areas of commonality between information processing and constraints-based approaches, currently lacks an adequate account of the neurobiological substrate from which the resultant movement behavior emerges.

One promising line of inquiry that addresses both the structure and function of the organism and the dynamical and social interaction between the organism and environment employs a neural modeling approach to motor control (Haruno et al., 2001; Wolpert et al., 2003). Wolpert and colleagues place motor control in the context of movement in general: “Movement is the only way we have of interacting with the world, whether foraging for food or attracting a waiter’s attention.” (Wolpert et al., 2003, p. 593)

And, in identifying the communication function of movement, Wolpert et al., add: “…the purpose of the human brain is to use sensory representations to determine future actions.” (Wolpert et al., 2003, p. 593)

Wolpert, Kawato, and colleagues suggest that the study of motor control is fundamentally the study of sensorimotor transformations, a view that is not always easily extracted from traditional textbooks that feature separate accounts of sensory systems and motor systems. Integration of the operations of the two systems is often left up to the reader yet the product of such integration is, with little uncertainty, motor control. The notion of constructing a comprehensive model to explain perceptual-motor skill is fraught with the challenge of trying to be all things to all skill contexts and in so doing trivialize specific skill characteristics. The models proposed by Wolpert, Kawato, and colleagues provide an insight to how the challenge might be met. The MOSAIC (Modular Selection and Identification for Control) model links both information processing and constraints-based characteristics that are strongly dependent on the known musculoskeletal structure and neural circuitry of the human organism. Sensorimotor transformations accommodate state, context, and hidden variables. State variables refer to body configuration (e.g., hand position, joint angles, head position); context refers to discrete or slowly changing parameters (e.g., an object being manipulated); hidden variables provide information not directly available to the central nervous system (e.g., there is no sensory receptor for hand in space—information is acquired from tactile and proprioceptors from which hand location can be estimated). Internal models (transformations performed by neural circuits) include forward (predictor) and inverse (controller) models that predict sensory consequences and determine motor commands, respectively. In explaining the production of accurate action, Wolpert, Kawato, and colleagues suggest: “The idea is that the brain simultaneously runs multiple forward models that predict the behavior of the motor system to determine the current dynamics of the body which will change when interacting with different objects.” (Wolpert et al., 2003, p. 596)

To map the MOSAIC model on to a hierarchically organized sensorimotor system the Hierarchical-MOSAIC (HMOSAIC) model evolved to “reconcile...
top-down plans and bottom-up constraints” (Wolpert et al., 2003). It is proposed that lower levels in the hierarchy learn elements of control for different states or contexts. The next level learns how to put elemental sequences together and progressively higher levels contain more abstract representations. As with information processing-based and constraints-based approaches, the success of neural modeling approaches like those promoted by Wolpert, Kawato, and their colleagues will inevitably depend on the extent to which they can be empirically validated. Their advantage is in their strong association with current knowledge of the structure and function of the intelligent biological organism.

Undoubtedly, forecasting the evolution of perspectives on the development of alternative views of coordination, control, and skill is worthy of some speculation. The extent to which speculation is informed by current research will be as much the reader’s interpretation as it is the authors’ message. An eye to history suggests we should not lose sight of Bernstein’s legacy, a legacy that appears, in the past, to have been selectively invoked to support both action systems and motor systems views of motor control and likewise, information processing and constraints-based views of skill acquisition. The dichotomous interpretation of Bernstein’s legacy was nicely summed up in the quote from Bongaardt at the beginning of this article (Bongaardt, 2001).

On disciplinary and philosophical grounds it is arguable that a holistic view of Bernstein’s perspective might not have necessitated a separation of information processing and constraints-based approaches into two competing (and sometimes antagonistic) emergent streams of knowledge pertinent to perceptual-motor skill acquisition, coordination, control, and learning. It is also arguable, however, that debates about the nature of skill might not have been enriched to the same “degrees of freedom” in the absence of divergence, polarization, and healthy antagonism. One could also ask whether the emerging models of Wolpert, Kawato, and colleagues do, in fact, lead us back to the future.

Donders, writing in 1868 “on the speed of mental processes,” said: “An explanation of mental phenomena, in the sense in which we consider phenomena explained, would be attainable only if they could be reduced to a universal law, such as the one on the conservation of energy, and, as we have seen, this possibility seems a priori ruled out. … But will all quantitative treatment of mental processes be out of the question then? By no means! An important factor seemed to be susceptible to measurement: I refer to the time required for simple mental processes.” (Donders, 1969 [1868]).

And writing at almost exactly the same time (1867) Helmholtz noted: “The sensations of the senses are tokens of our consciousness, it being left to our intelligence to learn how to comprehend their meaning.” (Helmholtz, 1867).

Curiosity about the relationship and role of the brain in coordination, control, and skill has a very long history that can be traced back at least to Aristotle and Galen (Meijer, 2001). In slightly more “modern” times Hebb’s contributions have provided a significant platform from which a vast neuroscience of the mechanisms and processes underlying learning and memory—the huge literature of long-term potentiation and long-term depression, for example, emerged (Hebb, 1949, 1951). We suggest that both “constraints” and “stages” descriptions of perceptual-motor
skill acquisition, coordination, and control will be strengthened if the basic premises are integrated and linked to the underlying biology of the moving organism. Carson and Kelso have effectively argued this position in representing coordination within motor control (Carson & Kelso, 2004) and Wolpert, Kawato, and colleagues have demonstrated one way in which it could be achieved (Haruno et al., 2001; Wolpert et al., 2003).

Upholding this suggestion will require a cautious approach similar to that recommended by Fitts when he argued the case for not separating verbal and motor literature in constructing a model to describe skill learning (Fitts, 1962, 1964). Fortunately, the emergence of neuroscience as a recognized discipline has provided an intellectual umbrella under which numerous topics relevant to coordination, control, and learning shelter.

Summary

We were intrigued by the observation that the processes leading to perceptual-motor skill performance, i.e., the processes of motor learning, were underpinned by two apparently unique theoretical perspectives. The information and constraints-based approaches are often described as independent notions yet the product of “skill acquisition” they seek to explain is one and the same. This theoretical independence might have evolved along straightforward historical lines—information processing was on the scene about 20 years before a constraints-based approach. Alternatively, a constraints-based approach could have been viewed as a replacement for information processing as a preferred explanatory rationale for skill acquisition, leaving information processing as an historical artifact of the knowledge generation machine. In a different vein, a constraints-based approach could have been proposed because of the perceived limitations of information processing. We think the latter reason is most plausible and that the targeted limitation of the information processing approach was, in contemporary terms, its lack of emphasis on representative task design (e.g., Vicente, 2003). This criticism is certainly valid but its validity, we think, applies not to information processing per se, rather, specifically to two significant theoretical representations of an information processing view of skill acquisition, the closed-loop and schema theories. In our view, had information processing and skill acquisition included representation by, for example, Fitts’ three-stage model, the often antagonistic debate would perhaps have been muted. Close inspection reveals that Fitts’ model accommodates both laboratory simulation and real-world movement tasks in seeking to explain coordination, control, and acquisition of skill.

Of equal interest is the conclusion that both Newell’s constraints-based model and Fitts’ three-stage model fit well in derivation terms with the theoretical perspective of coordination and regulation of movement outlined by Bernstein (1967, 1996). The goodness of fit is enhanced when the totality of Bernstein’s view is subscribed to, but is diminished when reference to Bernstein is selectively “Eastern” or “Western” in bias. Although we have argued that Newell’s constraints-based model and Fitts’ three-stage model are different sides of the same coin, we suggest that an exploration of common ground would be productive. As Kelso and Engstrom have noted, there is a need for, “…a science that embraces not only the extremes, but also the vast world of the in-betweens.” (Kelso & Engstrøm, 2006)
On both philosophical and scientific grounds it is likely that provision of adequate and acceptable explanations for the processes underlying a phenomenon as ubiquitous as movement skill will arise from an integrated rather than divergent view.

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