Kinesiology Review, 2017, 6, 221-231
https://doi.org/10.1123/kr.2017-0018

Human Kinetics
SCHOLARLY ARTICLE

Motor Control and Learning in the North American Society for the Psychology of Sport and Physical Activity (NASPSPA): The First 40 Years

Robert W. Christina

By 1967, motor control and learning researchers had adopted an information processing (IP) approach. Central to that research was understanding how movement information was processed, coded, stored, and represented in memory. It also was centered on understanding motor control and learning in terms of Fitts' law, closed-loop and schema theories, motor programs, contextual interference, modeling, mental practice, attentional focus, and how practice and augmented feedback could be organized to optimize learning. Our constraints-based research from the 1980s into the 2000s searched for principles of "self-organization", and answers to the degrees-of-freedom problem, that is, how the human motor system with so many independent parts could be controlled without the need for an executive decision maker as proposed by the IP approach. By 2007 we were thinking about where the IP and constraints-based views were divergent and complementary, and whether neural-based models could bring together the behavior and biological mechanisms underlying the processes of motor control and learning.

Keywords: information processing, dynamical systems, contextual interference, constraints

My charge with this presentation[1] was to summarize, celebrate, and highlight key historical landmarks in motor control and learning, especially within the North American Society for the Psychology of Sport and Physical Activity (NASPSPA), from 1967 to 2007. This presentation was developed solely from my perspective and I acknowledge that my colleagues might have selected some different points of emphases, research examples, paradigms, trends, issues, interpretations, and conclusions. Nonetheless, I am hopeful that my presentation will take you on a historical journey over 40 years that will act as a stimulus for at least two things. First, I hope that it is historically informative enough to stimulate an awareness and appreciation of what went on in the past with motor control and learning research. And second, I hope it prompts you to reflect on the challenges we experienced, and the evolution of our scientific thinking and research for the purpose of determining the extent to which our scientific findings contributed to the development of our subdiscipline and NASPSPA.

Information Processing Approach to Our Motor Control and Learning Research in the Early Years

Before the 1960s, motor control and learning research was guided by a Stimulus-Response (S-R) approach in which the performer was viewed as a passive recipient of stimulus information and emphases was placed on S-R contiguity and the role of reinforcement. The S-R approach was also referred to as a product-oriented approach (Stelmach, 1977) and task-oriented approach (Schmidt, 1989). Typically, responses from complex real-world and laboratory tasks were studied as a function of the manipulation of stimulus variables such as practice distribution and augmented feedback frequency. By the late 1960s we shifted away from the S-R approach toward an information processing approach (also referred to as a process-oriented approach) in which simple movement responses were used to study the cognitive processes acting on the stimulus information that elicited them.

Cognitive factors and processes associated with motor control and learning became our central interest and produced many new lines of research. We began to ask questions such as, "What are the mechanisms or processes responsible for registering, storing, and retrieving movement information and how do they operate? And, how is information processed about errors so that the learning and control of skilled movement occurs?" We tested various hypotheses from verbal learning and

---

Christina is professor emeritus in the Department of Kinesiology, School of Health and Human Sciences, University of North Carolina at Greensboro, Greensboro, NC. Address author correspondence to Robert W. Christina at rwchrist@uncg.edu.

[1] This article is based on the Historical Foundations keynote presentation given on June 4, 2017, at the 50th anniversary conference of NASPSPA in San Diego, CA.

short-term memory theories of psychology to determine the extent to which they are appropriate for the motor learning and short-term motor memory of simple movements in laboratory settings. For example, in our memory research we studied the extent to which Trace Decay and Interference theories of short-term verbal memory also held for short-term motor memory (e.g., Ascoli & Schmidt, 1969; Stelmach, 1969, 1974). We also went beyond verbal short-term memory and attempted to determine the movement cues, such as distance and location, that performers relied on to remember a simple linear positioning task. We found that the code for the position of a movement endpoint location was more effectively remembered than the code for a movement distance (e.g., Diewert, 1975; Kelso, 1977a, 1977b; Laabs, 1973; Marteniuk & Roy, 1972). And also, allowing performers to select the movement endpoint resulted in better retention than having the experimenter select it, which was referred to as the preselection effect (Kelso, 1977b; Roy, 1978; Toole, Christina, & Anson, 1982). By the mid-70s, NASPSPA scholars were well into using the process-oriented approach to study motor control and learning. And, Ron Marteniuk (1976) was certainly one of the leading scholars who was not only a strong advocate of this approach, with his book titled, *Information Processing in Motor Skills*, but advanced it with his research throughout his long, productive career (e.g., Marteniuk, 1986).

Emanating from the information processing approach in psychology in the early 1960s was a three-phase model of motor learning proposed by Paul Fitts (1964) that likened how computer programs govern the operation of data processing systems to how motor skill performance may be organized in humans. This computer analogy thought of motor programs and subprograms controlling the movement performance of humans in a way that was similar to how software programs and subroutines controlled data processing of computers. And, motor programs and subprograms were central to Fitts' three-phase model of motor learning. This analogy led to a great deal of motor control and learning research investigating the basic or inherent features of human motor programs as well as how they might function (for a historical review, see Summers & Anson, 2009).

Fitts' model was the precursor for several notable theoretical conceptualizations that followed in the early 1970s, such as Adams' (1971) *closed-loop theory of motor learning*, Gentile's (1972) *working model of skill acquisition with application to teaching*, and Schmidt's (1975) *schema theory of discrete motor skill learning*. Considerable testing of closed-loop theory predictions took place in the 1970s (e.g., Christina & Anson, 1981; Christina & Merriman, 1977; Newell, 1974; Schmidt & White, 1972), but its shortcomings, which were addressed by schema theory, led us to gravitate toward testing schema theory and its generalized motor program predictions from the latter half of the 1970s into the 1980s (e.g., Gabriele, Hall, & Buckholz, 1987; Margolis & Christina, 1981; for a review, see Shapiro & Schmidt, 1982).

There was a noticeable increase in research on motor learning as a function of practice and augmented feedback variables during the 1970s that tested predictions emanating from closed-loop and schema theories. However, that focus changed in 1979 with the appearance of a seminal article whose findings stimulated our research on practice variables beyond testing closed-loop and schema theory predictions. That article was authored by Shea and Morgan (1979) and was titled "Contextual Interference Effects on the Acquisition, Retention, and Transfer of a Motor Skill." Contextual interference is the interference in performance and learning that arises from executing one task in the context of other tasks. Essentially, they found that the higher level of contextual interference produced by random practice degraded acquisition performance, but resulted in better retention and transfer performance. They interpreted this finding to mean that the higher level of interference actually facilitated motor learning more than the lower level of interference produced by blocked practice. Their finding was instrumental in stimulating new interest and excitement in studying motor learning as a function of practice schedule variables to test various contextual interference explanations.

One of those explanations, proposed by Shea and colleagues (Shea & Morgan, 1979; Shea & Zimny, 1983, 1988), was the *Elaboration View*, which held that random practice drives the learner into more elaborative conceptual processing (i.e., more comparative and contrastive analyses) of the motor tasks to be learned. As a result, the representation of each task following random practice is more memorable than in blocked practice. The Elaboration View drew on many earlier concepts described in the *Levels-of-Processing* framework that was originally developed by Craik and Lockhart (1972) and also from Battig (1972, 1979). An alternative explanation, proposed by Lee and Magill (1983, 1985), held that random practice causes a short-term forgetting of the action plan when a different task must be performed. This is detrimental to acquisition performance, but beneficial to retention and transfer performance because it encourages the learner to engage in reconstructive processing. A similar type of reconstructive process was advanced by Cuddy and Jacoby (1982), who compared the recall abilities of two groups of children who practiced solving mathematical problems according to a random or blocked practice schedule. They also found that children who practiced in conditions of high contextual interference demonstrated superior recall at a later time.

Transfer design research from the mid-70s to about the mid-80s that manipulated practice and augmented feedback variables to test schema theory and contextual interference predictions led to a critical question asked by Schmidt and Young (1987). They asked, "Could the learning benefits of variable practice found when testing Schema theory predictions actually have been due to the contextual interference produced by random practice?" Some years later, Hall and Magill (1995) presented research evidence that provided an answer to this question. They found that the learning benefits from the amount of practice variability were more likely to occur when the motor tasks to be learned were actually parameter modifications of the same generalized motor program. Conversely, the learning benefits of contextual interference produced by random practice were more likely to occur when the motor tasks to be learned from different generalized motor programs were actually parameter modifications of the same generalized motor program.

As mentioned previously, much of our research on augmented feedback, like that on practice, was connected to testing predictions from closed-loop theory in the early 1970s and schema theory from the mid-70s into the early 1980s. However, we went beyond that connection when Salmoni, Schmidt, and Walter (1984) advocated the use of transfer designs whenever augmented feedback variables were manipulated in acquisition. They argued that the acquisition performance effects observed needed to be evaluated in a common, no-feedback transfer test to determine if they were temporary or relatively permanent. This transfer design recommendation was sufficient reason for many of us from the mid-1980s through the 1990s to revisit the augmented feedback effects of earlier research that did not use transfer designs.

Evidence emanating from transfer design research on augmented feedback variables from the mid-80s through the 1990s led to a major discovery. The discovery was that some of the commonly accepted ways in which augmented feedback was manipulated to bring about rapid achievement of criterion performance in acquisition were less than ideal for optimizing transfer performance and hence, motor learning. In fact, transfer design research revealed that the kind of augmented feedback manipulations that facilitated motor performance in transfer actually decreased the rate at which performance improved in acquisition. This augmented feedback effect was similar to the blocked-random practice effect found earlier by Shea and Morgan (1979) who also used a transfer design. Taken together, these augmented feedback and practice findings clearly reinforced the need for researchers to use transfer designs when studying motor learning as a function of augmented feedback, practice, or any other variables or conditions that were manipulated in acquisition.

One common denominator of the research in the 1980s and beyond that manipulated practice and augmented feedback variables was that the manipulations actually introduced *difficulties* in acquisition practice that challenged the learner (Christina & Bjork, 1991; Schmidt & Bjork, 1992). These manipulations, which quite often impaired motor performance in acquisition, not only seemed to help the learner to process the learning task more deeply, but also develop appropriate processes for transfer, particularly to related but distinct postacquisition tasks. These *difficulties* appeared to encourage the learner to engage in processes that resulted in a more elaborated mental representation of the motor task, a representation that could, to some extent, be used at a later time in a different context.

1986 Evaluation of Our Previous Motor Control and Learning Research and Future Directions

At a 1986 international symposium titled Future Research Directions in Exercise and Sport Science, held at Arizona State University, Dick Schmidt and I were invited to assess the motor learning research from about 1970–1985 and propose future research directions, and George Stelmach was invited to respond to what we presented. We all agreed that the same three effects resulted from our process-oriented research the previous 15 years. A positive effect that occurred was that theorizing returned to motor control and learning research. One negative effect was that we shifted away from using complex motor tasks such as those found in the real-world (e.g., sport or dance skills, manual skills involved in dental or surgical procedures, relearning basic movement skills following a stroke) and in the laboratory (e.g., tracking tasks, Mashburn task, two-hand coordination task, stabilometer) that possessed the properties or characteristics of movements that are central to the purpose of the motor control and learning research. One reason we shifted toward using simple movement tasks was that they were convenient and easy to use, measure, learn, and control. Another reason was that the shift seemed appropriate to study the control of simple movements based on Fitts' (1954) law, and motor learning and transfer predictions of Adams' (1971) closed-loop theory and Schmidt's (1975) schema theory. Quite often these simple tasks did not possess the properties or characteristics of the more complex laboratory tasks and real-world tasks that were essential for making the research findings relevant for application (Christina, 1987, 1989). Moreover, Schmidt (1989) pointed out that the amount of practice needed to learn them was much less than was needed to learn complex motor tasks. And, increasing the amount of practice with simple tasks often led to boredom for the learners because they were easily acquired. Another negative effect was that we confined our study of cognitive processes to controlled laboratory settings that often did not possess the crucial elements of real-world settings and, therefore, had little if any relevance for drawing inferences about application of the motor control and learning research findings to real-world contexts. The consequence of these three effects was a growth of theory-based knowledge about how people process information when learning and controlling simple movements in laboratory settings that quite often had little or no relevance to the more complex movement tasks and settings in which people engage in the real world (Christina, 1987, 1989).

In response to this research problem, Schmidt (1989) proposed that we should abandon the process-oriented approach we had been using since the late 1960s and readopt the product- or task-oriented approach to the study of motor learning. Stelmach (1989) challenged Schmidt's proposal by asking, "How can you really justify taking such a large step backward to a tradition we all rejected years ago?" (p. 408). Schmidt responded by saying that the task approach was nicely suited to study the new findings on augmented feedback and contextual interference. Moreover, Schmidt (1989) said, "The process approach has taken us away from situations that have much potential for practical application. Simple tasks and the focus on rather esoteric, overly simple theoretical ideas have not, in cold retrospect, proven to be very useful either as explanations of motor learning, or as guidance for application" (p. 408). Stelmach disagreed with Schmidt's position and argued that the process approach was better suited than the product approach to unravel the mechanisms that underlie these new augmented feedback and practice effects. Stelmach (1989) said, "I do not see how task-oriented paradigms can fully advance our understanding of why these phenomena occur" (p. 429). However, he was sympathetic with Schmidt's and my concern that our process-oriented research had a growing problem of relevance and went on to say that there was a need for more applied research. He argued that the problem wasn't so much with the process-oriented approach as our inappropriate use of it from a narrow perspective from the late 1960s through the 1980s, and that few motor behavior researchers have used process-oriented paradigms to study real-world problems and complex motor tasks such as those found in the real world.

Stelmach (1989) argued that the process-oriented approach is concerned with all aspects of skilled movement such as (a) how skilled movements are organized and executed, (b) how feedback is used, and (c) understanding the neural events associated with skilled motor behavior. He emphasized that the main point of process-oriented research is that it goes beyond merely examining movement outcomes and attempts to understand the manner in which the performance outcome is obtained. To add further support his position, he quoted Scott Kelso (1982), who stated that, "the process approach not only involves an understanding of the functional capacities and interactions among receptor, central, and effector mechanisms, but also a careful analysis of the kinematics of the output" (p. 12).

Adding more fuel to the fire of this heated debate, I argued that our narrow view of basic and applied research was another factor that greatly contributed to our decrease in applied research. That narrow view held that applied research was subordinate to and dependent on basic research and therefore, was an extension of it. Jack Adams (1971) advanced this narrow view when he stated that, "The villain that has robbed 'skills' of its precision is applied research that investigate an activity to solve a particular problem, like kicking a football, flying an airplane, or operating a lathe" (p.112). At the 1986 symposium I argued against Adams' narrow view that applied research should be viewed as an extension of basic research. I proposed the alternative view that basic and applied research should be viewed as independent, but cooperative endeavors. Stelmach (1989) responded to my proposal by saying, "So, I think Christina is right when he says that the adoption of a basic science point of view has relegated applied research to a second-class citizenship" (p. 429). "Although I strongly advocate that motor learning research retain its process-oriented approach, I am sympathetic to Christina's recommendation" (p. 424).

I am not sure of the extent to which the words spoken by Dick Schmidt, George Stelmach, and myself at the 1986 symposium, which also appeared in written form (Christina, 1989; Schmidt, 1989; Stelmach, 1989) had any direct influence on changing the research direction of motor control and learning from the late 1980s to 2007. But as compared with our studies before the mid-1980s, those after the mid-1980s appeared to me to have increased in (a) application, (b) relevance, (c) the use of more complex, real-world skills in real-world settings, (d) the use of the process approach from a broader perspective, and (e) the use of a constraints-based approach, which I will discuss later. Moreover, the model I proposed that viewed basic and applied research as independent but cooperating endeavors did reach at least one leading scholar (Weiss, 2008) in sport and exercise psychology, who stated that "Christina's (1987, 1989) depiction of basic and applied research provides a timely and important forum for addressing what I consider to be a turbulent wave in sport and exercise psychology" (p. 68).

Indeed, the position I took in 1986 was strongly reinforced by Gabrielle Wulf and Charles Shea (2002), who published a review article titled, "Principles Derived from the Study of Simple Skills do not Generalize to Complex Skill Learning." Needless to say, it was especially gratifying for me to read their article because it reinforced the position I took 16 years earlier. I argued for increasing our emphasis on applied motor learning research in which more real-world motor skills in real-world contexts are studied to validate the findings that emanated from hypotheses tested using simple skills in controlled laboratory conditions. I stated that, "To determine in a scientific manner if these precise laboratory-based predictions about motor learning actually hold in the real world, applied research that tests the appropriateness of these predictions in controlled practical settings will have to be conducted. You see, it simply is not possible in most instances to move from basic research predictions directly to practical application without at least one or more intervening steps of applied research. Yet, in spite of this critical role that applied research plays in determining the practical utility of fundamental knowledge generated by basic research, there was a noticeable decline in our effort to conduct it over the past 15 years or so" (Christina, 1989, pp. 413–414). Having said that, it was absolutely no surprise to me to read that Wulf and Shea (2002) concluded that, "principles derived from the study of simple skills do not generalize to complex skill learning" (p.185). They also stated that, "the findings reviewed here call into question the generalizability of results from research using simple laboratory tasks to the learning of complex motor skills. They also demonstrate the need to use more complex skills in order to gain further insights into the learning process" (p. 185).

Sample of Other Areas of Motor Control and Learning Research from the 1970s to 2007

There were far too many other areas of motor control and learning research from the late 1970s to 2007 for me to discuss all of them in this presentation, so I will selectively mention only a few of them. We continued our study of motor learning as a function of augmented feedback schedules with respect to factors such as its timing (e.g., Anderson, Magill, Sekiya, & Ryan, 2005; Swinnen, Schmidt, Nicholson, & Shapiro, 1990) precision (e.g., Reeve, Dornier, & Weeks, 1990), frequency (e.g., Guadagnoli & Kohl, 2001; Winstein & Schmidt, 1990), bandwidth (e.g., Butler, Reeve, & Fischman, 1996; Sherwood, 1988), summary and average (e.g., Yao, Fischman, & Wang, 1994), and whether feedback should be regulated by the experimenter or the learner (e.g., Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997). We did the same with contextual interference effects on motor learning (e.g., Wright, 1991; Wright, Li, & Whitacre, 1992). Motor learning as a function of practice distribution also received some attention (e.g., Dail & Christina, 2004; Lee & Genovese, 1989). Mental practice and imagery also received more attention with NASPSPA scholars such as Dan Landers, Deb Feltz, and Jen Etnier conducting some important aspects of that research (e.g., Etnier & Landers, 1996; Feltz, Landers, & Becker, 1988; Hird, Landers, Thomas, & Horan, 1991). Considerable research was conducted on observational learning or modeling and much of it was led by Penny McCullagh and Diane Ste.-Marie and their associates, who provided reviews of the research (McCullagh, Law, & Ste.-Marie, 2012; McCullagh, Ste.-Marie, & Law, 2013; Ste.-Marie, Law, Rymal, Hall, & McCullagh, 2012). I would be remiss if I did not mention the increase in research on motor learning as a function of attentional focus. This research was led by Gabrielle Wulf and her colleagues, and reviewed in her book titled, *Attention and Motor Skill Learning* (Wulf, 2007).

The information processing approach, especially Fitts' law (1954), became the basis for many of us attempting to understand the mechanisms underlying the control of simple aiming and limb movements from the late 1960s and beyond. We studied the empirical relationships involved in performing these movements in laboratory settings in terms of variables such as movement timing, amplitude, velocity, force, force variability, consistency, and accuracy. Emanating from this research were new movement control findings such as the discovery that increasing the speed of movements in timing tasks leads to increased timing consistency (e.g., Newell, 1980; Newell, Carlton, Carlton, & Halbert, 1980), and that early intermittent-control model accounts (e.g., Crossman & Goodeve, 1963/1983) of Fitts' law were incorrect. Our research also produced movement control explanations like *Impulse-Variability Models*, which described how programmed impulses influence the trajectory of rapidly aimed limb movements (e.g., Schmidt, Zelaznik, & Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Schmidt, Sherwood, Zelaznik, & Leikind, 1985). A very different view, the *Equilibrium-Point Model*, held that the limb moves to a position defined by an equilibrium point between the forces (torques) from the opposing muscles spanning a joint, and that the movement to this position depends on the mechanical, spring-like characteristics of the muscles (for reviews see Feldman, 2009; Feldman & Levin, 2009).

The basic information processing model was thought of as consisting of three stages: *Stimulus Identification*, *Response Selection*, and *Response Programming*. NASPSPA researchers in our subdiscipline did some research on the first two stages in the 1970s and 1980s, but psychologists did much of the research on these two stages. We conducted much more research on the response programming stage in the 1970s through the 1990s. For example, some of that research was focused on the reaction time analysis of programmed control of rapid movements and was stimulated by the classic study by Henry and Rogers (1960) and their *Memory-Drum Theory of Neuro-Motor Reaction*. Essentially, they found that simple reaction time increased as rapidly performed movements became more complicated. Henry proposed that simple reaction time increased for more complicated movements because the motor program was more complicated, and therefore took more time to run-off than for simple movements.

In our laboratory at Penn State University form the late 1970s to the early 1990s, my students and I extended previous research by searching for the crucial elements causing the complexity effect and also by fractionating reaction time to determine if, indeed, the increase in simple reaction time was reflected in the central, premotor-time component and not the peripheral, motor-time component. Based on the previous research of Greg Anson, Mark Fischman, Deb Rose and myself, one of our students (Ben Sidaway) was able to successfully identify one of the crucial elements causing the complexity effect. He found that element to be the demand for directional accuracy, which had an effect of confining the movement trajectory of the rapid arm response that was programmed. I presented a review of that research at the 1991 C. H. McCloy Lecture and published it, in which I also described the five major cognitive events that were assumed to be necessary to prepare the motor program during the premotor time (Christina, 1992). In addition, a factual record (including personal communications with Henry from 1979 to 1986) of an inadvertent error made by Henry in describing Henry and Rogers' (1960) most complicated movement (i.e., C movement) that was discovered nearly 20 years later was documented by Fischman, Christina, and Anson (2008), who also reported on revelations from Henry.

The 1970s and 1980s also saw a growing interest in motor control research that sought to understand what was being controlled, how the process was organized, and what purpose it served (e.g., Granit, 1981). This new focus generated many new areas of research that were investigated mainly by the joint efforts of neural control and motor behavior scientists who made use of ideas and methods from neurophysiology, biomechanics, computer science, and cognitive science. A number of investigators who were doing research on motor learning shifted to learn more about what was going on in the neurosciences of motor control and to conduct research on motor control problems at a behavioral level of analysis (see Keele, 1981, for a review).

Also reappearing during the 1970s were Bernstein's (1967) ideas on the coordination and control of movement, which were advanced in publications by Greene (1972) and Turvey (1977) and his associates (e.g., Fitch & Turvey, 1978; Fowler & Turvey, 1978; Turvey, Fitch, & Tuller, 1982). Their approach, given its strong connection with physical biology and ethology, was quite different from the traditional information processing approach. Essentially, it combined Bernstein's ideas on degrees-of-freedom, context-conditioned sensitivity, and functional synergy (i.e., coordinative structure) with the ecological perspective of James Gibson (1966, 1977, 1979). Gibson's perspective held that a performer's surroundings are structured by the environment to which his/her perceptual systems are responsive. Thus, the performer and environment are not functionally separable, nor are his/her perception of the environmental surroundings and the resulting action. Given the previous statement, it is easy to understand why proponents of the ecological perspective would advocate having research on motor control and learning be conducted in natural or real-world settings.

It also was not surprising that a constraints-based approach to coordination and development proposed by Newell (1985, 1986, 1991) emerged in the mid-1980s that was based on a strong connection to physical biology and ethology that combined Bernstein's ideas on degrees-of-freedom, context-conditioned sensitivity, and functional synergy with Gibson's ecological view. Newell (1985, 1986) suggested that the constraints-based approach emerged largely from the perceived limitations of previous motor control and learning explanations that failed to distinguish between processes of coordination, control, and skill. He proposed that clarification of these limitations could be achieved by interpreting motor behavior through a dynamical systems conceptual framework. Newell's mid-1980s constraints-based view rested on clearly identified ideas, connected strongly to the concept of muscle-response synergies or coordinative structures, and dynamical systems. His constraints-based approach was an attempt to bridge the perceived gap between motor control and learning principles and between behavioral and biological levels of analysis (Newell, 1985).

We also studied movement coordination in an attempt to understand how it comes about. One of those leaders was Scott Kelso, who studied coordination from a dynamical-systems perspective (e.g., Kelso, 1984, 1992; Kelso & Engstrom, 2005; Kelso & Zanone, 2002). The latter perspective proposed that coordinated movement develops over time as a result of the interaction among the body parts, and between the body parts and the surroundings that have been structured by the environment (e.g., Kelso, 1995). Haken, Kelso, and Bunz (1985) proposed a model (referred to as the HKB model) that conceptualized how movement coordination comes about as a decentralized self-organization system with cognition playing a diminished role. This diminished cognitive role in achieving movement coordination is like an orchestra playing without its conductor (Kelso & Engstrom, 2005). The HKB model has had considerable impact on advancing our understanding of movement coordination and stimulating further research. Another leader of that research was Stephan Swinnen, who conducted some important fundamental research on limb coordination from a cognitive neuroscience perspective (e.g., Swinnen, 2002; Swinnen & Wenderoth, 2004).

Information Processing and Constraints-Based Views of Motor Control and Learning: Complementary or Divergent?

Motor control and learning research from the 1980s to 2007 continued to search for principles and laws of *self-organization* of movement, and answers to the *degrees-of-freedom* problem; that is, how a human motor system with so many independent parts could be controlled without the need for an executive decision-maker and brain mechanisms such as memory, motor programs, and schemas as proposed by the information processing approach. Indeed, information processing and constraint-based approaches appeared to represent two distinct, often perceived as opposing, views of motor control and learning—but were they?

This question was formally addressed by Anson, Elliot, and Davids (2005). They compared information processing and constraints-based approaches from the perspective of Fitts' (1964) three-phase model and Newell's (1985, 1986, 1991) constraints-based model, respectively. They discovered that both approaches could be identified with ideas about skill described by Bernstein (1967, 1996) and found that the similarities between the approaches were greater than the differences. In fact, the authors argued that Newell's constraints-based model and Fitts' three-phase model were different sides of the same coin and that it would be more productive for us to explore common ground.

Thus, we came from viewing the information processing and constraints-based approaches as being opposing explanations of motor control and learning from the 1970s to the mid-2000s to the possibility of them having more in common in 2005 than was previously thought. This possibility left many of us in the mid-2000s thinking about where the information processing and constraints-based views of motor control and learning were divergent and complementary, and also whether neural-based models could be a viable home where behavior and biological mechanisms underlying the processes of acquisition, control, and coordination of skill might come together.

Concluding Remarks

Much of our information processing research from 1967 to 1985 produced a scientific body of knowledge about the (a) cognitive processes involved in the learning, transfer, and retention (including short-term motor memory) as a function of practice and augmented feedback manipulations in laboratory settings, and (b) mechanisms underlying and variables affecting the control of simple aiming and limb movements (e.g., based on Fitts' law). One problem with some of this knowledge was that it often had little relevance or potential for application to solving real-world problems involving real-world motor skills and settings. This problem resulted because the knowledge was based on research findings that came from a narrow research perspective of the information processing approach. It could have been avoided if a broader perspective was taken in which process-oriented paradigms were used to study real-world problems using real-world motor tasks and settings. It also could have been avoided if a broader view of the relationship between basic and applied research was taken. Rather than viewing applied research as an extension of basic research, they should have been viewed as independent, but cooperating, endeavors. One resulting effect of this narrow processing perspective and our narrow view of the relationship between basic and applied research was a noticeable decline in applied research, especially from 1970 to 1985. This lack of relevance and application problem persisted beyond 1985 and was recognized not only for the scientific body of knowledge generated from 1970 to 1985, but also for the scientific knowledge (e.g., practice and augmented feedback) produced from 1986–2001.

Despite the lack of relevance and application problem with some of our scientific motor control and learning knowledge, research did produce a major discovery with regard to the conditions of learning. The discovery was that some of the commonly accepted ways in which conditions (e.g., augmented feedback, practice) were manipulated to bring about rapid achievement of criterion motor performance in acquisition were less than ideal for optimizing transfer performance and hence, learning. In fact, our transfer design research revealed that the kind of conditions that facilitated motor performance in transfer actually decreased the rate at which performance improved in acquisition. This major discovery stimulated considerable additional research beyond 2007 and has had a major impact on how practitioners structure training conditions to optimize the learning of real-world skills in real-world settings. Although some early scientific knowledge produced by motor control and learning researchers in NASPSPA lacked relevance and the potential for application in the real world, there was a very important side benefit. By engaging in the research process during this 40-year period we (a) were critical of our research ideas, methodology, and evidence, (b) learned from our mistakes, (c) improved the relevance and potential for application of the problems studied, and (d) improved scientific and statistical methodology, which in effect laid a strong foundation for those who followed in our subdiscipline.

A substantial amount of research studying motor control and learning as a function of other factors from 1967 to 2007 did generate many findings that had considerable relevance, potential for application, or are already being applied in the real world today. Some of these other factors include manipulations of augmented feedback, who controls the augmented feedback, physical and mental practice, imagery, modeling, and attentional focus. Compared with our studies before the mid-1980s, those after the mid-1980s appeared, at least to me, to have increased in (a) relevance, (b) application, (c) the use of real-world skills in real-world settings, (d) the use of the process-oriented approach from a broader perspective, and (e) the use of a constraints-based, dynamical systems approach. One reason this latter approach emerged was because of the perceived limitations of the information processing approach in explaining various aspects of motor control and learning. Central to the differences between the two approaches was the role of cognition in motor control and learning. For example, the information processing approach held that cognition plays a central role in the development of coordination, whereas the dynamical systems model (e.g., HKB model) proposes that movement coordination comes about as a decentralized self-organization system with cognition playing a diminished role. It held that coordinated movement develops over time as a result of the interaction among the body parts and between the body parts and the surroundings that have been structured by the environment. Advocates of the information processing approach might counter by asking how a human motor system with so many independent parts (*degrees-of-freedom*) could be controlled without the need for an executive decision maker and brain mechanisms such as memory, motor programs, and schemas.

A 2005 appraisal of both approaches found that the similarities between them were greater than the differences, and it was recommended that it would be more productive for motor control and learning researchers to explore common ground. This possibility left many of us thinking about where the common ground was for the two views, and also whether neural-based models could serve to bring together the behavior and biological mechanisms underlying the processes of motor control and learning. In spite of the differences between these two approaches, both have greatly contributed to advancing our understanding of motor control and learning and stimulating further research well beyond 2007.

References

Adams, J.A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111–150. doi:10.1080/00222895.1971.10734898

Anderson, D.I., Magill, R.A., Sekiya, H., & Ryan, G. (2005). Support for an explanation of the guidance effect in motor skill learning. *Journal of Motor Behavior, 37,* 59–66. doi:10.3200/JMBR.37.3.231-238

Anson, J.G., Elliot, D., & Davids, K. (2005). Information processing and constraints-based views of skill acquisition: Divergent or complementary? *Motor Control, 9,* 217–241. doi:10.1123/mcj.9.3.217

Ascoli, K.M., & Schmidt, R.A. (1969). Proactive interference in short-term motor retention. *Journal of Motor Behavior, 1,* 29–35. doi:10.1080/00222895.1969.10734831

Battig, W.F. (1972). Intratask interference as a source of facilitation in transfer and retention. In R.F. Thompson & J.F. Voss (Eds.), *Topics in learning and performance* (pp. 131–159). New York, NY: Academic Press.

Battig, W.F. (1979). The flexibility of human memory. In L.S. Cermak & F.I.M. Craik (Eds.), *Levels of processing in human memory* (pp. 23–44). Hillsdale, NJ: Erlbaum.

Bernstein, N.A. (1967). *The co-ordination and regulation of movements*. Oxford, UK: Pergamon Press.

Bernstein, N. (1996). On dexterity and its development. In M.L. Latash & V.M. Zatsiorsky (Eds.), *Dexterity and its Development* (pp. 3–244). Hillsdale, NJ: Erlbaum.

Butler, M.S., Reeve, T.G., & Fischman, M.G. (1996). Effects of the instructional set in the bandwidth feedback paradigm on motor skill acquisition. *Research Quarterly for Exercise and Sport, 67,* 355–359. doi:10.1080/02701367.1996.10607964

Christina, R.W. (1987). Motor Learning: Future lines of research. In M. Safrit & H. Eckert (Eds.), *The academy papers: The cutting edge in physical education and exercise science research* (pp. 26–41). Champaign, IL: Human Kinetics.

Christina, R.W. (1989). Whatever happened to applied research in motor learning? In J. Skinner, C. Corbin, D.M. Landers, P.E. Martin, & C. Wells (Eds.), *Future directions in exercise and sport science research* (pp. 411–422). Champaign, IL: Human Kinetics.

Christina, R.W. (1992). The C. H. McCloy research lecture: Unraveling the mystery of the response complexity effect in skilled movements. *Research Quarterly for Exercise and Sport, 63,* 218–230. doi:10.1080/02701367.1992.10608737

Christina, R.W., & Anson, J.G. (1981). The learning of programmed- and feedback-based processes controlling the production of a positioning response in two dimensions. *Journal of Motor Behavior, 13*, 48–64.

Christina, R.W., & Bjork, R.A. (1991). Optimizing long-term retention and transfer. In D. Druckman & R. Bjork (Eds.), *In the mind's eye: Enhancing human performance* (pp. 23–56). Washington, DC: National Academy Press.

Christina, R.W., & Merriman, W. (1977). Learning the direction and extent of a movement. *Journal of Motor Behavior, 9,* 1–9. doi:10.1080/00222895.1977.10735089

Craik, F.I.M., & Lockhart, R. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11,* 671–676. doi:10.1016/S0022-5371(72)80001-X

Crossman, E.R.F.W., & Goodeve, P.J. (1963/1983). Feedback control on hand-movements and Fitts' law. *The Quarterly Journal of Experimental Psychology, 35A,* 251–278.

Cuddy, L.J., & Jacoby, L.L. (1982). When forgetting helps memory: An analysis of repetition effects. *Journal of Verbal Learning and Verbal Behavior, 21,* 451–467. doi:10.1016/S0022-5371(82)90727-7

Dail, T.K., & Christina, R.W. (2004). Distribution of practice and metacognition in learning and retention of a discrete motor task. *Research Quarterly for Exercise and Sport, 75,* 148–155. doi:10.1080/02701367.2004.10609146

Diewert, G.I. (1975). Retention and coding in motor short-term memory: A comparison of storage codes for distance and location. *Journal of Motor Behavior, 7,* 183–190. doi:10.1080/00222895.1975.10735032

Etnier, J.L., & Landers, D.M. (1996). The influence of procedural variables of the efficacy of mental practice. *The Sport Psychologist, 10,* 48–57. doi:10.1123/tsp.10.1.48

Feldman, A.G. (2009). Origin and advances of the equilibrium-point hypothesis. In D. Sternad (Ed.), *Progress in motor control* (pp. 637–643). Berlin, Germany: Springer. doi:10.1007/978-0-387-77064-2_34

Feldman, A.G., & Levin, M.F. (2009). The equilibrium-point hypothesis – past, present and future. In D. Sternad (Ed.), *Progress in motor control* (pp. 699–726). Berlin, Germany: Springer. doi:10.1007/978-0-387-77064-2_38

Feltz, D.L., Landers, D.M., & Becker, J.J. (1988). A revised meta-analysis of the mental practice literature on motor skill learning. In D. Druckman & J.A. Swets (Eds.), *Enhancing human performance: Issues, theories, and techniques* (pp. 19–88). Washington, DC: National Academy Press.

Fischman, M.G., Christina, R.W., & Anson, J.G. (2008). Memory drum theory's C movement: Revelations from Franklin Henry. *Research Quarterly for Exercise and Sport, 79,* 312–318.

Fitch, H.L., & Turvey, M.T. (1978). On the control of activity: Some remarks from an ecological point of view. In R. Christina & D. Landers (Eds.), *Psychology of motor behavior and sport* (pp. 3–35). Champaign, IL: Human Kinetics.

Fitts, P.M. (1954). Information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381–391. doi:10.1037/h0055392

Fitts, P.M. (1964). Perceptual-motor skill learning. In A.W. Melton (Ed.), *Categories of human learning* (pp. 243–285). New York, NY: Academic Press. doi:10.1016/B978-1-4832-3145-7.50016-9

Fowler, C.B., & Turvey, M.T. (1978). Skill acquisition: An event approach with special reference to searching for the optimum of a function of several variables. In G. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 1–40). New York, NY: Academic Press. doi:10.1016/B978-0-12-665960-3.50006-2

Gabriele, T.E., Hall, C.R., & Buckholz, E.E. (1987). Practice schedule effects on the a acquisition and retention of a motor skill. *Human Movement Science, 6,* 1–6. doi:10.1016/0167-9457(87)90019-4

Gentile, A.M. (1972). A working model of skill acquisition with application to teaching. *Quest, 17,* 3–23 (Monograph XVII). doi:10.1080/00336297.1972.10519717

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

Gibson, J. (1977). The theory of affordance. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting and knowing: Toward an ecological psychology*. Boston, MA: Houghton-Mifflin.

Gibson, J. (1979). *An ecological approach to visual perception*. Boston, MA: Houghton-Mifflin.

Granit, R. (1981). Comments on the history of motor control. In V. Brooks (Ed.), *Handbook of physiology* (pp. 1–16). Baltimore, MD: Williams & Wilkins.

Greene, P. (1972). Problems of organization of motor systems. In R. Posen & F Snell (Eds.), *Progress in theoretical biology* (Vol 2, PP. 303-338). New York, NY: Academic Press. doi:10.1016/B978-0-12-543102-6.50013-3

Guadagnoli, M.A., & Kohl, R.M. (2001). Knowledge of results for motor learning: Relationship between error estimation and knowledge of results frequency. *Journal of Motor Behavior, 33,* 217–224. doi:10.1080/00222890109603152

Haken, H., Kelso, J.A.S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51,* 347–356. doi:10.1007/BF00336922

Hall, K.G., & Magill, R.A. (1995). Variability of practice and contextual interference effects in motor skill learning. *Journal of Motor Behavior, 27,* 299–309. doi:10.1080/00222895.1995.9941719

Henry, F.M., & Rogers, D.E. (1960). Increased response latency for complicated movements and a “memory drum” theory of neuromotor reaction. *Research Quarterly, 31,* 448–458.

Hird, J.S., Landers, D.M., Thomas, J.R., & Horan, J.J. (1991). Physical practice is superior to mental practice in enhancing cognitive and motor task performance. *Journal of Sport & Exercise Psychology, 13,* 281–293. doi:10.1123/jsep.13.3.281

Janelle, C.M., Barba, D.A., Frehlich, S.G., Tennant, L.K., & Cauraugh, J.H. (1997). Maximizing performance feedback effectiveness through videotape replay and self-controlled learning environment. *Research Quarterly for Exercise and Sport, 68,* 269–279. doi:10.1080/02701367.1997.10608008

Keele, S.W. (1981). Behavioral analysis of movement. In V. Brooks (Ed.), *Handbook of physiology* (pp. 1391–1414). Baltimore, MD: American Physiological Society.

Kelso, J.A.S. (1977a). Planning and efferent components in the coding of movement. *Journal of Motor Behavior, 9,* 33–47. doi:10.1080/00222895.1977.10735092

Kelso, J.A.S. (1977b). Motor control mechanisms underlying human movement reproduction. *Journal of Experimental Psychology. Human Perception and Performance, 3,* 529–543. doi:10.1037/0096-1523.3.4.529

Kelso, J.A.S. (1982). The process approach to understanding human motor behavior: An Introduction. In J.A.S. Kelso (Ed.), *Human motor behavior: An introduction* (pp. 3–19). Hillsdale, NJ: Erlbaum.

Kelso, J.A.S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology, 15,* R1000–R10004.

Kelso, J.A.S. (1992). Theoretical concepts and strategies for understanding perceptual-motor skill: From information capacity in closed system to self-organization in open, nonequilibrium systems. *Journal of Experimental Psychology. General, 121,* 260–261. doi:10.1037/0096-3445.121.3.260

Kelso, J.A.S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Kelso, J.A.S., & Engstrom, D.A. (2005). *The complementary nature*. Cambridge, MA: MIT Press.

Kelso, J.A.S., & Zanone, P.G. (2002). Coordination dynamics of learning and transfer across different effector systems. *Journal of Experimental Psychology. Human Perception and Performance, 28,* 776–797. doi:10.1037/0096-1523.28.4.776

Laabs, G.J. (1973). Characteristics of different reproduction cues in motor short-term memory. *Journal of Experimental Psychology, 100,* 168–177. doi:10.1037/h0035502

Lee, T.D., & Genovese, E.D. (1989). Distribution of practice in motor skill acquisition: Different effects for discrete and continuous tasks. *Research Quarterly for Exercise and Sport, 60,* 59–65. doi:10.1080/02701367.1989.10607414

Lee, T.D., & Magill, R.A. (1983). The locus of contextual interference in motor skill acquisition. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 9,* 730–746. doi:10.1037/0278-7393.9.4.730

Lee, T.D., & Magill, R.A. (1985). Can forgetting facilitate skill acquisition? In D. Goodman, R.B. Wilberg, & I.M. Franks (Eds.), *Differing perspectives in motor learning, memory and control* (pp. 3–22). Amsterdam, Netherlands: North-Holland. doi:10.1016/S0166-4115(08)62528-5

Margolis, J.F., & Christina, R.W. (1981). A test of Schmidt’s schema theory of discrete motor skill learning. *Research Quarterly for Exercise and Sport, 52,* 474–483. doi:10.1080/02701367.1981.10607893

Marteniuk, R.G. (1976). *Information processing in motor skills*. New York, NY: Holt, Reinhart & Winston.

Marteniuk, R.G. (1986). Information processes in movement learning: Capacity and structural interference effects. *Journal of Motor Behavior, 18,* 55–75. doi:10.1080/00222895.1986.10735370

Marteniuk, R.G., & Roy, E.A. (1972). The codability of kinesthetic location and distance information. *Acta Psychologica, 36,* 471–479. doi:10.1016/0001-6918(72)90027-3

McCullagh, P., Law, B., & Ste-Marie, D.M. (2012). Modeling and performance. In S. Murphy (Ed.), *The oxford handbook of sport and exercise performance psychology* (pp. 250–272). New York, NY: Oxford University Press.

McCullagh, P., Ste.-Marie, D.M., & Law, B. (2013). Modeling: Is what you see what you get? In J. Van Raalte & B. Brewer (Eds.), *Exploring sport and exercise psychology* (3rd ed.) (pp. 139-162). Washington, DC: American Psychological Association.

Newell, K.M. (1974). Knowledge of results and motor learning. *Journal of Motor Behavior, 6*, 235–244.

Newell, K.M. (1980). The speed-accuracy paradox in movement control: Error of time and space. In G.E. Stelmach (Ed.), *Tutorials in motor behavior*. Amsterdam, Netherlands: Elsevier. doi:10.1016/S0166-4115(08)61965-2

Newell, K.M. (1985). Coordination, control and skill. In D. Goodman, R.B. Wilberg, & I.M. Franks (Eds.), *Differing perspectives in motor learning, memory, and control* (pp. 295–317). Amsterdam, Netherlands: North-Holland. doi:10.1016/S0166-4115(08)62541-8

Newell, K.M. (1986). Constraints on the development of coordination. In M. Wade & H.T.A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control*. Amsterdam, Netherlands: Martinus Nijhoff Publishers. doi:10.1007/978-94-009-4460-2_19

Newell, K.M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42,* 213–237. doi:10.1146/annurev.ps.42.020191.001241

Newell, K.M., Carlton, L.G., Carlton, M.J., & Halbert, J.A. (1980). Velocity as a factor in movement timing accuracy. *Journal of Motor Behavior, 12,* 47–56. doi:10.1080/00222895.1980.10735204

Reeve, T.G., Dornier, L.A., & Weeks, D.J. (1990). Precision of knowledge of results: Consideration of the accuracy requirements imposed by the task. *Research Quarterly for Exercise and Sport, 61,* 284–290. doi:10.1080/02701367.1990.10608693

Roy, E.A. (1978). Role of preselection in memory for movement extent. *Journal of Experimental Psychology. Human Learning and Memory, 4,* 397–405. doi:10.1037/0278-7393.4.4.397

Salmoni, A.W., Schmidt, R.A., & Walter, C.B. (1984). Knowledge of results and motor learning: A review and reappraisal. *Psychological Bulletin, 95,* 355–386. doi:10.1037/0033-2909.95.3.355

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225–260. doi:10.1037/h0076770

Schmidt, R.A. (1989). Toward a better understanding of the acquisition of skill: Theoretical and practical contributions of the task approach. In J.S. Skinner, C.B. Corbin, D.M. Landers, P.E. Martin, & C.I. Wells (Eds.), *Future directions in exercise and sport science research* (pp. 395-364). Champaign, IL; Human Kinetics.

Schmidt, R.A., & Bjork, R.A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science, 3,* 207–217. doi:10.1111/j.1467-9280.1992.tb00029.x

Schmidt, R.A., Sherwood, D.E., Zelaznik, H.N., & Leikind, B.J. (1985). Speed-accuracy trade-offs in motor behavior: Theories of impulse variability. In H. Heuer, U. Kleinbeck, & K.H. Schmidt (Eds.), *Motor behavior: Programming control, and acquisition* (pp. 79–123). Berlin, Germany: Springer-Verlag. doi:10.1007/978-3-642-69749-4_3

Schmidt, R.A., & White, J.L. (1972). Evidence for an error-detection mechanism in motor skills: A test of Adams' closed-loop theory. *Journal of Motor Behavior, 4*, 143–153.

Schmidt, R.A., & Young, D.E. (1987). Transfer of motor control in motor skill learning. In S.M. Cormier & J.D. Hagman (Eds.), *Transfer of training* (pp. 47–79). Orlando, FL: Academic Press.

Schmidt, R.A., Zelaznik, H.N., & Frank, J.S. (1978). Sources of inaccuracy in rapid movement. In G.E. Stelmach (Ed.), *Information processing in motor control* (pp. 183–203). New York, NY: Academic Press. doi:10.1016/B978-0-12-665960-3.50014-1

Schmidt, R.A., Zelaznik, H.N., Hawkins, B., Frank, J.S., & Quinn, J.T. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review, 86,* 415–451. doi:10.1037/0033-295X.86.5.415

Shapiro, D.C., & Schmidt, R.A. (1982). The schema theory: Recent evidence and developmental implications. In J.A.S. Kelso & J.E. Clark (Eds.), *The development of movement control and coordination* (pp. 113–150). New York, NY: Wiley.

Shea, J.B., & Morgan, R.L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology. Human Learning and Memory, 5,* 179–187. doi:10.1037/0278-7393.5.2.179

Shea, J.B., & Zimny, S.T. (1983). Context effects in memory and learning in movement information. In R.A. Magill (Ed.), *Memory and control of action* (pp. 345–366). Amsterdam, Netherlands: North Holland. doi:10.1016/S0166-4115(08)61998-6

Shea, J.B., & Zimny, S.T. (1988). Knowledge incorporation in motor representation. In O.G. Meijer & K. Roth (Eds.), *Complex motor behavior: "The" motor-action controversy* (pp. 289–314). Amsterdam, Netherlands: North Holland. doi:10.1016/S0166-4115(08)62562-5

Sherwood, D.E. (1988). Effect of bandwidth knowledge of results on movement consistency. *Perceptual and Motor Skills, 66,* 535–542. doi:10.2466/pms.1988.66.2.535

Stelmach, G.E. (1969). Prior positioning responses as a factor in short-term retention of a simple motor task. *Journal of Experimental Psychology, 81,* 523–526. doi:10.1037/h0027913

Stelmach, G.E. (1974). Retention of motor skills. In J.H. Wilmore (Ed.), *Exercise and sport sciences reviews, 2* (pp. 1–31). New York, NY: Academic Press.

Stelmach, G.E. (1977). Toward an information-processing approach in motor behavior research. In L. Gedvilas & M. Kneer (Eds.), *Proceedings of the NCPEAM/NAPECW National Conference* (pp. 199-207). Chicago, IL: University of Illinois at Chicago Circle.

Stelmach, G.E. (1989). The importance of process-oriented research. In J. Skinner, C.B. Corbin, D.M. Landers, P.E. Martin, & C. Wells (Eds.), *Future directions in exercise and sport science research* (pp. 423–432). Champaign, IL: Human Kinetics.

Ste-Marie, D.M., Law, B., Rymal, A.M., Hall, O.J., & McCullagh, P. (2012). Observation interventions for motor skill learning and performance: An applied model for the use of observation. *International Review of Sport and Exercise Psychology, 5,* 145–176. doi:10.1080/1750984X.2012.665076

Summers, J.J., & Anson, J.G. (2009). Current status of the motor program: Revisited. *Human Movement Science, 28*, 566–577.

Swinnen, S.P. (2002). Intermanual coordination: From behavioral principles to neural-network interactions. *Nature Reviews. Neuroscience, 3,* 348–359. doi:10.1038/nrn807

Swinnen, S.P., Schmidt, R.A., Nicholson, D.E., & Shapiro, D.C. (1990). Information feedback for skill acquisition: Instantaneous knowledge of results degrades learning. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 16,* 706–716. doi:10.1037/0278-7393.16.4.706

Swinnen, S.P., & Wenderoth, N. (2004). Two hands, one brain: Cognitive neuroscience of bimanual skill. *Trends in Cognitive Sciences, 8,* 18–25. doi:10.1016/j.tics.2003.10.017

Toole, T., Christina, R.W., & Anson, J.G. (1982). Preselected movement accuracy as a function of movement time, distance, and velocity. *Journal of Human Movement Studies, 8,* 93–102.

Turvey, M.T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing* (pp. 211–265), Hillsdale, NJ: Erlbaum.

Turvey, M.T., Fitch, H.L., & Tuller, B. (1982). The Bernstein perspective: 1. The problems of degrees of freedom and context-conditioned variability. In J.A.S. Kelso (Ed.), *Human motor behavior: An introduction* (pp. 239–252). Hillsdale, NJ: Lawrence Erlbaum Associates.

Weiss, M.R. (2008). “Riding the wave”: Transforming sport and exercise psychology within an interdisciplinary vision. *Quest, 60,* 63–83. doi:10.1080/00336297.2008.10483569

Winstein, C.J., & Schmidt, R.A. (1990). Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 16,* 677–691. doi:10.1037/0278-7393.16.4.677

Wright, D.L. (1991). The role of intertask and intratask processing in acquisition and retention of motor skills. *Journal of Motor Behavior, 23,* 139–145. doi:10.1080/00222895.1991.9942031

Wright, D.L., Li, Y., & Whitacre, C. (1992). The contribution of elaborative processing to the contextual interference effect. *Research Quarterly for Exercise and Sport, 63,* 30–37. doi:10.1080/02701367.1992.10607554

Wulf, G. (2007). *Attention and motor skill learning*. Champaign, IL: Human Kinetics.

Wulf, G., & Shea, C.H. (2002). Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin & Review, 9,* 185–211. doi:10.3758/BF03196276

Yao, W., Fischman, M.G., & Wang, Y.T. (1994). Motor skill acquisition and retention as a function average feedback, summary feedback and performance variability. *Journal of Motor Behavior, 26,* 273–282. doi:10.1080/00222895.1994.9941683