Change in Motor Learning: A Coordination and Control Perspective

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Mudança em aprendizagem motora: Uma perspectiva de Coordenação e Controle

Resumo - Este trabalho examina a questão relativa a mudanças em aprendizagem motora a partir do esquema de referência dos sistemas dinâmicos. Existe mudança qualitativa e quantitativa no desempenho ao longo do tempo que é resultado de um conjunto intrincado de sistemas dinâmicos em evolução, cada um em sua própria escala de tempo de mudança. A aprendizagem ocorre através da busca e da evolução e dissolução de regiões dinâmicas estáveis dos modos de coordenação para uma dada tarefa motora. Assim, o aprendizado é a descoberta (busca) de leis dinâmicas. A natureza das informações relevantes que facilitam a busca e as transições de modos estáveis de performance é a chave para a eficácia de estratégias de aprendizagem.

Palavras- chave: Aprendizagem motora, graus de liberdade, dimensão, restrições da tarefa.

Abstract - This paper examines the issue of change in motor learning from a dynamical systems framework. There is qualitative and quantitative change to performance over time that is driven by an embedded set of evolving dynamical systems each with its own time scale of change. Learning arises through searching and the evolution and dissolution of the stable dynamical regions of coordination modes for a given task. Learning then is discovering (searching for) the dynamic laws. The nature of the relevant of information that facilitates the search and the transitions of the stable modes of performance is the key to the efficacy of learning strategies.

Key Words - motor learning, degrees of freedom, dimension, task constraints.

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The study of human motor learning and control is predicated in part on the promise if not expectation of the application of the derived theoretical principles to physical activity in context. This not to say that basic research in motor learning and control cannot be undertaken in the natural physical settings of physical education and sport, but the reality is that it rarely is. Thus, the translation and extension of theoretical principles and experimental findings is inevitably required in considering motor learning and performance in physical education and sport contexts.

The link between theory and practice is also not as direct in the physical education and sport arenas as it might be (NEWELL; ROVEGNO, 1989). This is not simply because of the many potential mediating factors of context and activity, but rather that the types of questions emphasized in current motor learning and control research are in many cases not directly relevant to the learning and performance needs of physical activity in context. In short, the amount of current research directly examining the kinds of questions that are of interest in physical education and sport is very limited. This unfortunate situation is driven to a large degree by the lack of research money directed to these practical issues by government and the various physical education and sport agencies.

In this paper, I will outline some of the interesting questions that pertain to the nature of change in the learning and performance of physical activities in education and sport settings. The formulation of this list is driven by both the needs of the applied settings and the recent research conducted in laboratory motor learning and control. Full accounts of the relevant theory and practice of each question are provided with the general and specific references that follow.

Change Through Learning and Practice

Theoretical Background to Discussion

Before outlining key issues and questions for consideration I want to briefly mention that the metaphors that drive and organize research for the learning and performance of motor skills have changed over the years. The last 20 years have seen the introduction and now emphasis of the self-organization construct to the movement domain (KELSO, 1995; KUGLER; KELSO; TURVEY, 1980, 1982; KUGLER; TURVEY, 1987). This theoretical framework focuses on the self-organization of the dynamics of the system at multiple levels of analysis over multiple time scales of change (NEWELL; MAYER-KRESS; LIU, 2001). This framework holds different propositions for learning and performance than the more traditional theories of reflex chaining, learning theory, motor programs and schema. I hope to capture key elements of the new approach to motor learning, and their implications for physical education and sport, through a perspective on the role of practice and learning for change in physical activity.

Physical activity requires the organization of a system with many degrees of freedom, a good proportion of which may be redundant to satisfy the immediate task demands of the activity or sport in question (BERNSTEIN, 1967). It should be noted though that the special demands of high-level performance in sport tend to reduce the redundancy problem. The organization and reorganization of the system in learning involves a mapping of information and movement dynamics to produce stable but continually evolving dynamical solutions to satisfy the relevant task constraints. I now try to unpack these briefly introduced assumptions of current theory by amplifying their impact through questions about the role of practice in learning and performance in physical education and sport. The theoretical background to the questions and answers now outlined are more fully discussed in several papers from our laboratory (NEWELL, 1991, 1996; NEWELL; MCDONALD, 1994; NEWELL; VALVANO, 1998; NEWELL; LIU; MAYER-KRESS, 2001; NEWELL; KUGLER; VAN EMMERIK; MCDONALD, 1989).

What is the Nature of the Change in Performance over Time?

Performance in a physical education or sport activity is the product of a continually evolving dynamical organization of the human system. The dynamics for the performance of a particular skill are embedded in a broader set of dynamical organizations and reorganizations that support the conduct of all activities of daily living. The broad organization of the dynamics of human performance has been continually evolving since conception of the individual. The evolving changes in the structural and functional (e.g., anatomy and physiology) constraints provide natural patterns of organizations to the system dynamics. These natural organizations tend to hold more dynamical stability than other patterns of movement performance.

Motor learning over the life span involves the continual evolution of the system dynamics and the ebb and flow of stable and unstable solutions to task demands. Learning involves the change in the qualitative organization of movement dynamics and this naturally involves periods of instability to performance at a variety of levels of analysis. Thus, learning requires the establishment of new stable patterns of dynamics that can be brought together over a sufficient time scale to realize the demands of either a new task to be learned, or the continued improvement in the performance of a given task.

There are multiple time scales to the qualitative change in the learning and performance of physical skills. Motor learning is concerned primarily with those changes to performance that are relatively persistent (such as those evident in the study of learning curves), but there are many influences to performance, and many of these are on short time scales reflecting trial to trial and even within-trial variation. These time scales of change in performance over time can be linked to the nature of the stable dynamics supporting performance and the transitions between the evolving stable modes to performance. Thus, there is qualitative and quantitative change to performance over time that is driven by an embedded set of systems each with its own time scale of change. This leads naturally to the next question as to how these changes occur.

Learning as Searching

Changes in performance over time occur through a mixture of deterministic and chance influences to the evolving dynamics. Teachers of physical activities try to enhance the probability of systematic change in performance over time through the planned introduction of interventions in the form of learning strategies. These learning strategies can be viewed as another constraint to the channeling of dynamics and their evolution over time.

Searching arises from the natural exploration and specific strategic approach to the change in the dynamics over time. Searching affords information about the interaction of the performer with the environment and the nature of the underlying supporting dynamics for action. Searching allows an individual performer to know the stability boundaries to the current attractor dynamic supporting the activity. The motion of the body-environment interaction provides information about this relation and searching provides the vehicle to picking up that information.

Learning requires the search beyond the boundaries of a local stable coordination mode to the less stable environment on a more global scale of an unformed (unstable) dynamic for a given task demand. Infants are naturally passing beyond these boundaries when, for example, they fall over many times in learning to stand. Teachers need to consider principled ways in which to channel a performer to dissolve a relatively successful dynamic (in task output terms) in the search for an even more task rewarding dynamic that will temporarily be unstable and probably less rewarding (for a while) in task performance.

Learning transpires through searching and the evolution and dissolution of the stable dynamical regions of coordination modes for a given task. We need to understand more the nature of the relevant of information that facilitates the search and the transitions of the stable modes of performance. Learning then is discovering (searching for) the dynamics laws.

Augmented Information and Channeling the Search for Task Relevant Stable Solutions

Augmented information is that information that is not normally available to the learner when learning and performing the task. It is information that is augmented to that normally available in the organism-environment interaction during practice of the task. The increasing technological developments make the distinction of natural and augmented information a fine line and a matter of definition, particularly in person-machine interactions, where information that is construed as augmented one day can subsequently be permanently built into the system of future machine designs, to in essence provide natural information the next day. There are a number of different types of augmented information and media through which that information can be conveyed.

There appear to be at least 3 categories of augmented information that are used to facilitate motor learning and performance. These categories include prescriptive information, information feedback, and transition information. These information categories can be considered in a common augmented information framework in which the augmented information provides the support for facilitating the search of the perceptual-motor work-space, the construction of attractor dynamics, and the realization of the task goals.

Prescriptive Information. Augmented information that is prescriptive provides information about the to-be-achieved end-state movement kinematics. The information can specify the relative, absolute and common motion components of a to-be-achieved coordination and control solution to the task demands. This information, or elements of it, is most typically conveyed by oral instructions and/or a demonstration of a behavioral outcome of a to-be-achieved coordination and control solution. The demonstration may be via some medium such as film or videotape, or it can be a live demonstration by an instructor.

The presentation of prescriptive augmented information for the acquisition of movement skills is a common occurrence in activities of dance, sport, and music. This is based upon the intuitive perspective that this category of information is effective for learning, and that "a picture is worth a thousand words". The empirical evidence in support of such a proposition is not as compelling as the intuition, however, which suggests subtle interactions between the effects of this category of information, the nature of the skill and the skill level of the performer.

Information Feedback. This category of augmented information provides information about some past state or states of the movement dynamics produced by the learner in an evolving movement sequence or on a just-completed movement trial. The information feedback could be provided about any absolute, relative or common motion property, but there are principles about the most useful information to provide. Concurrent information feedback provides information about prior states of the still ongoing movement sequence. Terminal information feedback provides information about earlier movement properties or their consequences (movement outcome) on completion of the trial.

A major challenge is to understand the nature of *what* information feedback is appropriate for each learner at each stage of learning a skill. Information feedback has been shown to be a variable that strongly influences the learning and performance of movement skills. In the learning of one or two degree of freedom movement tasks the principle emerging is that the degrees of freedom contained in the information should match the degrees of freedom requiring constraint in the task. However, the problem of what information feedback is appropriate in the learning of whole-body actions is more profound because many informational properties of the action may be considered. In tasks requiring the coordination of many biomechanical degrees of freedom it is the case that information feedback is often not very direct about the nature of the change that needs to be made on the next trial. The consequence is that in many task situations information feedback does not constrain the search sufficiently for the learning of new coordination modes, leading to less effective and efficient learning than has been apparent in investigations of the learning of single-limb tasks under the same information feedback conditions.

Transition Information. A category of augmented information that has not been studied systematically is that of transition information. This is information that relates directly to the change in the coordination and control solution that needs to occur at some future time of the ongoing trial or on the next trial in a learning sequence. This type of information would appear to be particularly useful in the acquisition of a new set of relative motions or movement form for the task at hand. Transition information is that which specifies a to-be-achieved property of a coordination and control solution that should be searched for in the upcoming movement trial, but in the act of realizing that goal, a transition to another coordination and control solution emerges. Thus, transition information is not prescriptive information in that it is not prescribing the to-be-achieved end state dynamics of the to-be-learned movement skill, and it is not information feedback in that it does not provide information about past movement states and their goals realized. Rather, it provides information more *directly* about the change in movement coordination and control, than either prescriptive or feedback information. Theoretically, transition information may be viewed as a control parameter that facilitates the search through the perceptual-motor work-space for the realization of a task relevant coordination and control solution, and it may appear unrelated to the to-be-achieved end state dynamics.

A key issue for a theory of motor learning is how to integrate the concept of information into the Bernstein coordination problem and the changing regulation of redundant degrees of freedom. The categories of augmented information sketched out above provide different forms of information to the learner and support the information naturally available for motor learning and control in the organsim-environment interaction. These categories of augmented and natural information are rarely considered in a cohesive theoretical framework but they can be usefully viewed as information that facilitates the search for task relevant coordination and control solutions. The respective categories of information provide different types and degrees of constraint on the search behavior and the emergent channeling of the task relevant movement dynamics. In practice, instructors tend to intertwine the use of each of these categories of information, according to the nature of the task and the skill level of the performer, to facilitate motor learning.

In general then, augmented information acts as an environmental constraint to action. The different categories of information provide varying boundary conditions to the search through the perceptual-motor workspace in the realization of new task goals. How information facilitates exploratory behavior in motor learning is an integral part of coming to terms with Bernstein's problems of learning to regulate redundant degrees of freedom, and practice as repetition without repetition.

Practice Schedules and Search Strategies in Learning?

A long standing problem in motor skill learning is the establishment of the most appropriate schedule of practice for the activity at hand. This problem is usually considered under what is called massed and distributed practice schedules. The schedule of practice constructed tends to be very task specific, due to the particular constraints present in the learning and performance of a given skill.

The idea that learning reflects an evolving set of dynamical relations extends to studies of the cortical organization and activity that arises from use and disuse over time of actions. Recent research has shown that the homunculus layout of effector connections in the motor cortex can be reconfigured as a consequence of use and disuse. This striking finding adds further evidence to the evolving state of systems that support physical performance and that modify performance over time.

Regular and sustained physical practice then is essential to sustaining the effectiveness of the system output in particular tasks, although mental practice can also induce system changes. The limits of practice may relate more to the problems of fatigue and the generation of inappropriate movement patterns, and the loss of attention in task execution through motivational losses. Practice does not make perfect as the old adage holds, but it is essential in the pursuit of high performance. Deliberate practice in a task with attentional effort is the key and not ere repetition of the movement and activity.

Are there Critical Periods to Motor Learning?

Many teachers of physical education and coaches of sport subscribe to the view that there are "critical periods" for the learning of motor skills. This concept is part of a broader view to the notion of critical or sensitive periods to the acquisition of various skills over the life span. The most well supported example may be in regard to the acquisition of languages.

There is no compelling evidence available in regard to critical periods and the acquisition of motor skills. Nevertheless, the idea follows in principle from a dynamical approach to motor learning. The evolution and dissolution of certain stable attractor dynamics for tasks may be more or less attainable in qualitative terms and/or may vary in the time scale of its accomplishment. A working proposal is that the acquisition of new movement forms is more efficient the younger the performer due to the greater flexibility for system reorganization. The notion of critical periods is related strongly to the general principles of learning, transfer and retention.

Is Skill Specific?

The answer to this traditional question from the current framework is yes. This is because the performance observed at any moment in time is the product of an evolving set of dynamical interactions that will be specific to a particular task outcome. This is not to say that transfer (positive or negative) cannot be present between the organization and performance to different task demands or that the same task outcome cannot be produced via different dynamic organizations (redundancy). Rather, it is to say that skill, as we typically infer it in regard to a special level of advanced performance in physical activity, is the product of a particular set(s) of dynamical interactions that have been assembled over a long period of time, practice and experience.

Are there Limits to Learning in Physical Activity?

Again, this is an old question that has not been addressed very satisfactorily from traditional or contemporary frameworks for motor learning. The dynamical framework here would lead to the position that there are no limits on learning but there may exist limits to performance. In other words, the systematic change that we interpret as learning can continue over the life span but the associated performance as measured in task space, may decline. This decline in physical performance may well be the result of changes in the potential of particular subsystems (flexibility, strength etc). Nevertheless, it is well established that the enhancement of skill can occur over very long time periods often involving tens of years.

Learning can continue with sustained searching, even to (or because of) the new constraints that can arise though the deteriorating dynamical potential of particular subsystems. This distinction points up explicitly the difficulty of inferring learning from performance measures. Thus, learning is a life long process, although it too can be mediated and even compromised by motivation and other states of the system.

Summary of Perspective

There is nothing as basic as a good applied question and nothing as applied as a good basic theory. The problem of practice captures well the essence of this statement. Motor learning is not about acquiring more relevant and better symbolic representations for action but rather the ability to temporarily map information to movement dynamics in the assembly of a task relevant coordination solution that is influenced by the dynamics of previous engagements in activity and the local constraints. The outline to the issues of change and learning addressed here, although only representing a beginning, provide a coherent basis for a more principled consideration of the role of practice in physical activity.

References

B BERNSTEIN, N. **The co-ordination and regulation of movements**. New York: Pergamon, 1967.

KELSO, J. A. S. **Dynamic patterns:** the self-organization of brain and behavior. Cambridge, MA: MIT Press, 1995.

KUGLER, P. N.; TURVEY, M. T. **Information, natural law, and the self-assembly of rhythmic movement:** Theoretical and experimental investigations. Hillsdale, NJ: Erlbaum, 1987.

KUGLER, P.N.; KELSO, J. A. S.; TURVEY, M. T. On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In STELMACH, G. E.; REQIUN, J. (Eds.), **Tutorials in motor behavior**. p. 1-49. New York: North–Holland, 1980.

KUGLER, P.N.; KELSO, J. A. S.; TURVEY, M. T. On the control and coordination of naturally developing systems. In KELSO, J. A. S.; CLARK, J. E. (Ed.), **The development of movement control and co-ordination.** p. 5-78. New York: Wiley, 1982.

NEWELL, K. M. Motor skill acquisition. **Annual Review of Psychology**, 42, p. 213-237, 1991.

NEWELL, K. M. Change in movement and skill: Learning, retention, and transfer. In LATASH, M.; TURVEY, M. (Ed.), **Dexerity and its development.** Hillsdale, NJ: Erlbaum, 1996.

NEWELL, K. M.; ROVEGNO, I. Physical Education and motor learning. **Quest**, 42, 184-192, 1990.

NEWELL, K. M.; VALVANO, J. (1998). Therapeutic intervention as a constraint in learning and relearning movement skills. **Scandanavian Journal of Occupational Therapy**, 5, 51-57.

NEWELL, K. M.; MCDONALD, P. V. Learning to coordinate redundant biomechanical degrees of freedom. In: SWINNEN, S.; HEUER, H., MASSION, J.; CASAER, P. (Ed,), **Interlimb coordination:** neural, dynamical, and cognitive constraints. p. 515-536. New York: Academic Press, 1994.

NEWELL, K. M.; MAYER-KRESS, G.; LIU, Y-T. Time scales in motor learning and development. **Psychological Review**, 108, 57-82, 2001.

NEWELL, K. M.; MORRIS, L. R.; SCULLY, D. M. Augmented information and the acquisition of skill in physical activity. In TERJUNG, R. L. (Ed.), **Exercise and Sport Sciences Reviews**, 13, 235-262, 1985.

NEWELL, K. M.; KUGLER, P. N.; VAN EMMERIK, R. E. A.; MCDONALD, P. V. Search strategies and the acquisition of coordination. In WALLACE, S. A. (Ed.), **Perspectives on the coordination of movement.** p. 85-122. Amsterdam: North-Holland, 1989.

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