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An Adaptive Process Model of Motor Learning: Insights for the Teaching of Motor Skills

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Abstract: *This article presents an outline of a non-equilibrium model, in which motor learning is explained as a continuous process of stabilization and adaptation. The article also shows how propositions derived from this model have been tested, and discusses possible practical implications of some supporting evidence to the teaching of motor skills. The stabilization refers to a process of functional stabilization that is achieved through negative feedback mechanisms. Initially, inconsistent and incorrect responses are gradually reduced, leading to a spatial-temporal patterning of the action. The adaptation is one in which new skills are formed from the reorganization of those already acquired through the flexibility of the system, reorganization of the skill structure, or self-organization. In order to provide learners with competency for adaptation, teachers should (a) guide students to learn motor skills taking into account that the stabilization of performance is just a transitory state that must be dismantled to achieve higher levels of complexity; (b) be clear which parts (micro) compose the skills and how they interact in order to form the whole (macro); (c) manipulate the skills in terms of their temporal, spatial, and/or spatiotemporal dimensions; (d) organize practice initially in a constant way, and then in a varied regimen (random) when the motor skills involve requirements of time and force; and, inversely for motor skills with spatial demands; and (e), provide a moderate frequency of feedback.*

Key Words: adaptation, complexity, non-equilibrium, teaching-learning, motor skill.

INTRODUCTION

How individuals learn motor skills has intrigued researchers and professionals in educational fields (e.g. physical education teachers), probably because effective teaching methods are closely related to the knowledge about

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how individuals learn. In fact, there is an expectation that the knowledge produced in the motor learning field provides insights for professionals and researchers in the movement pedagogy field (Magill, 1994; Rink, 2010; Schmidt, 1977, 1989; Silverman, 1994; Silverman & Skonie, 1997; Tani, 2006; Tani & Corrêa, 2004). These fields focus, respectively, on how individuals learn motor skills and how to teach them.

The motor learning field has a quite long history. Initial research goes back to the late ninetieth century. An important aspect to be emphasized here is that traditional and contemporary influential models and theories of motor learning (e.g. Adams, 1971; Gentile, 1972; Newell, 1996; Schmidt, 1975) conceived of motor skills acquisition as a stabilization of the performance process (e.g. structure formation), in which initial inconsistency and lack of coordination in movement are gradually eliminated and replaced by patterned and accurate movements. In other words, motor skill learning is explained by an equilibrium model based on negative feedback mechanism.

As is well known, a negative feedback mechanism makes possible the acquisition and maintenance of system´s stability, but it cannot explain how systems achieve new states of organization, which is the basic nature of open systems seeking for growing complexity (von Bertalanffy, 1950, 1952). To put it in another way, not all systems submit themselves to the second law of thermodynamics. There are systems in which entropy can increase, remain in steady state, or decrease. These are the cases of complex adaptive systems, as they import "negative entropy" (Gell-Mann, 1994; Holland, 1995; Kauffman, 1995a, 1995b, 1997; Lewin, 1999). Thus, taking into account the open systems nature of human beings in constant search of more complex states of organization, motor learning models or theories need to explain how new structures emerge from old ones. Regarding the importance of stabilization in open systems, another aspect to be considered is their ability to reach new states of organization by dismantling existing stability or organizations, i.e. adaptation.

In an attempt to explain motor skill learning as a process beyond stabilization, a model characterizing motor learning as an adaptive process has been proposed (e.g. Choshi, 1982, 1985; Choshi & Tani, 1983; Corrêa, Ugrinowitsch, Benda, & Tani, 2010; Corrêa, Massigli, Barros, Gonçalves, Oliveira, & Tani, 2010; Corrêa, Alegre, Freudenheim, Santos, & Tani, 2012; Fonseca, Benda, Profeta, & Ugrinowitsch, 2012). The main objective of this article is to present an outline of this model, to show how propositions derived from the model have been tested, and to discuss possible practical implications of some supporting evidence to the teaching of motor skills.

THEORIES AND MODELS OF MOTOR LEARNING

Science advances by means of revolutions that create new paradigms and change the way that human beings view the world and nature, and seek to understand phenomena in general (Kuhn, 1970). Thus, it is essential for any researcher to be aware of and be in tune with paradigmatic changes because, as Kuhn suggests, a paradigm change does not simply mean new subjects of investigation but also the revisiting of old questions. For instance, the systemic thinking developments of the twentieth century (Dupuy, 1996; Fleener & Merritt, 2007; Guastello, 2007; Jantsch, 1980; Pask, 1992; Vijver, 1992) have influenced the development of models and theories in different areas of knowledge, including that of motor learning (Abernethy & Sparrow, 1992; Guastello, Nathan & Johnson, 2009; Ingvaldsen & Whiting, 1997; Tani, Corrêa, Benda, & Manoel, 2005).

Emphasis on the negative feedback mechanism predominated in the first half of the twentieth century under the influence of Shannon and Weaver's (1949) and Wiener's (1948) seminal works on communication and control. In the motor learning field, the traditional models (Fitts & Posner, 1967; Gentile, 1972) and theories (Adams, 1971; Schmidt, 1975) were based on self-regulation and control models. For instance, in Adams´s closed loop theory (Adams, 1971), the reduction of error was attained by the comparison of movement-generated feedback information with a reference in memory during performance. Schema theory (Schmidt, 1975) also addressed information processing, but focused on control mechanisms based on abstract rules called schema, and on a memory structure called generalized motor program. In both theories, motor skill learning involves a process of error reduction by comparing movement generated feedback information to a cognitive structure stored in the central nervous system (e.g. motor program or schema). This process is based on negative feedback mechanism.

In all the foregoing theories, motor skill learning is conceived of as a process that unfolds in identifiable phases. For instance, Fitts and Posner (1967) describe motor skill learning as occurring in three phases: cognitive, associative and autonomous. In the first phase the learner is overwhelmed by a wealth of information surrounding the performance context, and attempts to reduce it. The cognitive phase is the understanding of the demands of the task and the elaboration of a plan of action. In the associative phase, the learner understands the task goal, and tries to gradually reduce the discrepancy between the intended and the actual performance by means of repeated practice. In the last phase, the execution of skill typically involves a minimal amount of conscious involvement, whereby accurate and coordinated movements are performed autonomously.

In the second half of the twentieth century, a shift in emphasis to the interplay of positive and negative feedback mechanisms and self-organization (e.g.von Foerster, 1960; Jantsch, 1980; Maruyama, 1963; Prigogine, 1967; Prigogine & Stengers, 1984; Weiss, 1967, 1969; Yates, 1987) influenced the development of contemporary models in the motor learning field (Newell, 1996; Schöner et al., 1992; Zanone & Kelso, 1991, 1997).

Contemporary models consider the nonlinear and self-organizational characteristics of the motor system (Kelso, 1995), which explain the ability of the motor system to work autonomously and without mediation by internal representational structures such as motor programs and schemata. Based on Bernstein's (1967) and Gibson's (1966, 1979) ideas on the problem of degrees of freedom and on direct perception, respectively, the dynamic models use concepts from nonlinear dynamical systems theory (NDS), such as phase transition, critical point, bifurcation, stability, attractor, and others (Haken, Kelso & Bunz, 1985) to explain motor skill learning.

There are three main contemporary models. The first one, Jacobs and Michaels' model bases learning on three main tenets: information space, learning as moving through the space, and information-for-learning (Jacobs & Michaels, 2007; Michaels & Romaniak-Gross, 2012). First, the information required to perform a task is available in a manifold, an abstract information space. During the practice, learners are driven by direct perception and move into information space toward the locus that represents the optimal condition for performing the task (Jacobs & Michaels, 2007; Michaels & Isenhower, 2011). In order to achieve this behavior, the learner needs to be pushed toward that locus. The force that drives perceivers to learning is called information-for-learning and is represented as a vector (Michaels, Arzamarski, Isenhower, & Jacobs, 2008; Michaels & Romaniak-Gross, 2012). Whereas information-for-perception (represented as a point) allows presentation of a specific performance, information-for-learning moves the learner into information space during practice. The displacement presented by vectors, then, is based on information that drives learners to practice the optimal control of information (Jacobs & Michaels, 2007; Michaels et al., 2008).

In the second model, learning is seen as the stability and instability of movement patterns resulting from constraints on action (Newell, 1996).Changes at the task level are products of an evolving set of dynamical subsystems at multiple levels of analysis of the organism-environment interaction, each with its own changing timescale (Newell, Liu, & Mayer-Kress, 2001). Learning can be seen as a process of searching, exploring, discovering, assembling, and the functional stabilization of movement patterns (Davids, Button, & Bennet, 2008; McDonald, Oliver, & Newell, 1995), occurring in three stages: (a) assembling a coordination pattern, (b) gaining control of a coordinative structure, and (c) skilled optimization of control.

Interestingly, as in traditional models, these two contemporary models conceptualize motor skill learning as a process that unfolds in phases toward functional stabilization.. In other words, while motor skill learning has been explained as a process of automation or cognitive structure formation (motor program or scheme) in the traditional models, these contemporary models postulate a skilled optimization of control or optimal control of information as the last learning phase.

It has been pointed out that there is a crucial limitation in theories of motor learning in that they are concerned only with the functional stabilization (Choshi, 1981, 1982, 1985, 2000; Choshi & Tani, 1983; Ingvaldsen & Whiting, 1997; Tani, 1982, 1995, 2005a). This criticism is based on the limited capacity of these models to explain phenomena characterized by processes of increasing complexity. The aforementioned traditional and contemporary theories of motor learning are all focused on the functional stabilization that ends when the autonomous phase or optimal control is reached. In other words, they have a finite view of the motor skill learning process so that they have limitations in terms of explaining the dynamic process of motor skill learning, which is marked by continuous changes of growing complexity.

Both traditional (closed-loop and scheme) and contemporary (direct-learning and skilled optimization of control) theories are unable to explain the difference in motor learning between a basketball lay-up performed by a professional and that performed by an ordinary player with regards to how they achieved the actual competencies. Both can perform it automatically, but the difference is of course marked. Where is the difference? One possible answer is that it appears when perturbations are faced. An ordinary basketball player would probably not be able to manage a single opponent block during the execution of a lay-up without collapsing. The professional facing the same situation could handle it by changing the parameters of the final movements such as the arm path or delaying the ball delivery. Moreover, when facing a double opponent block, he can still achieve the goal by changing the structure of the movement itself by transferring the ball from one hand to another and throwing it into the basket successfully. In the critical situation of a triple opponent block, he can even create a totally new structure such as making a 180-degree turn in the air giving the back to the opponents and making a dunk with both arms. Neither theory is able to explain the process that leads to the remarkable differences between the professional and the ordinary player. For the present purpose, we are suggesting that the top professionals have gone through successive processes of adaptation that enable their lay-up skill to become increasingly more complex and, therefore, will have more resources to cope with perturbations.

The systems concept is essential for the comprehension of the limitations of the stabilization-oriented models in explaining motor skill learning. Systems can be classified according to many criteria, but the distinction between open and closed systems has important implications for the understanding of the phenomenon of motor skill learning. Closed systems do not exchange energy, matter and information with the environment, therefore the only possible exchange is in their internal activities. As a consequence, they tend to reach states independent of time, or rather, independent of the past and future conditions that maintain their characteristics (Prigogine, 1997; Prigogine & Stengers, 1984). Open systems, on the other hand, can obtain, use and exchange matter or energy and information with their environment, which allows them to change the content and the organization of their contexts and become more complex and elaborate as a result (Jantsch, 1980). Open systems remain in a state far from equilibrium and consequently they can change, develop, and increase in complexity.

The capacity of changing toward more complex states of organization is a fundamental property of living systems (Cook, 1980; Kelso, 1995; Kelso & Haken, 1997). This property involves two basic processes. The first is stability, which is attained through self-regulatory mechanisms relying on negative feedback. In this way, the system's structure is maintained. The second is adaptation, which involves the formation of more complex structures from existing ones. To this end, there must be a breakdown of stability (e.g. phase shift or bifurcation) followed by another regime of stability, but in a new level of complexity. This characterizes adaptation of structures in the neuromotor system.

The notion of increased complexity in motor skill learning is based on the supposition that new components are incorporated into the previous structures. For instance, in Corrêa et al.'s (2010a) experiment 2, fifty-four children, with an average age of 12.4 years (±1.2), performed a complex task of coincident timing (five sequential movements with the dominant hand interacting with a visual stimulus) under different practice schedules (constant, random, constant-random, and random-constant). Results showed that when a perturbation was inserted (i.e., a new response pattern was required) children who practiced under the constant and constant-random schedules showed better performance, because they were able to modify the movement pattern's structure (i.e., relative timing) in relation to two components (i.e., third and 5th sub-movements of the task) in order to adapt themselves. Therefore, the new stability regimen was achieved by two new components in the task structure. Taking these two processes together, there is a clear need to reconsider the meaning of stability in open systems. Stability in living systems can be seen as a transitory state.

Human beings, as open systems, are in constant interaction with their environment. Hence, they are affected by changes in the environment and consequently they must have the capacity to adapt to these changes. Adaptability is essential for open systems. When open systems face perturbations that cause instability they can: (a) attempt to keep stability, or (b) attain a new macroscopic pattern created out of instability and resulting in an increase of complexity. The capacity to eliminate uncertainties generated by changes in the environment is clearly a necessary condition for the maintenance of a given pattern or organization within the system. Examples of such are human homeostatic control of body temperature and immunological control processes. However, the maintenance of stability does not guarantee systems' development to states of higher complexity. For this purpose, it is necessary to make the instability a source of change towards new states of organization.

What implications for the study of human motor skill learning can be drawn from the consideration of human beings as an open system? Later theoretical developments in the system paradigm such as the thermodynamics of irreversible processes (Prigogine, 1997), self-organization (Jantsch, 1980; Yates, 1987) and synergetics (Haken, 1977) have led to a reconsideration of the role and significance of randomness, variability, uncertainty, and noise amongst other factors related to disorder, in many fields of science (e.g. Sprott, 2013). These new developments call attention to the need to formulate theories of motor learning that go beyond stabilization.

The dynamic systems theory of motor coordination is the third contemporary model of motor skill learning (Schöner, Zanone, & Kelso, 1992;

Zanone & Kelso, 1992a, 1997). In fact, recent developments in the dynamic systems theory have explained how new skills are acquired based on the modification of those old ones (Kelso, 2012; Kostrubiec, Zanone, Fuchs, & Kelso, 2012). Learning occurs as new behavioral information (e.g. intention or task goal) is specified, i.e. a learning task or intention, functioning as a new control parameter. In this process the actual pattern stability is broken and driven to another attractor state. In other words, the change from a pattern to another occurs as a consequence of the competition between intrinsic dynamics and behavioral information (Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992a/b, 1997).

However, not all new behavioural information will generate the same level of perturbation on the intrinsic dynamics and, consequently, learning. Recently Kelso and colleagues (Kelso, 2012; Kostrubiec et al., 2012; Mayer-Kress, Newell, & Liu, 2009) have proposed that the adaptive changes might occur by a shift mechanism or a bifurcation mechanism depending on the learner's motor repertory, for example. Learning by a shift mechanism refers to those not qualitative but gradual changes within the overall attractor characteristics. In turn, the learning through bifurcation mechanism refers to changes in stability regimen. Bifurcation implies a qualitative change in previous skill repertoire by adding new stable pattern. According to Kelso (2012), the bifurcation route leads to better learning than shift route.

In fact, the dynamic systems theory of motor coordination has brought about remarkable advances, especially in relation to the mechanisms of control and coordination of cyclical and rhythmical movements, such as those involved in the bimanual finger flexion-extension task (Kelso, 2012; Kostrubiec et al., 2012). Nevertheless, although promising, its development in the field of motor skill learning has been still incipient. For instance, complex motor skills such as those taught in the physical education and sport contexts have only recently been focus of investigation (e.g. Button, Lee, Mazumder, Tan, & Chow, 2012; Chow, Davids, Button, Rein, Hristovski, & Koh, 2009; Schöllhorn, Hegen, & Davids, 2012). Although there have been recent efforts toward physical education and sport pedagogy (Chow et al., 2007; Henderien & van Geert, 2013), it should be acknowledged that most of the contributions in these contexts are still in the field of motor control. Furthermore, conceptions of bifurcation and shift routes seem to need further explorations in order to show specifically in what aspect motor skills are modified in order for adaptation to take place. One could also say that relative phase is still a difficult concept to be used as instruction in the aforementioned learning/teaching contexts.

This is not to say that the dynamic systems model does not have the potential to contribute to the understanding of the motor skills acquisition process. By conceiving the motor learning as a process of self-organization and using conceptual tools such as attractor, pattern formation, intrinsic dynamics, and so on, it can tackle change, which is the very essence of the learning process (Mayer-Kress, Newell, & Liu, 2009). In sum, it is important to emphasize that the adaptive process model we present is an alternative approach to both traditional and contemporary models and theories to investigate the motor learning phenomenon.

THE ADAPTIVE PROCESS MODEL OF MOTOR LEARNING

Adaptation is a broad concept largely used on scientific investigation. Biological, social, or cultural adaptation is common. Adaptation occurs when changes in the environment perturb the system, challenging its stability and causing uncertainties (Conrad, 1983). Thus, in open systems, uncertainties are not just elements to be eliminated to maintain stability; they are sources for the emergence of order (Prigogine & Stengers, 1984; Yates, 1984, 1987).

An alternative model of non-equilibrium has been proposed in which motor skill learning is explained as a continuous process in which new skills are formed from the reorganization of existing skills, that is, an adaptive process (Choshi, 1981, 1982, 1985, 2000; Choshi & Tani, 1983; Tani, 1982, 1995, 2005a). Two hierarchical phases are proposed: stabilization and adaptation. The first refers to a process of functional stabilization that is achieved through negative feedback mechanism. Initially inconsistent and incorrect responses are gradually reduced, leading to a spatial-temporal patterning of the action. When this takes place, it is inferred that a motor skill structure (movement pattern) has been formed. For example, when an individual is learning a lay-up of basketball, he/she presents "coarse movements", differentiated from trial to trial, and the task is achieved only with difficulty. With practice, however, the learner acquires control over all elements of the lay-up (e.g. steps, jump, and shot), integrating them in a patterned way so the shot goal is achieved successfully. As previously described, the autonomous phase in traditional models, and skilled optimization of control in contemporary models, are examples of a functional stabilization phenomenon.

In this model, the skill structure is assumed to be organized hierarchically at macroscopic and microscopic levels (Manoel, Basso, Corrêa, & Tani, 2002; Tani, Connolly, & Manoel, 1998; Tani, 1995, 2005b). According to this proposition, the macrostructure refers to the overall pattern that emerges from the interaction of the components that is understood to be responsible for making actions consistent. The microstructure, in turn, corresponds to these components themselves. It is oriented to disorder, leading to variability in the actions.

Graphic skills have been used to test these propositions. Specifically, a graphic pattern to be reproduced was composed by 10 straight segments similar to a Chinese character. Macrostructure was examined by looking at the standard deviations of sequencing, relative size, relative timing and relative pause time, while microstructure was examined by looking at the standard deviations of total size, total movement time, and total pause time (Manoel, Basso, Corrêa, & Tani, 2002; Tani, 1995). The interpretation of the variant and invariant aspects of motor skills depends on the theoretical stance one assumes (see, for example, different interpretations of relative timing made by Schmidt (1985) and Zanone & Kelso, (1992a), but the existence of such features in the organization of skills has been strongly supported by empirical studies (Kelso, 1997; Newell, 1996). It is well established in the literature that relative timing, relative force and sequencing are features that remain relatively unchanged; movement time, total force and muscle selection vary from trial to trial. This finding provides a rationale for use of measures related to macrostructure and microstructure.

Once stabilized, the skill is challenged by new demands, such as new goals and external perturbations that create uncertainties. The next phase, adaptation, is one in which new skills are formed from the reorganization of those already acquired to respond to those uncertainties. It might occur in three ways: (a) through the flexibility of the system, i.e. alteration of parameters (parametric adaptation); (b) by reorganization of the skill structure (structural adaptation); and (c) through the emergence of a completely new structure (self-organizational adaptation). As we saw, in order to adapt to the presence of a defender during the execution of a lay-up in a basketball game, the individual could perform the same movement, but more quickly, change a structural component such as the position of the hand at the time of shooting, or even perform a completely new movement. For instance, a recent study in the sports context (Corrêa et al., 2012) showed evidence of the game of futsal as an adaptive process. It was shown that throughout the game the teams presented these adaptations in an unpredictable manner both in attack and defense.

In the last few years, a number of studies have been carried out in order to explain how motor skill learning takes place from an adaptive process perspective. Their findings allow us to infer implications for the teaching.

Adaptive Process, Stabilization Level, and Type of Perturbation

Considering that learning beyond stabilization requires instability, it is essential to investigate the mechanisms by which the system adapts to it, which basically depends on when and how much instability is introduced. A set of studies was developed in order to investigate these aspects (Cattuzzo & Tani, 2012; Fonseca, Benda, Profeta, & Ugrinowitsch, 2012; Ugrinowitsch et al., 2010; Ugrinowitsch et al., 2011; Ugrinowitsch & Tani, 2004). For example, Ugrinowitsch et al. (2010) investigated the effects of the stabilization level on adaptation to perceptual perturbation in motor skill learning. The participants were 62 college students and the task was to perform a predetermined sequence of five movements in a coincident timing task. In this task the perceptual information referred to a light stimulus with duration of 1,700 msec. The stabilization level was defined based on two criteria of performance: three consecutive trials with an error of $\leq$ 25 msec (stabilization group), or six blocks of three trials with an error of $\leq$ 25 msec (super-stabilization group). After that, a new time constraint (1,550 ms) was inserted as a perturbation and the learners had to perform the task within the same level of error of $\leq$ 25 msec. Thereafter the time constraint returned to 1,700 ms and both groups practiced until they met the criterion once more. Results showed that with the change in task the groups had similar errors, but the stabilization group had to change their task structure more (relative timing of the movement sequence) than the super-stabilization group. It appeared that the extensive practice during the stabilization phase provided the learners with more capacity to adapt.

In a later study, Ugrinowitsch et al. (2011) investigated motor skill adaptation in relation to levels of perturbation. In this study they manipulated the perceptual-motor perturbation, such that both temporal (visual stimulus duration) and spatial (sequence of movements) dimensions of a complex coincident timing task were modified. Three levels of performance stabilization were established: pre-stabilization, stabilization, and super-stabilization. Each group practiced the task until it reached its level of stabilization in a constant sequence of movements and under a constant time constraint before exposure to perturbation. The results showed that during the adaptation phase the super-stabilization group had smaller error than the stabilization and pre-stabilization groups, and that the stabilization group had smaller error than the pre-stabilization group. Interestingly, results also showed that the pre-stabilization group did not adapt itself, inasmuch as it did not meet the criteria of performance stabilization.

In sum, the results of these studies suggest that: (a) stabilization is a prerequisite for adaptation; (b) practice beyond stabilization criteria favors adaptation; and (c) the adaptation is dependent on the type of perturbation, being higher when it involves simultaneous changes in spatial and temporal parameters of the task, and lower when it involves only temporal parameter changes.

Adaptation and Stabilization in Constant-Random Practice

If functional stabilization implies formation of a structure, what kind of structure would promote adaptation? The structure formed should reflect the two basic characteristics of skillful actions: consistency and variability (Connolly, 1977; Glencross, 1980; Turvey, 1977). Consistency is necessary to achieve goals with reliability and variability is fundamental to cope with environmental instability. How these apparently contradictory characteristics could be reconciled within a single structure? As previously presented in the adaptive process model, such structure is viewed as hierarchically organized in two levels: macrostructure (responsible for consistency) and microstructure (responsible for variability). Thus, an important question is how the practice should be organized in order to facilitate the acquisition of a structure with these characteristics?

In Corrêa et al.'s (2003) study, 80 children of both sexes, with an average age of 12.4 years (±1.2), practiced a manual force control task using a digital handgrip dynamometer in order to reach pre-determined performance goals. They were divided into four practice groups: constant, random, constant-random, and random-constant. In the stabilization phase, when the practice was constant the children performed the task with 60% of the maximum grasping force. For the random practice, the task involved three goals: 20, 60 or 80% of the maximum grasping force. In the adaptation phase the task goal changed to 40% of the maximum grasping force. Results showed that the children in the constant and constant-random groups had better performance in the adaptation phase than the children in the other groups.

Corrêa et al.'s (2010a) study had similar experimental groups, but they performed three experiments in which children, with an average age of 12.2 years (±0.9), performed a task that involved temporal and spatial requirements in terms of touching five targets sequentially interacting with a visual stimulus. In experiment 1, practice involved different velocities of the visual stimulus. Thus, the constant group performed all of the trials at a single speed of the visual stimulus; the random group performed all of the trials with a random variation of three speeds of the visual stimulus; the constant-random group performed the first half of the trials in the same manner as the constant group, and the subsequent trials in three speeds of the stimulus similar to the random group; the random-constant group performed the first half of the trials randomly varying the speed of the stimulus, and the subsequent trials in a single speed. Results showed worse performance for the random-constant group in the adaptation phase.

Experiment 2 required different movement sequences. In the constant group performed all of the trials in a single sequence of movements, and the random group performed the trials with a random variation of three movement sequences; the constant-random group children executed the first half of the trials in the same manner as the constant group, and the previous trials in three different sequences. Contrary to the constant-random group, the random-constant performed the first half of the trials randomly varying three sequence of movements, and the second half of the trials in a single sequence. Results showed that the children in constant-random practice had better performance in the adaptation phase than the children in the remaining groups.

Finally, in experiment 3 the practice was manipulated in terms of both the velocities of the visual stimulus and the movement sequences. Similarly to the previous experiment, better performance was observed for the constant-random practice group. The successful adaptation in most experiments for learners who had constant followed by random practice in the stabilization phase led the authors to suggest that constant practice facilitates the pattern formation enhancing the consistency of macrostructure and subsequent varied practice makes its diversification possible by assuring variability of microstructure.

Optimal Amount of Practice

How many initial constant practices in the stabilization phase would be necessary to promote the macrostructure formation of the skill? Three studies were carried out in order to investigate the effects of different amounts of constant practice, before varied practice, on the adaptive process of motor learning (Corrêa, Gonçalves, Barros, & Massigli, 2006; Corrêa, Barros, Massigli, Gonçalves, & Tani, 2007; Corrêa et al., 2010b). For instance, in Corrêa et al. (2010b) the temporal, spatial, and spatiotemporal dimensions of a complex task of coincident timing were varied for diversification. Interestingly, results in all experiments showed no difference in the adaptation phase with regard to the groups with different amounts of constant practice. Thus it was concluded that the minimum amount of practice was enough for the formation of a macrostructure of the skill.

Task Specificity

How to teach is closely dependent on what to teach. In fact, task characteristics have long been important aspect to be considered for the elaboration of models and theories in the motor learning field (Newell, 1989, 1991). Consequently, studies were carried out to investigate whether the beneficial effects of constant-random practice were influenced by task characteristics such as specificity.

Barros and Corrêa (2006) verified whether the effects of practice schedule on the adaptive process of motor skill learning were specific to the task. Three experiments were conducted, in which the tasks were to touch three targets with pre-determined timing, force, and spatial requirements, experiments 1, 2 and 3 respectively. Similarly to the others, these experiments involved stabilization and adaptation phases. For each one sixty children with an average age of 11.3 years (±1.2) were assigned to four practice groups: constant, random, constant-random, and random-constant. The results showed complementarity of specificity and the generality of the effects of the different practice schedules on the adaptive process for the different tasks. In experiments 1 and 2, constant-random practice promoted better adaptation in tasks demanding time and force, respectively. In experiment 3 (spatial requirement), the children of the random-constant group showed better performance in adaptation.

Feedback Schedule

In conjunction with the organization of practice, supplying feedback to the learner constitutes an important role of the teacher. In fact, how to provide feedback in order to optimize learning has been the focus of investigations in the motor learning field since the first half of the twentieth century (Adams, 1987; Salmoni, Schmidt, & Walter, 1984; Swinnen, 1996). Recent research has been concerned with the degree of uncertainty involved in different feedback schedules. For instance, under a relative frequency of 100% of feedback, the learner would receive feedback after each trial, i.e. during all practice. On the other hand, in a practice with a frequency of 25% the learner would receive it after three trials, that is, he/she would perform two trials without feedback (Oliveira, Corrêa, Gimenez, Basso & Tani, 2009).

In the adaptive process model of motor learning, the main question is whether the uncertainty provided by low frequencies of feedback would be prejudicial to skill stabilization and, thereafter, adaptation, or whether it would be a source of order and would facilitate adaptation. Meira, Maia, and Tani (2012) investigated the effects of frequency and precision of knowledge of results (KR) on the learning of a more complex task: linear positioning associated to manual force control. One hundred and twenty college students were assigned to six groups of different KR: frequency (100%, 66%, or 33%) and accuracy (specific or general). In the adaptation phase the KR was withdrawn and an electromagnetic opposite traction force was introduced. Results showed better adaptation for learners who practiced with 66% of KR in the stabilization phase.

INSIGHTS FOR THE TEACHING OF MOTOR SKILLS

It could be said that one of the main challenges of education process is to teach for adaptation. That is, to provide learners with the capacity to continuously adapt the content learned throughout their lives and in different contexts towards growing complexity. In this perspective and in the light of the findings from a non-equilibrium model of motor skill learning, it is possible to suggest the following:

1. Teachers should guide students to learn motor skills taking into account the open systems nature of human beings, i.e., systems that are in a state far from equilibrium and consequently able to change, develop, and increase in complexity. In this sense, learning does not end with the stabilization of performance. It is just a transitory state that must be dismantled to achieve higher levels of complexity.

2. As an instructional content area, motor skills should be conceived of as hierarchically organized at macroscopic and microscopic levels. Thus, teachers should be clear which parts (micro) compose the skills and how they interact in order to form the whole (macro). It is important to consider that the macrostructure of the skill is order-oriented (consistency) and the microstructure is disorder-oriented (variability).

3. For functional stabilization of motor skills teachers could organize practice initially in a constant way, and then in a varied regimen (random). It is suggested that constant practice facilitates the pattern formation regarding the macrostructure of motor skill, and subsequent varied practice promotes its diversification bringing about variability in the microstructure, which is important for adaptation. The minimal amount of constant practice for macrostructure formation is suggested.

4. Although all motor skills involve interaction between time, space, and force, they differ in terms of goal demand: for instance, sprinting (time), the floor needed for artistic gymnastics (space), and weightlifting (force). In turn, teaching motor skills with time and force demands should organize practice in relation to the constant-random schedule; and for teaching skills with spatial demand, random-constant practice seems the best regimen.

5. Finally, teachers should provide a moderate frequency of feedback.

Obviously, although these teaching propositions have been based on experimental evidence, as with all model and theory development they need to be replicated in order to achieve the necessary consistency. This is a question for future studies.

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