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Different Faces of Variability in the Adaptive Process of Motor Skill Learning

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Abstract: *This study investigated the variability by considering an action programme as hierarchically organized, which reconciles invariant and variant features of motor skills at the macro- and microstructural level of analysis. It was assumed that invariant aspects of skilled actions express the macrostructure and therefore measures of sequencing, relative size, relative timing, relative force and relative pause time. The microstructure was related to the variant aspects so that total size, total movement time, total force, and total pause time were selected as its measures. These propositions were tested in an experimental design comprised by three learning phases: a stabilisation phase that entailed a given number of trials to achieve the functional stabilization on a graphic task, followed by transfer and retention phases. In the transfer phase, the graphic task was modified to yield different demands upon skill reorganization. Two such modifications demanded parametric changes (i.e. microstructure changes), in which graphic size and drawing speed were altered. Another modification demanded structural alterations (i.e. macrostructure change), in which drawing was changed. Overall, results supported the main predictions by showing that parametric changes in the task affected the microstructure, but did not affect the macrostructure consistently. Furthermore, a structural change affected both macro- and microstructure.*

Key Words: adaptation, motor learning, hierarchical organization, internal-external variability

INTRODUCTION

Variability is a phenomenon that has intrigued scientists for decades, possibly because of its importance for the development of living systems (Conrad, 1983). In the motor behavior field, the variability phenomenon has

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been investigated regarding its nature, magnitude, structure, and function in the control, development, and learning of motor skills (Cohen & Sternad, 2009; Davids, Bennett, & Newell, 2006; Newell & Corcos, 1993; Newell & Slifkin, 1998; Tani, 2000; Touwen, 1993). Generally, studies have addressed two main concerns: first, to understand the internally-induced variability based on the fact that two movements are never performed in exactly the same way (Barttlet, 1932; Bernstein, 1967), and the ability of individuals to achieve the same skill goal through different ways, i.e. equifinality (Hebb, 1949; Lashley, 1930, 1951; von Bertalanffy, 1950, 1952). These two kinds of variability are named *motor variability* and *motor equivalence*, respectively. Investigations into these concerns have focused mainly on the inter-individual variability by comparing states of different persons on the same measures, and the intra-individual variability by comparing the states of individuals with themselves on the same measures through time (Ford & Lerner, 1992).

It is longstanding that variability is related to adaptive human behavior (Bartlett, 1932; Bernstein, 1967; Fiske & Rice, 1955). Even in the 19th century, Woodworth's classic work had already proposed some possible positive effects of variability on motor behavior: "The variability of a species or of a performance is conceived as the result of the varying combination of a lot of small causes, some of which act in one direction and some in other – some acting, let us say, to increase, and others to decrease, the accuracy of a movement" (Woodworth, 1899, p.100).

Although such assumptions are not so recent, variability did not become a regular theme of research in motor behavior field, probably because the existing theories could not provide a reasonable explanation about its role in biological systems (Newell et al., 2006). However, from the development of a dynamical systems view (e.g., Kugler, Kelso, & Turvey, 1980, 1982), variability became subject of several studies, which were more regularly conducted in the 1990s (e.g., Carlton & Newell, 1993; Kelso & Ding, 1993; Newell & Corcos, 1993, Newell & Slifkin, 1998). Important to take into account that originally dynamical systems view did not consider variability as central to the theory. It was added *a posteriori* to the original proposal as new methods of research and findings were presented.

For example, new quantitative methods of analyses were developed during the 2000s in order to address different questions that would deepen the understanding of variability in motor behavior. Since then, variability has been considered an important component of a flexible and healthy system (Diniz, Barreiros, & Crato, 2010; Harbourne & Stergiou, 2009; Gottschall, Peinke, Lippens & Nagel, 2009; Sternard & Abe, 2011; van Emmerik, Hamill, & McDermott, 2005). By contrast, invariance has been viewed as a result of aging process or even disease (Stergiou & Decker, 2011; van Emmerik & van Wegen, 2002).

Variability under dynamic system framework is not viewed as totally random phenomenon, which was shown by statistic methods. For example, to be variable does not mean being random (Riley & Turvey, 2002; Starnard &

Dijkstra, 2004), and stability does not mean no variability (Kelso, 2012; Ronsse & Sternard, 2010, Torre & Balasubramaniam, 2011). Thus, it means that variability structure has some determinism (Riley & Turvey, 2002; Slifkin & Newell, 1998; Yamada, 1995). One interesting result has been showed by several studies that reported a specific noise represented by 1/*f* power spectrum (e.g., Chen, Ding & Kelso, 1997; Kello & van Orden, 2009; van Orden, Holden, & Turvey; 2003), when 1/*f* noise has been understood like a signature of complexity in human behavior. Another recent method used to access variability in motor behavior is detrended fluctuation analysis by calculating the Hurst exponent (*H*) for long-range correlations in a time series (Amoud et al., 2007; Kantelhardt, et al., 2002). Moreover, Hurst exponents seem to be directly related to 1/*f* noise (Torre & Balasubramanian, 2011).

The second concern for variability in the motor behavior field refers to understanding the externally-induced variability based on the practice schedule. That is, variability between performances is caused by intentional manipulations of the task or environment, which has been related to schema theory (Schmidt, 1975) and the contextual interference approach (Battig, 1979). This kind of variability has been one of the phenomena most focused in the studies on motor skill learning over the last 40 years (Barreiros, Figueiredo, & Godinho, 2007).

In fact, variability is a broad and complex phenomenon, which can be observed from molecular to ecosystem levels of analysis (Conrad, 1983). For instance, in terms of motor skills one could study variability by considering the macroscopic changes of the movement pattern or, still, at a microscopic level concerning the motor units activation or kinematic trajectories performed. Variability is part of human nature and is present in any human motor skill (Klingsporn, 1973; Newell & Slifkin, 1998). However, depending upon the level or scale of analysis a motor skill might be more or less variable.

Moreover, the complexity of this phenomenon implies the need of investigating it under different perspectives. In the present paper, we discuss the variability phenomenon under a specific theoretical perspective: adaptive process of motor skill learning (Corrêa, Alegre, Freudenheim, Santos, & Tani, 2012; de Paula Pinheiro, Marques, Tani, & Corrêa, 2015; Tani, 2000; Tani et al., 2014; Ugrinowitsch, Benda, Corrêa, & Tani, 2014).

VARIABILITY AND ADAPTIVE PROCESS OF MOTOR LEARNING

Over the past decades several descriptive models of motor learning process have been proposed based on different theoretical perspectives (for a review, see Tani et al., 2014). Coincidently, all of them describe the process based on stage or stages within a functional stabilization process, in which learners presents particular behavioral characteristics. Another similar feature of the current models of motor learning is that, although some of those (e.g., Jacobs & Michaels, 2007; Newell, 1986) have been developed under a contemporary view of variability, they emphasize the decrease of variability along the stages. In order to illustrate this statement, we have summarized the variability characteristics occurring in the learning phases by considering two acknowledged models by Fitts and Posner (1967) and Newell and colleagues (Newell, 1986; Vereijken, van Emmerik, Whiting, & Newell, 1992).

Great variability is expected in the first phase because: (a) learner has difficulty in understanding the skill goal and the ways to achieve it, or (b) he/she did not establish relationships among the key components of the dynamical movement systems (e.g., body parts such as legs, hips, trunk, and arms). Diminishing of variability occurs in the second phase because (a) the learner can associate sensory information produced by the movement performed to the desired performance, or (b) he/she can explore and adjust coordinative structures to the environment. Finally, low variability might be observed in the third phase because (a) the learner is able to perform skills with minimal attentional expenditure, or (b) the learner can optimize the control of the coordinative structures and explore the forces the movement to ensure flexible and efficient actions. In sum, based on these statements, one could suggest that the variability would be nonfunctional in the beginning of the learning and, functional at the final stage.

However, the main question here is not about the nature of the variability during the process of pattern forming comprising those three phases, but about the effects of initial and final variabilities on the adaptation of such pattern. In the last few years a non-equilibrium model of motor learning has been developed, which proposes that motor skill acquisition occur through continuous process of performance stabilization and adaptation (Tani et al., 2014). The first, concerns to the spatiotemporal patterning of the action - a functional stabilization process reached predominantly by negative feedback mechanisms. And, the second refers to the reorganization of such pattern based on the breakdown of the reached stability to respond to perturbations. The variability occurs because, given the open systems nature of the human being, once stabilized the skill is challenged by new demands, such as external and internal perturbations (e.g., changes in the task and/or environment). In this case, the system functions based on influence of positive feedback (mechanisms of deviation amplification). According to Tani et al. (2014), observed variability after perturbation can be result of three kinds of adaptation: (a) alteration of parameters; (b) modifying of a motor skill's components; or (c) self-organization of whole skill's structure.

The Different Natures of Variability

Under this motor learning perspective a sequence of studies was developed in our lab in order to investigate the effects of different variabilities during the stabilization process on the adaptation of motor skills. First, Benda, Corrêa, Lustosa de Oliveira, and Tani (2000) investigated whether the variability that remains after extensive practice characterizes additional flexibility to adapt to new demands. Volunteers performed a task to control 60% of maximal voluntary force followed by adaptation to 40% of maximal voluntary force. Three groups were formed according to standard deviation of absolute error in the last two blocks of the first phase: high, medium, and low variability but only high and low variability groups (HG and LG) were analyzed. Results showed that although both groups presented similar adaptation, only HG retrieved the performance showed in the stabilization phase indicating that high performance variability remained in extensive practice indicates flexibility and from LG with superstabilization indicates rigid behavior.

Benda et al. (2010) tested whether variability before and after stabilization were of distinct nature comparing high and low variability before and after stabilization. During the stabilization phase two groups performed five trials (pre-stabilization) and two groups performed 120 trials (super-stabilization), all divided in high and low variability that resulted in HPG, LPG, HSG and LSG, respectively, transporting three tennis balls among six containers in a sequence and a target time pre-established. In adaptation phase, participants performed 20 more trials in a new situation. Results showed that before stabilization, high variability could indicate an unstable system, and after stabilization high variability could indicate system flexibility. In this case, variability would be considered as a redundancy (abundance) indicative, which is a capacity reserve that allows human beings to respond to perturbation (Tani, 2000).

Gallo, Ugrinowitsch, Portes, and Benda (2014) focused on the magnitude and structure of variability. Twenty-two participants performed a pointing task similar to Fitts task, but in a digital tablet. They performed two blocks of 1,024 traces between two targets (24 cm away and a 0.6 cm width) with an ID of 6.3 bits/resp. After 24 hours, they performed one block of 1,024 traces (24 cm away and a 0.4 cm width) with an ID of 6.9 bits/resp. Variability magnitude was measured by standard deviation of movement time and variability structure was measured by Hurst exponent of movement time. When variability structure was used as criterion to separate groups, they showed to be structured, that is, higher Hurst group and lower Hurst group presented values close to 1. As a result, both groups were similar to face a new task. On the other hand, when variability magnitude was used as criterion to separate groups, high variability group presented better performance in new task than low variability group. One explanation for such results might be that higher variability of movement time implied that velocity was not kept, and when it was reduced, it led to an increase hit target. Another explanation might be that with both groups of structured variability, higher variability magnitude could mean a redundancy of the system in an extensive practice.

Another sequence of studies investigated behavior at superstabilization level comparing with stabilization or even pre-stabilization using a coincident timing task. Extensive practice was used to allow the neuro-motor system to reach a skillful performance. Once a level of skillful performance has been attained, it is possible to identify a behavior called superstability (Benda, 2001; Ugrinowitsch, 2003) or metastability (Kelso, 2012). Metastability is known in statistical physics as a property of physical systems near their critical points, in which fluctuations are often seen (Kello, Bosman, Hasselman, Cox, & van Orden, 2008) and could improve adaptation. In the motor behavior field, metastability refers to a system having distinct coordination modes with identical parameter values; that is, it switches among numerous patterns that co-exist (Kello et al., 2008; Kelso, 1995). At this moment the system has transient periods of stability observed on frequent switches among stable regimes (Friston, 1997), which is a property of flexible systems (Kello & van Orden, 2009; Kelso, 2012). In a metastable behavior, performer should present intermittency, reached through power spectrum analysis with a set of possibilities available and the 1/*f* noise would be observed (Kelso, 1995; Kelso & Haken, 1997).

Benda et al. (2000) and Ugrinowitsch et al. (2011) adopted a criterion of performance to guarantee all volunteers had similar level of performance at the end of the first phase. Three groups were compared: Pre-stabilization practiced only 15 trials, not enough to reach stabilization; Stabilization practiced until performed three trials in a row with error < 30 ms; Superstabilization practiced six blocks of the same criterion. Later it was inserted a perturbation (new sequence and velocity of visual stimulus) and the results showed that variability in early learning results from inconsistency and in late learning is beneficial to adaptation.

The comparison between pre-stabilization, stabilization and superstabilization on adaptation was tested with unpredictable (Fonseca et al., 2012) and predictable changes on stimulus velocity (Ugrinowitsch et al., 2014) using the same coincident task. In the experiment by Fonseca et al. (2012) superstarbilization showed better performance under perturbation condition as well as lower variability of the macrostructure, indicating that at superstabilization macrostructure was more adaptable. Later Ugrinowitsch et al. (2014) found that different to unpredictable, adaptation to predictable perturbation does not require reaching superstabilization. Moreover, at pre-stabilization level variability did not change with perturbation but at superstabilization level variability was beneficial to adaptation since it diminished. The authors also analyzed the correlations between changes on performance caused by perturbation with different variability. At pre-stabilization level performance was poor and its change was related to inconsistency, indicating that performance variability before stabilization is detrimental to adaptation. At superstabilization level performance was accurate and its change was related to flexibility, indicating that structure variability after stabilization is beneficial to adaptation.

Based on the proposal that new skills emerge when facing perturbations (Tani et al., 2014), variability might be seen as a perturbation produced by the own system to be far from equilibrium or a state of organization that allows to occurrence of changes. Our results indicate that superstabilization produces these conditions and remaining variability "swings" the system. We have thought about different mechanisms that can explain variability at superstabilization. Variability may increase due to exploratory behavior (Lorenz, 2010) observed when one try to apply many behavioral patterns to reach a goal. Variability may also increase due to playful behavior (Bruner & Bruner, 1968), in which performers only play with the task regardless of the reaching the goal. While exploratory behavior is goal directed, in playful behavior is not. However, at any time a performer can return to the best motor solution performing the right motor pattern and reach the goal of the task. In both situations, as in opens systems the increment of variability should occur due the equifinality acquired as a consequence of the practice. “Equifinality” refers to the capability of a stabilized open system to reach its function by varying means and from varying initial points (von Bertalanffy, 1950, 1952).

In sum, from the presented statements and experimental results on the adaptive process of motor learning we are suggesting that variability observed at the early learning is not adaptive; it is a result of the lack of coordination in movement within and between trials. After functional stabilization is achieved, practice leads the motor skill to a metastability state. By considering that when the functional stabilization is achieved we can infer that a dynamic structure of control was formed (Tallet, Krostrubiec, & Zanone, 2008), how could be such in order to make possible the adaptive variability characteristics of self-challenge or play behaviors. This will be addressed experimentally later.

The Externally-Induced Variability

If variability is present throughout functional stabilization process and its nature changes over practice, how should practice be scheduled in order to benefit adaptation of motor skills? In the last few years, this concern has been investigated regarding the effects of different degrees of externally-induced variability, also known as variability of practice (Corrêa et al., 2010b; Corrêa, Ugrinowitsch, Benda, & Tani, 2010a; Corrêa, Walter, Torriani-Pasin, Barros, & Tani, 2014; de Paula Pinheiro, Marques, Tani, & Corrêa, 2015).

Low and high degrees of variability have been manipulated in the studies by the constant and random practice schedules, respectively. Constant practice did not involve changes trial-to-trial; it is characterized by performances in constant conditions. On the other hand, the random practice involves unpredicted alteration in the skill trial-to-trial. Results have led to two main conclusions on the foregoing question: first, adaptation of motor skill is favored when practice with high level of variability (random) is conducted after practice without variability (constant) (Corrêa, Benda, Meira, & Tani, 2003, 2010a; Gonçalves, Santos, & Corrêa, 2010). For instance, in Corrêa et al. (2010a) learners were assigned into four practice schedules: constant, random, constant followed by random, and random followed by constant. Results of three experiments showed that learners from constant followed by random group had adapted better than other groups in performing a complex task of coincident timing task.

It has been hypothesized that no additional variability (constant practice) facilitated the diminishing of variability to a level of forming the macrostructure of the action programme and later to reach functional stabilization. After that, the externally-induced variability of practice seems to have provided an increase in the learners’ capacity of adaptation by diversifying its microstructure (Corrêa et al., 2010a; de Paula Pinheiro et al., 2015; Tani et al., 2014).

Second, there seems to be an optimal combination of low and high variability (Corrêa, Barros, Massigli, Gonçalves, & Tani, 2007; Corrêa, Gonçalves, Barros, & Massigli, 2006; Corrêa et al., 2010b). Studies have asked about how much emphasis should be given on the low variability in order to prepare the motor skill to introduction of high variability. For instance, Corrêa et al. (2010b) investigated the adaptation of motor skills when stabilization process occurred by different amounts of constant practice before the random practice. Using the same coincident timing task, three groups were assigned in relation to a stabilization criterion (three consecutive trials within 50 msec of error). One group performed the constant practice until they reached this criterion; the other two groups performed this practice schedule in a number of trials that exceeded the stabilization criterion in 33% and 66%. Results showed similar adaptation for all groups. Thus, the prior minimum amount of low variability condition seems to be enough for the action programme formation and later initiate the diversification of motor skill by a high variability condition. On the other hand, similarly results have pointed to a minimum amount of variability as an optimal level to provide the needed flexibility for adaptation in the motor skill (de Paula Pinheiro et al., 2015).

VARIABILITY AND ACTION PROGRAMMING

Independently of theoretical perspective, intention and goal have long been acknowledged as important hallmarks of motor skills (Connolly, 1977; Kelso, 2003, 2008, 2014; Tani, 2005). The operationalization of the intention to move in order to achieve a desired goal is thought to involve the elaboration of a plan of action (Requin, 1992; Shaffer, 1992) or an action programme that constrain a movement pattern to be executed. Although in the dynamic systems approach the motor system is seen to function autonomously and rather independently of mental representations, intention and its consequent action programme are seen by some as one of the constraints working on the emergence of motor patterns (Kelso, 2003, 2008, 2014; Kelso & Engstrom, 2006; Summers & Anson, 2009; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Turvey & Fonseca, 2009). Nevertheless, at least for the kind of motor skills with a high cognitive involvement, such as typing, handwriting, piano playing and drawing (Colley, 1989; van Wieringen, 1988), the role played by an action programme in constraining a movement pattern that brings about a given environmental consequence is pretty clear. In sum, rather than phenomena exclusive and dichotomous (e.g., programmes versus self-organization; representations versus dynamic), the structure we are assuming comprises complementarily constraint and emergence.

Here an action programme is conceived under a hierarchically organized complex systems view (Lewin, 1991; Pattee, 1973; Salthe, 1985; Weiss, 1967, 1969). This is a kind of multileveled adaptive system in which each level is neither fully consistent nor inconsistent in space and time by presenting macro-order and micro-disorder (Corrêa et al., 2012; de Paula Pinheiro et al., 2015; Kelso, 2000, 2002, 2013). In such system, the constancy observed at a macroscopic level gives rise to variability when it goes down to microscopic levels (Weiss, 1967, 1969).

Motor skill is a system comprised by many components in interaction. Thus, it is proposed that an action programme has a hierarchically organized structure with a macro and micro configuration (Choshi, 1981; Manoel, Basso, Corrêa & Tani, 2001; Tani, 2005). The macrostructure of an action programme refers to the pattern that emerges out of the interaction of components. It is constrained by the coupling between intention and task specificity. And the microstructure refers the components themselves. Each component behaves in a loose rather than in a stereotyped or rigid way. There is a relatively wide range of variations in the behavior of all components that enables dynamic interaction among them making possible the emergence of macrostructure. As a result, a set of constraints will be imposed upon the behavior of these same components (Weiss, 1967). A constraint does not establish how a component must act (Newell, 1986), rather it sets what cannot be done and a wide range of alternatives is left for each component (Allen & Starr, 1982; Koestler, 1969; Salthe, 1985). The variation shown by each component is then a result of changes in the allocation of parameters such as time, force and displacement in the microstructure of the action programme. In order to make clear this hierarchical organization, let us consider de Paula Pinheiro et al.'s (2015) example: invariably an attacking in the game of volleyball is formed by sequential interaction of (a) running, (b) vertical jumping, (c) hitting the ball, and (d) landing. This characterizes the macrostructure. However, the amplitude and number of steps in the running, the height of the vertical jump, how to hit the ball and to land all vary according to the sport context (e.g., speed of the ball, blockers' displacement, etc.).

The main problem is how the macrostructure is initially formed and then improved as a result of practice. In the initial phase of learning the learner presents numerous and varied errors, stereotyped movement patterns regardless of environmental change, uncertainty about the relationship between the key components or parts of the body relevant to the execution of the skill (Newell, 1986; Vereijken, van Emmerik, Whiting, & Newell, 1992), slow response time, high demand attentional for performing the skill, and excess verbalization (Fitts & Posner, 1967). It occurs because the macrostructure might be quite inconsistent and ill-defined in terms of spatial and temporal organization, that is, the interaction between skill's components is not well established. It implies components with too many degrees of freedom and high variability in the interaction between them. Thus, at this phase both macro- and microstructures are disordered and inconsistent. Variability in the microstructure at this phase means inconsistency. It must be adequately constrained by the macrostructure to achieve consistency in the later learning. As mentioned, macrostructure emerges and increases in consistency as the pattern of interaction among components becomes well established. Therefore, it is important to acknowledge that the macrostructure is not a pre-organized, rigid and well-defined entity that comes from somewhere and determines how components must interact. It is an emergent global order that results from a dynamic interplay of the constituting elements, which in turn feeds back and influence the behavior of the components. In sum, the proposition is an action programme that has a macro-order and a micro-disorder within a hierarchical configuration.

Conceivably, information provided from the outside such as instructions, demonstrations as well as observations of a criterion pattern can contribute to the initial grasping of the macrostructure. However, it improves as a result of practice and feedback in which macro-micro interaction happens in both a top-down and bottom-up fashion. Macrostructure is at the same time a cause and effect of microstructure patterning. When macrostructure becomes well organized (i.e., functional stabilization is reached), it is predicted that sequencing, relative timing and relative force, which are relatively invariant aspects of skilled actions, will become well established.

The increase of consistency in the macrostructure leads to a reduction in the degrees of freedom in the microstructure. However, that reduction must be viewed as relative because when it is excessive it may cause a loss of flexibility in the action programme reducing the capacity to adapt to the environmental demands. Therefore, when the macrostructure becomes well established, it does not mean that variability is completely eliminated. On the contrary, it means that the degrees of freedom of the microstructure were reduced up to a point but it still maintains an optimal level of variability. This complementary of macro and micro levels as measures of motor skills has been suggested as a characteristic of living systems (Kelso, 2006).

In the experiment that is described next, we tested the hierarchically organized structure of an action programme with a macro-order and micro-disorder configuration using a graphic skill. It was assumed that invariant aspects of skilled actions express the macrostructure of an action programme and therefore sequencing, relative size, relative timing, relative force and relative pause time were selected as its measures, since relative measures represent structure of control in different theories (Newell, 1996). The microstructure, on the other hand, was assumed to be related to the variant aspects so that total size, total movement time total force and total pause time were selected as its measures.

In order to test these propositions an experimental design comprised by three learning phases was delineated: a stabilisation phase that entailed a given number of trials to achieve stabilization on a graphic task, followed by transfer and retention phases. In the transfer phase, the graphic task was modified to yield different demands upon skill reorganization. Two such modifications demanded parametric changes (i.e. microstructure changes), which graphic size and drawing speed were altered. Another modification demanded structural alterations (i.e. macrostructure change), in which drawing was changed. The rationale for this design was that parametric changes in the task would affect microstructure measures (increase of variability) but not consistency of the macrostructure. If the same result was obtained during the retention phase, this would be an evidence for the acquisition of an action programme with macro and microstructures. In the same vein, a structural change would be met by a decrease in the consistency of both macro and microstructure.

METHOD

Participants

Forty-three children from a Brazilian school, both male (*n* = 20) and female (*n* = 23), with an average age of 10.6 years (± .73) were randomly divided into three groups differing in the task aspect modified during the transfer and retention tests. Participation required the written consent of those responsible for the children, which was obtained through the school management where the study was carried out. This study was conducted within the guidelines of the American Psychological Association.

Task and Apparatus

The reproduction of a graphic pattern was performed with a pressure-sensitive cordless pen on a graphic tablet (Quora Cordless model QC-A4) connected to a microcomputer Macintosh. The X and Y coordinates and the axial pen pressure were sampled at a rate of 100 mhz.

The graphic pattern to be reproduced referred to a combination of a Chinese character that resulted in a graphic pattern composed by 10 straight segments (Fig. 1). It was printed in a 25x25mm square on the top center of the response sheet. This pattern was reproduced in 20 empty boxes of the same size, 20 mm apart, and presented in a 4 boxes x 5 rows format in the response sheet. Response sheets were changed after 20 trials and it took approximately 90 seconds for each trial.

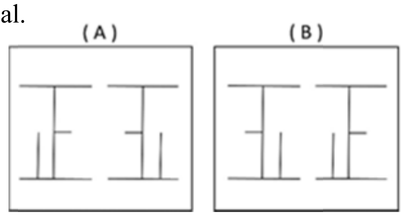

Fig. 1. Illustration of the task performed during acquisition (A) and transfer phases (B).

The reproduction of a visually presented graphic pattern involves, in the first place, the “linearization” of a sequence of strokes in the sense that the segments which compound the graphic pattern must be transformed in a sequence of movements (Thomassen & Tibosch, 1991). Secondly, it involves the execution of a sequence of strokes in a given temporal pattern. Since the economy of time and energy to achieve a predetermined goal is the key aspect of motor skills, it can be predicted that, regardless of the rules being applied, as the learning process unfolds a given sequential order begins to be adopted and performed repeatedly. In the end a very consistent and unique sequence of strokes will prevail, which means that the structure of the graphic pattern in terms of its spatial and temporal organization of components has been properly established. In other words, a stable action programme of the graphic pattern has been acquired.

Design and Procedure

Participants were requested to start the reproduction at the top left of the response sheet, move across and then go down to the next row and so on. They were instructed they could reproduce the pattern in any sequence of strokes they wanted, but that the strokes must have a clear beginning and end point. They were also instructed not to stop a stroke until it has been completed, and not go back to correct any errors. Finally, that there were no time constraints to reproduce the graphic, so that they could choose their own time to finish the task trying to do it as accurately as possible in terms of shape and size.

Before the start of the session, participants were allowed to adjust the tablet placing it in a comfortable position. When they were ready to begin they were requested to touch a small circle at the corner of the response sheet and then after the clear signal they started the trial.

The experiment was carried out in three distinct phases: stabilization, transfer and retention. In the stabilization phase, participants performed 100 trials. The transfer phase followed immediately, comprising another 20 trials. Ten minutes interval separated transfer and retention phases when further 20 trials were performed in the latter.

All three groups performed the same graphic pattern in the stabilization and retention phases (Fig. 1A). In the transfer phase the task was changed in different ways to match the problem being investigated. *Structural group* (ST) was requested to reproduce a different pattern in which the position of the right and left parts of the criterion pattern was inverted but keeping their sizes unchanged (Fig. 1B). *Velocity group* (VL) was requested to perform the same pattern, both shape and size, but as quick as possible. Finally, *size group* (SI) was requested to perform the same pattern in terms of shape but in a bigger size (in 35 x 35 mm box).

When a reproduction did not match the required pattern (e.g., higher or lower amount strokes, or different graphical configuration) it was considered incorrect and therefore omitted from the analysis. However, very few reproductions were incorrect. The main reasons to account for that result is that there were no time constraints to reproduce the pattern.

Data Analyses

Seven *dependent variables* were analyzed in blocks of ten trials:

1. *Overall movement time* was defined as the within-subject standard deviation of total movement times, which provided a measure of the movement variability.

2. *Relative timing* was defined as the within-subject standard deviations of percentage of movement time for each stroke, which provided a measure of the relative timing consistency. The mean standard deviations of all strokes provided a measure of consistency in the graphic pattern as whole in a block of trials.

3. *Overall size* was defined as the within-subject standard deviation of

total movement sizes, which provided a measure of the total size variability.

4. *Relative size* was defined as the within-subject standard deviations of percentage of movement size for each stroke, which provided a measure of the relative size consistency that each subject exhibited in each stroke. The means of standard deviations of all strokes provided a measure of consistency in the graphic pattern.

5. *Overall pause time* was defined as the within-subject standard deviation of total pause times in a block of trials provides a measure of the total pause time variability;

6. *Relative pause time* was defined as the within-subject standard deviations of percentage of pause time for each pair of strokes provided a measure of the relative pause time consistency. The mean of standard deviations of all strokes provided a measure of consistency in the graphic pattern as whole.

7. *Sequencing* was defined as the sequence of strokes that was identified by retrieving the sequential order in which they were made. It was calculated by the number of different strokes in each location of the sequential order from one to ten in a given number of trials. The sum of these numbers for the whole pattern indicated the level of consistency in the sequencing. The increase in 1-10 scale indicated the increase in variability.

A one-way ANOVA was run for each group to assess main effects of each of these measures. For this purpose, we considered the first (1^{st}-St) and last (10^{th}-St) blocks of the stabilization phase, the first (1^{st}-Tr) and second (2^{nd}-Tr) blocks of transfer, and first (1^{st}-Rt) and second (2^{nd}-Rt) blocks of retention. Observed significant effects were further assessed using Fisher LSD post-hoc tests. These analyses were based on Shapiro-Wilk's W and Bartlett's tests of normality and homogeneity of variance. For all analyses, the level of significance was set at $p < .05$, using STATISTICA® 12.0 software.

RESULTS

Macrostructure

Sequencing

The one-way ANOVAS revealed effects for all groups: ST (F (5, 60) = 16.97, $p < .01$, $\eta^2 = .59$), VL (F (5, 65) = 5.69, $p < .01$, $\eta^2 = .30$), and SI (F (5, 75) = 6.09, $p < .01$, $\eta^2 = .29$). For ST and SI the Fisher LSD test showed that the variability in the 1^{st}-St was larger than those in the remaining blocks ($p < .01$); 10^{th}-St and 1^{st}-Tr had lower variability than 2^{nd}-Tr and 1^{st}-Rt ($p < .01$). The 2^{nd}-Tr and 1^{st}-Rt had larger variability than 2^{nd}-Rt ($p < .01$). Finally, for VL the post hoc tests showed that the variability in the 1^{st}-St was larger than those in the remaining blocks ($p < .01$).

Relative Timing

The one-way ANOVAS revealed effects for all groups: ST (F (5, 60) = 4.01, $p < .01$, $\eta^2 = .25$), VL (F (5, 65) = 8.30, $p < .01$, $\eta^2 = .39$), and SI (F (5, 75) = 9.73, $p < .01$, $\eta^2 = .39$). For ST the Fisher LSD test showed that the variability in the 1st-St was larger than those in the 10th-St, 2nd-Tr, and 1st-Rt; in addition, 10th-St had lower variability than 2nd-Tr and1st–Rt ($p < .01$). For VL and SI, post hoc indicated higher for the 1st-St compared to the other blocks, and the 1st-Tr had lower variability than 1st-Rt ($p < .01$). Additionally, 1st-Tr and 1st-Rt were more variable than retention 2nd blocks ($p < .05$).

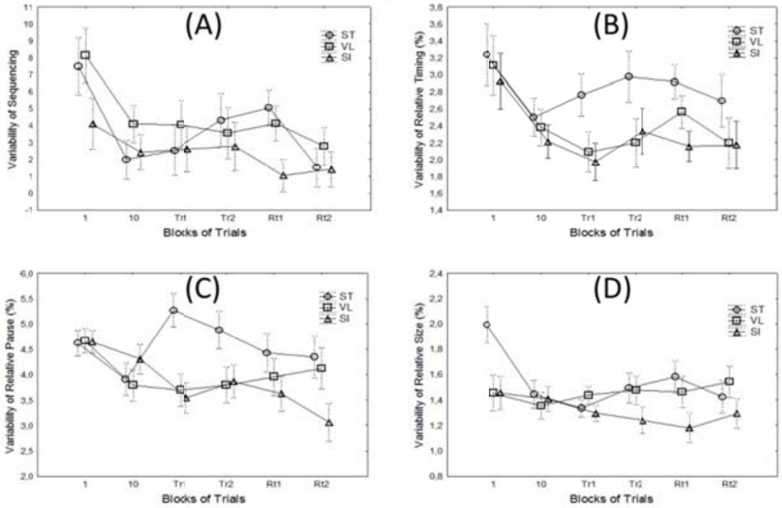

Fig. 2. Means of variabilities of sequencing (A), relative timing (B), relative pause (C), and relative size (D), in the first (1) and tenth (10) blocks of the acquisition trials, and in the blocks of transfer (Tr1 and Tr2) and retention (Rt1 and Rt2).

Relative Pause Time

The one-way ANOVAS revealed effects for all groups: ST (F (5, 60) = 8.03, $p < .01$, $\eta^2 = .40$), VL (F (5, 65) = 5.58, $p < .01$, $\eta^2 = .30$), and SI (F (5, 75) = 14.78, $p < .01$, $\eta^2 = .50$). For ST, the Fisher LSD test showed that the variability in the 1st-St was larger than that observed in the 10th-St; 10th-St had variability lower than those in all blocks; and, transfer blocks had superior variability to retention blocks ($p < .01$). For VL the post hoc indicated higher variability of the 1st-St in relation to the other blocks, and that the 1st-Tr had inferior variability than 2nd-Rt ($p < .05$). Finally, for SI it was found that the variability in the 1st-St was larger than those in all other blocks and that the 10th-St had inferior variability than the remaining blocks. In addition, 1st-Tr, 2nd-Tr, and 1st-Rt were more variable than 2nd-Rt ($p < .05$).

Relative Size

The one-way ANOVAs revealed effects only for STG (F (5, 60) = 8.03, $p < .01$, $\eta^2 = .40$) and SI (F (5, 75) = 14.78, $p < .01$, $\eta^2 = .50$). For ST the Fisher LSD test showed that the variability in the 1st-St was larger than those in remain blocks. The variability of 1st-Tr was less than that of 1st-Rt; the latter was more variable than 2nd-Rt ($p < .05$). For SI it was found that the variability in the 1st-St was greater than those in all other blocks, and that the 10th-St had greater variability than the remaining blocks. In addition, 1st-Rt was more variable than 2nd-Rt ($p < .05$).

Microstructure

Total Time

The one-way ANOVAS revealed effects for all groups: ST (F (5, 60) = 8.3, $p < .01$, $\eta^2 = .42$), VL (F (5, 65) = 34.07, $p < .01$, $\eta^2 = .72$), and SI (F (5, 75) = 22.93, $p < .01$, $\eta^2 = .60$). Still, for all groups the Fisher LSD test showed that the variability in the 1st-St was larger than that observed in the remaining blocks ($p < .05$). Other differences were: for ST the post hoc showed that the 10th-St had lower variability than 1st-Rt; 1st-Tr and 1st-Rt were less variable than 2nd-Rt, and 2nd-Tr was less variable than 1st-Rt ($p < .05$). For VL the post hoc indicated lower variability of the 10th-St compared to 1st-Tr, 2nd-Tr, and 2nd-Rt, and 2nd-Tr was less variable than 1st-Rt ($p < .05$). Finally, lower variability for SI was found variability for the 10th-St compared to the other blocks; 1st-Tr and 2nd-Tr had lower variability compared to 1st-Rt, and 1st-Rt was more variable than 2nd-Rt ($p < .05$).

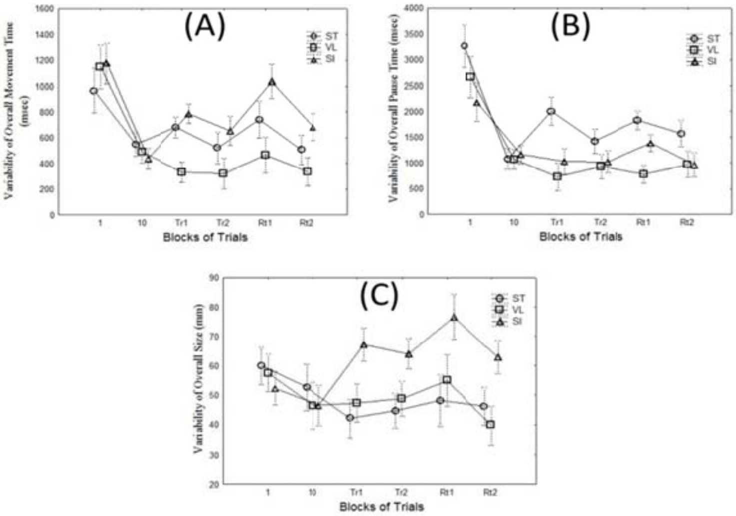

Fig. 3. Means of variabilities of overall movement time (A), overall pause time (B), and overall size (C).

Total Pause Time

The one-way ANOVAs revealed effects for all groups: ST (F (5, 60) = 21.89, $p < .01$, $\eta^2 = .65$), VL (F (5, 65) = 46.97, $p < .01$, $\eta^2 = .72$), and SI (F (5, 75) = 22.19, $p < .01$, $\eta^2 = .60$). Similar to the previous results, for all groups the Fisher LSD test showed that the variability in the 1st-St was larger than that observed in the remaining blocks ($p < .05$). Other differences were as follows: For the ST group, the post hoc test showed that the variability of 10th-St was less than that observed for 1st-Tr; 1st-Rt and 2nd-Rt, 1st-Tr were less variable than 2nd-Rt, and 2nd-Tr was less variable than 1st-Rt ($p < .05$). For VL the post hoc pointed to inferior variability of the 10th-St in relation to 1st-Tr and 1st-Rt ($p < .05$). Finally, for SI it was found inferior variability of the 1st-Tr and 2nd-Tr to 1st-Rt; and, 1st-Rt was less variable than 2nd-Rt ($p < .05$).

Total Size

The one-way ANOVAs revealed effects for all groups: ST (F (5, 60) = 5.95, $p < .01$, $\eta^2 = .35$), VL (F (5, 65) = 3.45, $p < .01$, $\eta^2 = .24$), and SI (F (5, 75) = 10.64, $p < .01$, $\eta^2 = .41$). For the ST group the Fisher LSD test showed that the variability in the 1st-St was larger than that observed in the remaining blocks, and 10th-St was less variable than 1st-Tr, 2nd-Tr and 2nd-Rt ($p < .05$). For the VL group the post hoc showed that 1st-St was larger than that observed in the remaining blocks except 1st-Rt; 10th-St had lower variability compared to 1st-Rt, and 2nd-Tr and 1st-Rt were more variable than 2nd-Rt ($p < .05$). Finally, for SI lower variability was found in the 1st-St condition compared to the others excepting 10th-St. 10th-St had lower variability than the other blocks, 1st-Tr and 2nd-Tr were less variable than 1st-Rt, and 1st-Rt was more variable than 2nd-Rt ($p < .05$).

DISCUSSION

Recent developments in the understanding of phenomena as complex adaptive systems have fostered changes in viewing of variability (Cohen & Sternad, 2009; Davids, Bennett, & Newell, 2006; Glazier & Davids, 2009; Newell & Corcos, 1993; Newell & Slifkin, 1998; Tani, 2000, 2005). In terms of acquisition of motor skills, if before the variability was seen as something to be eliminated to pave the way for consistency in the actions, recently it has been proposed as a source of adaptation. For instance, from an adaptive process perspective of motor skill learning it has been proposed that the variability changes its nature throughout the functional stabilization process. Variability observed in the beginners is not adaptive; it is a result of the lack of coordination in movement within and between trials, since the macrostructure is not formed or is under formation. When the functional stabilization is achieved, variability reflects the behavior of a hierarchically organized system. We assumed that at least the motor skills with high cognitive requirements are influenced by an action programme reconciling invariant and variant features. Such reconciliation would make possible by an action program hierarchically organized at macro- and microstructure. This proposition was experimentally focused in this manuscript.

Considering the main predictions of this study the results might be summarized as follow. First, all groups decreased the magnitude of variability in action programme's macro and microstructure through practice, that is, from the first to the last block of the stabilization phase and also to learning tests.

Second, when the task was modified in parametric terms, the VL group showed no differences between the last block of the stabilization phase and the other blocks regarding all macrostructure measures. Differences were found only because time acted as a perturbation, that is, as something that causes change or uncertainty to the individual (de Paula Pinheiro, 2015). Thus, variability's magnitude increased from the first transfer block to the first retention block. This conclusion can also be considered in relation to the SI group. The levels of variability of macrostructure reached in the last block of stabilization phase were maintained or diminished in the following two transfer blocks and at the end of retention. These results confirm the hypothesis in relation to parametric changes and maintenance of the action programme's macrostructure.

Third, with respect to the effects of parametric changes on the microstructure measures, the results showed that, as expected, the VL group decreased the variability of the overall movement time and the overall pause time. Moreover, the SI group increased the variability of the overall movement time and the overall size. Similar to the results described above, it appears that the time for the retention test characterized itself as a perturbation for both groups. These results support the hypothesis in relation to parametric changes and the changes of action programme's microstructure.

Fourth, concerning the structural change, results showed that unlike what was expected, the variabilities of the relative and overall pause time increased from the last stabilization to all other blocks and, therefore, they were not resumed. Although these results may appear negative, in fact one could say that they make sense, since the structural changing in the task might have led the participants to reflect more about where to go and programming the next stroke. Furthermore, such changes did not imply dismantling the action programme's macrostructure, since it was robust enough to deal with structural change in terms of other measures. For instance, results showed that for the relative size measure the variability was only changed because of the time to the retention test (1^{st}-Tr to 1^{st}-Rt). Therefore, in the last retention phase the level of variability was similar to that in the last of stabilization phase. Interesting, overall size became more consistent. For the sequencing and relative timing measures, the level of variability of the last stabilization block was resumed in the last retention block.

In sum, overall results supported the main predictions by showing that parametric changes in the task affect microstructure, but not consistency of the macrostructure. And, that a structural change affected both macro- and microstructure.

Although our insights on variability have been based on logical rationale and experimental evidence, we are assured that they need to be put at further evidence in order to verify their consistency. Further studies should also analyze variability based on nonlinear measures by considering its structure in conjunct-tion to magnitude. Obviously, given the number of motor skill classes, this poses as an interesting challenge. Moreover, a shape matching measure (e.g., bidimensional regression) should also be considered for evaluating the performance.

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