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Motor Skill Adaptation depends on the Level of Learning

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***Abstract*—**An experiment was conducted to examine the effect of the level of performance stabilization on the human adaptability to perceptual-motor perturbation in a complex coincident timing task. Three levels of performance stabilization were established operationally: pre-stabilization, stabilization, and super-stabilization groups. Each group practiced the task until reached its level of stabilization in a constant sequence of movements and under a constant time constraint before exposure to perturbation. The results clearly showed that performance stabilization is a pre-condition for adaptation. Moreover, variability before reaching stabilization is harmful to adaptation and persistent variability after stabilization is beneficial. Moreover, the behavior of variability is specific to each measure.

***Keywords*—**adaptation, motor skill, perturbation, stabilization.

I. INTRODUCTION

THE human being is characterized by its adaptability, especially to constant environmental changes like in daily activities (e.g., driving a car) or in sports (e.g., hitting a tennis shot). The ability to adapt, particularly in sports, can be tested through changes (perturbations) in movement time, movement sequence, or still in a combination of both. In general, it is assumed that adaptation when performance returns to the non-perturbation condition [1]. However, its complexity makes it difficult to simulate study conditions. Some studies investigated either the adaptation to visual perceptual perturbations in a hitting task [2] or stimulus response coherence in a synchronization task [3]. These studies manipulated perturbations of the task perceptual demand. Other studies manipulated perturbations related to the task motor demand with tasks like arm positioning control [4], lifting and transport movements [5], drawing with display rotation [6], achieving fast movements [7], and catching [8]. In general, adaptation is related to both the type of perturbation and task. For example, in a study of positioning control task [4], there was a significant reduction in angular amplitude resulting from triceps activation. In a lifting and transport task, the adaptation to moving a heavy object was easier than the adaptation to moving a light one [5]. In hitting tasks [9], early onset occurred when the auditory stimulus was either above or below the startle blink reflex threshold.

Task and result specificity make it difficult to anticipate how adaptation occurs in a task such as hitting a tennis shot by combining perceptual and motor perturbations. One possibility of test this question is using the task presented in Fig. 1, in which the volunteer has to point five sensors in order to touch the last sensor in accordance to a perceptual stimulus. In this case, when we change the perceptual stimulus or the movement sequence the perceptual and motor perturbations, respectively may be manipulated. This question is particularly important to understand the relationship between persistency and change (i.e., adaptation), a problem and challenge for motor learning theorists [10].

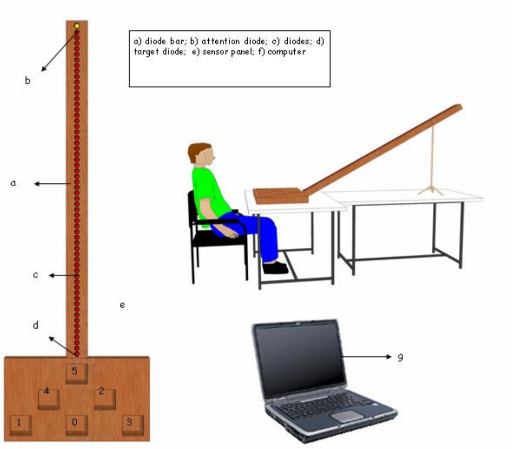

Fig. 1 – Coincident timing task.

Motor behavior adaptation is related to both persistency and change [1], also known as stability and variability [11]. We can say that although stability and variability coexist, they have different mechanisms of control [12], [13]. Motor skill stability can refers the capacity to return to the initial state after a perturbation has moved it away [14] or a spontaneous behavior observed even before practice [15]. It is often assessed through a dependent variable related to the task goal (e.g. absolute error) that shows the distance from the performance to the task goal. Variability is assessed through measurements like standard deviation. Until the 1970's, variability was an index of low performance, but nowadays it is associated to both skillful behavior and adaptability [16]. This change resulted in different variability inference measurement techniques like coefficient of variation [17] and information entropy [18], [19]. Recent studies have shown that variability is related to the level of learning and performance stabilization [11], and consequently to adaptation as well. This hypothesis strengthens the assumption of [20] that variability

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in early learning is a result of inconsistency, while in late learning it is indicative of adaptability.

This paper proposed to investigate the adaptation to perceptual-motor perturbations at different levels of performance stabilization (i.e., levels of learning). The levels were operationally defined through a pilot study: pre-stabilization, with only a few practice trials; stabilization, with practice until the performance became stable, and super-stabilization, with much more practice than necessary to reach performance stabilization. Moreover, the second purpose of this study was to investigate the function of variability in adaptation and whether variability is affected by the level of stabilization.

II. METHOD

These propositions were tested with 45 volunteer task-naïve university students (22 males and 23 females) aged 23.43 ± 2.17. All participants were self-reported right-handed and had normal or corrected-to-normal vision. All participants gave their informed consent of participation and were treated in accordance to the University Committee of Human Research guidelines. The study complied with the ethical standards laid down by the 1964 Helsinki Declaration, amended in 1989.

The apparatus consisted of a horizontal panel (110 X 60 cm) with six sensors (5 X 12 cm) [sensor 0 measured the reaction time (RT)] within similarly easy reach to the subjects and one 1.83-m bar with 100 diodes in line (the first as an attention diode and 99 diodes simulating a moving object) raised 30° in front of the sensor panel. Both sensors and diodes were controlled by a computer (Fig. 1), which also recorded all data for later analysis. The volunteer sat at the panel with the right hand on sensor 0 and the body median line aligned with the sensor. The first diode (yellow) turned on as an alert. When it turned off, the red diodes turned on and off in sequence simulating an object moving towards the panel at 1.10415 m/s, the velocity used in hitting task studies [21]. At this moment, the volunteer had to touch the other five sensors in a pre-determined sequence (1, 4, 3, 2, 5) so that the last sensor was touched simultaneously, i.e., coincidently, as the last (100th) diode turned on. The task was analyzed in five components: component 1, the movement from sensor 0 to sensor 1; component 2, the movement from sensor 1 to sensor 4, and so forth.

The experiment was organized in two phases as follows: the first was the pre-exposure phase, in which the volunteers were grouped and practiced until they achieved the learning measure determined in a pilot study: pre-stabilization (PSG), with 10 trials (far too few trials for the subjects to achieve performance stabilization), stabilization (STG), three trials in a row with absolute error $\leq$30 ms in a maximum of 120 trials, and super-stabilization (SSG), six blocks of three trials in a row with absolute error $\leq$30 ms in a maximum of 300 trials. One volunteer did not reach the super-stabilization criterion and was not included in the data analysis. In this phase, all groups were submitted to the same constant perceptual stimulus and performed the same pre-established sequence of movements mentioned before. In the second phase, exposure phase, all volunteers were exposed to a perceptual-motor perturbation characterized by a new perceptual stimulus and a new sensor-touching sequence during 25 trials. The perceptual stimulus was manipulated through varying the diode switching velocity, which was constant during the pre-exposure phase. During the exposure phase, the first 49 diodes were slowed down and the last 50 diodes were accelerated; however, the total time remained the same as that in the pre-exposure phase. The sensor-touching sequence was changed from 1, 4, 2, 3, 5 to 1, 4, 3, 2, 5. As a result, the volunteers had to organize a new sequence of movements with a new perceptual stimulus, which was adopted as a perceptual-motor perturbation. In order to define the perceptual stimulus and sequence of movements we run pilot studies where each volunteer practiced 100 trials with one perceptual stimulus and sequence of movements specific. It was tested four velocities and four sequences and, in both cases, the easiest (lower absolute error) was used in pre-exposition and the most difficult (higher absolute error) in exposition phase. Moreover, volunteers did not have information about how to do the task (i.g. rhythmically or as fast as possible and just wait to touch the last sensor) but only that the he(she) had to touch all sensors only once with the only restriction to touch the last sensor in coincidence with the firing of the last diode. Visual feedback was available during both phases of the experiment and there was no augmented feedback.

The parameters used were: a) performance absolute error, i.e., difference in milliseconds between the time that the last diode turned on and the touching of the last sensor; b) relative timing of each component, defined as the time spent to move from one sensor to the next divided by the total time spent to complete the task; it is related to the skill macrostructure; and c) total movement time, defined as the difference between the total time and Reaction Time (RT); it reflects the skill microstructure. The underlying reasoning is that actions can be controlled by motor planning [9], [22], that macrostructure and microstructure measures are complementary [23]. Both, macrostructure and microstructure can explain the co-existence of stability and variability in the human motor system because the first is oriented to order and pattern, while the second is oriented to disorder and uncertainty [23]. They interact and constraint each other in complementarity [24]. Precision and stability were analyzed as a function of measure means, and of variability through the coefficient of variation (CV).

Data Analysis

Performance and movement time data were analyzed in blocks of five trials and result reliability was tested by ANOVA. Only the first and last blocks of the pre-exposure phase were used because the stability measure resulted in different amounts of practice and because adaptation was a primary interest of investigation as well. However, these stability measures lead the volunteers of the each group to similar level of learning. All exposure phase trials were analyzed. The relative time analysis was conducted by

MANOVA (Wilks λ test). When necessary, pair comparison was run through post hoc Tukey$_{HSD}$ (ANOVA) or univariate test (MANOVA).

III. RESULTS

The first way to analyze adaptation is by observing the performance measure behavior. The hypotheses here are that PSG has the highest absolute error (AE), and STG and SSG have the lowest ones as a result of the stabilization level. Moreover, if variability is related to the level of learning and is beneficial to late learning adaptation, SSG will have the highest variability before the exposure to the perturbation. ANOVA showed that from the beginning to the end of the pre-exposure phase STG diminished EA $F(1, 42) = 48.285$, $P < .00001$ as well as SSG $F(1, 42) = 42.510$, $P < .0002$. Moreover, PSG was less accurate than STG and SSG $F(2, 42) = 6.118$, $P < .005$. There was no other reliable effect. When the groups were exposed to the perturbation (Fig. 2), accuracy dropped in three blocks $F(5, 210) = 4.061$, $P < .001$ before returning to the level prior to exposure. In addition, SSG was more accurate than PSG was ($P = .001$), and STG had an intermediate performance, similar to both groups ($P = .08$). These results confirm the first hypothesis that adaptation occurs as a function of the level of performance stabilization. Another conclusion is that without performance stabilization, there is no adaptation since PSG performance was far below the expectation in this type of task [25].

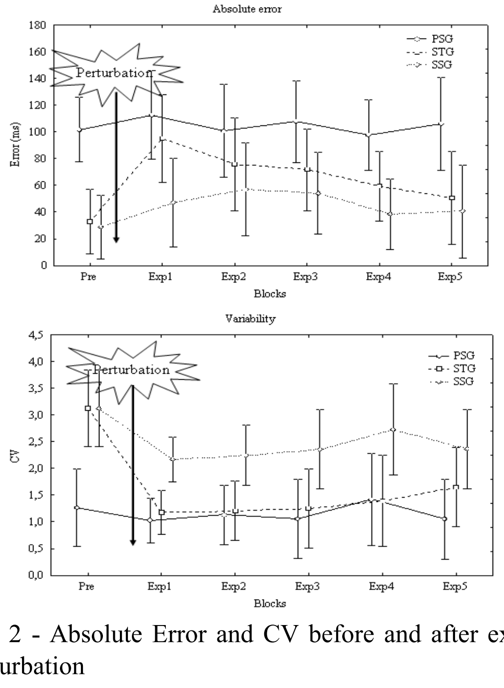

Fig. 2 - Absolute Error and CV before and after exposure to perturbation

The CV analysis confirmed that in the end of the first phase, STG and SSG were more variable than PSG $F(2, 42) = 9.946$, $P < .0002$. These measurements show that performance stability and variability co-exist [11]. Furthermore, the hypothesis that variability is beneficial to adaptation in late learning was confirmed by statistical analysis $F(2, 42) = 11.443$, $P < .0001$, and SSG was more variable than PSG and STG, and that STG was more accurate than PSG as well. These results are in accordance with the proposition that variability is related to the level of learning [11] and that variability before stabilization results from error. However, variability after stabilization is beneficial to adaptation [20] and accuracy [18].

The relative timing was analyzed as a measure that reflects skill organization unattached to any theory [8]. The hypotheses here are that with perturbation PSG changes the relation between the components because of insufficient practice to form a structure. Moreover, as a consequence of reaching stabilization STG changes less than PSG does. SSG practiced more than necessary to stabilize performance and if its variability decreases [26], it will be an indication that the actions are programmed [9], [22], which must be assessed.

Fig. 3 shows that the relative timing hypotheses were relatively confirmed: although there was no statistical difference between the three groups, the component behaviors were different: PSG changed four components ($P < .03$) and STG and SSG only decreased in component 4 to allow more time for adjustments in component 5 ($P < .05$).

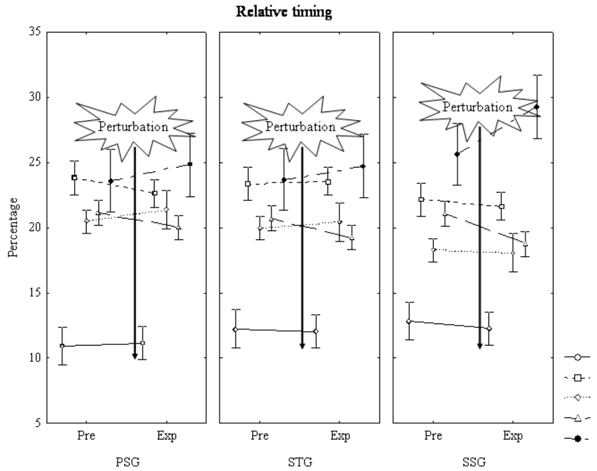

Fig. 3 - Relative time one block before and after exposure perturbation.

Fig. 4 shows that the variability of PSG was different from that of SSG, a result statistically confirmed by Wilks $\lambda = .610$, $F(10, 76) = 2.126$, $P < .032$. Variability was affected by the perturbation and so was Wilks $\lambda = .687$, $F(5, 38) = 3.455$, $P < .011$. The variability of the four components of PSG ($P < .003$), of two of STG ($P < .05$), and of one of SSG ($P < .01$) were affected as well (Fig. 4). These results show that the relation between the components cannot be formed without achieving performance stabilization. The PSG changed four components because this group did not practice the necessary to learning the task. , resulting in a poor adaptation. However, with super-stabilization, it becomes ordered. These results indicate that macrostructure becomes organized with different levels of learning, which indicates that the actions are programmed [20]. Moreover, the low macrostructure variability after reaching stabilization can still be beneficial to adaptation [27]. These results indicate that after learning macrostructure diminishes the variability.

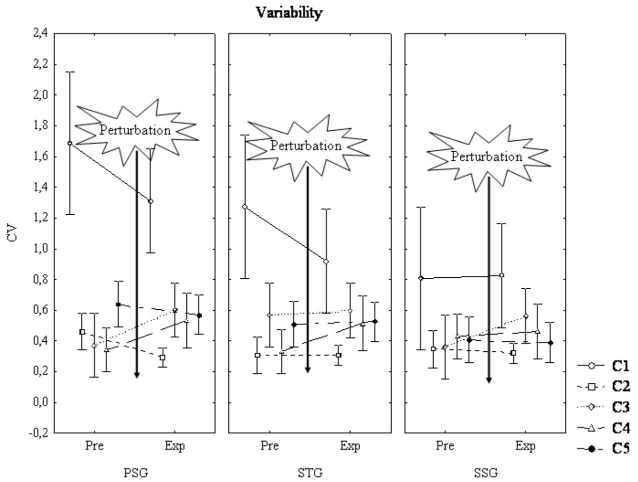

Fig. 4 - CV of relative time one block before and after exposure to perturbation.

Movement time, the last measure, is the total time minus RT. The first hypothesis for this measure is that PSG has the shortest movement time because this group attempts to stabilize the relation between the components and does not have enough practice to learn the task temporal adjustments. The second hypothesis is that the variability of SSG is low since this group has a large amount of practice and this measure is related to the time constraint. It is not possible to have other hypotheses.

The first hypothesis was partially statistically confirmed since PSG had a shorter movement time than STG and SSG did in the pre-exposure phase $F(2, 42) = 5.07$, $P < .01$. However, these results were not repeated in the exposure phase ($P < .659$) (Figure 5). Nevertheless, the exposure phase results show that the attention of PSG was directed to learning the sequence of movements, which led to a fast movement with high AE. In other words, PSG did not succeed in adjusting the movement to the temporal constraint. The second hypothesis was partially statistically confirmed as well, $F(2, 42) = 24.271$, $P < .00001$, and SSG was less variable than STG ($P < .0001$) was. However, the variability of PSG was similar to that of SSG ($P < .501$) and lower than that of STG ($P < .0001$). While the low variability of PSG results from the first learning stage (i.e., when the volunteers made the movement as fast as possible, a condition that reduces the variability outcome [9]), the low variability of SSG is related to its high ability to achieve the task goal, which is supported by its low AE. Moreover, SSG could keep the low variability of the movement time and achieved the task goal, i.e., coincident time, by changing the relation of the components, which is a characteristic of skillfulness [28]. The SSG results show that the microstructure variability has a function in adaptation since this group diminished this measure when perturbed. In combination with relative time measures, these results give support to the [20] proposal that learned actions are controlled by motor program organized in two levels: macrostructure that gives the stability to the action and microstructure that gives capacity to adapt.

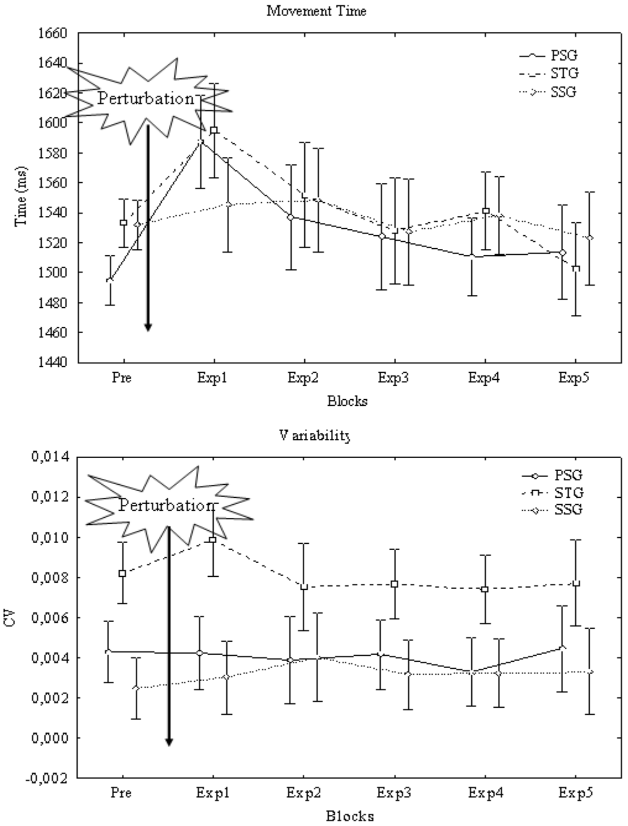

Fig. 5 - Movement time and CV before and after exposure to perturbation.

IV. CONCLUSION

In general, the results show that it is necessary to reach performance stabilization to adapt to perceptual-motor perturbation, but adaptation is easier when it is possible to reach super-stabilization. Variability in early learning results from inconsistency and in late learning results from surplus practice, which is beneficial to adaptation. Moreover, the behavior of variability is specific to each measure. At last, the results support the hypothesis that actions are programmed.

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