



PRACTICE EFFECTS ON FAST AND ACCURATE SPATIALLY CONSTRAINED MOVEMENTS

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ABSTRACT

Purpose. The effects of practice were analyzed in the control of fast and accurate spatially constrained movements. **Methods.** Twenty men (20–26 years old) evenly divided into an experimental and control group were analyzed in three time periods: pre-test, post-test, and retention. Discrete Aiming Task ver. 2.0 software simulated Fitts' task (1954) and provided kinematic analysis of mouse cursor movements (displacement, velocity, and acceleration). The task consisted of using the mouse to click on two parallel targets as fast and accurately as possible. Four target widths ($W = 2.0, 1.0, 0.5,$ and 2.5 inches) and three distances between the targets ($D = 2.0, 4.0,$ and 8.0 inches) were used to provide indexes of difficulty (ID) from 1 to 6 bits. The experimental group performed 108 practice trials (three blocks of 36 trials on different days) while the control group had no practice. **Results.** Movement time (MT) decreased in the experimental group largely due in part to a reduction of time used for feedback. It is suggested that the improvement in performance as a function of practice occurred through the interdependence of programming and the feedback process. As the task was practiced, there was decreased need for feedback due to better pre-programming of the primary submovement and the improved use of sensorial feedback information. This strategy and a lengthened deceleration phase can help explain the paradigm of fast and accurate movement as a result of practice. **Conclusions.** Despite the improved performance changes as a consequence of practice, Fitts' Law proved to be robust enough to predict MT as a function of ID.

Key words: motor learning, speed-accuracy trade-off, motor control

Introduction

Rapid hand movements aimed at a spatial target are subject to an inverse relationship between speed and accuracy; the higher the accuracy demands necessary to perform the motor task, the lower the movement velocity (speed-accuracy trade-off). This is known as Fitts' Law and is determined by the relationship between movement time (MT) and the index of difficulty (ID – determined by the distance [D] between the target and the target's width [W] along the axis of motion by the equation $ID = \log_2 [2D/W]$) of repetitive [1] or discrete [2, 3] aiming tasks. The applicability of Fitts' Law has been verified in several studies analyzing various tasks such as: grasping [4, 5], aiming a mouse cursor using a computer display [6–9], intercepting moving targets [10], head movements [11], and bimanual movements [12, 13]. These empirical verifications have led the speed-accuracy trade-off to be regarded as one of the most consistent phenomena in motor behavior [14], inspiring researchers to try to understand the underlying basis of this paradigm.

Initially, the speed-accuracy trade-off was explained by a feedback process expressed as the Iterative Corrections Model [15]. This model theorized that increased

velocity decreases the amount of time available for the use of sensorial feedback for movement correction. On the other hand, slower movements allow for successive corrections to be made throughout the task thereby providing greater accuracy. Unfortunately, this model did not explain the speed-accuracy trade-off in movements with no time for feedback use [16, 17]. Subsequently, the Impulse Variability Model [18] was also proposed to explain these kinds of movements. This model suggested that fast movements (shorter than 200 ms) generate more neural noise from such factors as information processing, the transmission of information to effector systems, and movement production in the effector systems [18]. Such noise was used to explain greater variability in movement response and decreased accuracy when movement velocity increases. Nevertheless, this model was not able to take into consideration the feedback process for movement regulation [16, 17].

Attempting to combine the two previous models and address their particular limitations, a more expanded model was proposed by Meyer et al. [16] labeled as the Stochastic Optimized Submovement Model. This model proposed that movement is partially controlled by pre-programming and by feedback processes. Therefore, if a primary pre-programmed submovement is designed to hit a target and able to achieve this goal, no additional submovement is necessary. However, if this primary submovement travels outside the limits that allow the

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target to be reached, for example as a consequence of the perturbations arising from neuromotor noise, a secondary submovement would be used to adjust movement trajectory [16]. Another alternative explanation of the speed-accuracy trade-off was the Triggered Deceleration Time Model proposed by Zelaznik [17]. This model hypothesized that movement is controlled by two impulses of force, one related to movement acceleration (agonist muscles) and another to deceleration (antagonist muscles), where speed-accuracy is regulated by a trigger that marks the time when the deceleration forces start. According to this model, faster movements would be possible through the lengthening of the movement deceleration phase thereby allowing for additional possibilities to use feedback for movement adjustments. However, despite the contribution these two different explanations provided for explaining the speed-accuracy trade-off, these models were not designed to account for practice effect. Therefore, in order to analyze their robustness in explaining the speed-accuracy trade-off, it is necessary to test these models while considering practice effect. However, there are few studies in the literature that have examined this issue.

With the systematic practice of a given motor task, an individual becomes relatively independent of feedback information, regulating movements essentially through pre-programming before the movement begins [19, 20]. The logic of this supposition lies in the argumentation that, with learning, the practitioner can better specify the required control parameters more accurately and therefore requires less feedback [21, 22]. This hypothesis received support in Pratt and Abrams's study [20], which analyzed the effects of visual information in learning a fast and accurate movement. These authors showed that, after practice, the duration and distance of primary submovements increased while the duration and distance of secondary submovements decreased. These practice-related changes were explained by better movement pre-programming that allowed for lower movement time and greater accuracy, whereas visual information did not appear to affect control-movement strategies [20]. However, attention was drawn [20, 23] to the importance of feedback information on movement control, especially when a movement is performed at larger velocities.

Some studies suggest that while learning a motor ability, even simple tasks such as hitting spatial targets, the practitioner acquires the capacity to integrate sensory feedback information in a more effective manner, functionally coupling feedback with centrally generated motor commands [20, 23]. In this context, Khan and Franks [24] showed the importance of feedback through the occlusion of visual information during learning. The group that practiced with visual information showed greater accuracy and movement time in comparison with the group that practiced without visual information. The lengthened movement time in the group that prac-

ticed with visual information was possibly due to performing adjustments through feedback, which is in consonance with the greater accuracy found in this group. The time of the primary submovement decreased for the group that practiced with visual information while remaining relatively constant for the group without visual information. Consequently, it was suggested that visual information is important for both the programming phase and the feedback adjustment phase during movement regulation [24].

Elliot et al. [19, 25, 26] showed that practice can increase both accuracy and movement velocity. One of the strategies observed was to anticipate time to peak velocity (lengthening of the deceleration movement phase) and to increase peak velocity. This allowed greater velocity, smaller movement time, and lower primary submovement variability beyond the reduction of submovement adjustments [19, 25]. They suggested that the improvement of performance as a function of practice enhanced programming and the feedback process. Their results suggest that practice could improve both the speed and accuracy of a given task. Nevertheless, it is not yet known if this improvement would violate Fitts' Law.

Despite the various control strategies that explain the speed-accuracy trade-off, based mainly on either better programming or better feedback processing, it is important to understand the changes in the parameters of movement control as a function of practice as they may allow for a better understanding of different speed-accuracy strategies. Such analysis can also help test the proposed models of the speed-accuracy trade-off. For example, Pratt and Abrams's study [20] gives support to the model proposed by Meyers et al. [16], where practice effect was found to allow a practitioner to better specify the control parameters of primary submovements and depend less on secondary movement adjustments. However, it appears as if the studies by Khan and Franks [24] and Elliott et al. [19, 25, 26] lend credence to the model proposed by Zelaznik [17], where practice is believed to have resulted in faster and more accurate movements through a lengthening of the deceleration phase using feedback information.

On the basis of the two theories outlined above, the following hypotheses were formulated: (a) considering the Stochastic Optimized Submovement Model, practice would cause movement to be guided mainly by primary submovements, while, (b) considering the Triggered Deceleration Time Model, practice would cause movement to be guided mainly by secondary submovements and a lengthened deceleration phase. With the above in mind, the aim of the present study was to analyze the effect of practice on the control strategies of a discrete spatially constrained task simulated using a computer and further understanding of movement control strategies in the speed-accuracy trade-off paradigm.

Material and methods

Twenty male adults aged between 20 and 26 years old participated in this study. Subjects were randomly assigned to an experimental group ($n = 10$) that performed practice and a control group ($n = 10$) that performed no practice. The study procedure was approved by the local university's research ethics committee and all participants were informed of the experimental procedure.

All participants were tested by performing a discrete movement task in a virtual environment using software specially developed for this study (Fitts' Discrete Aiming Task ver. 2.0). The task is fundamentally similar to the one used in Fitts' paradigm [1] although it was simulated using a computer and mouse instead of a stylus. Simulating Fitts' task with the use of computer software and digital input devices has been confirmed in studies on the speed-accuracy trade-off paradigm [27–29]. The task consisted of using a mouse to click a cursor on two parallel buttons (shown on a monitor) where the target width ($W = 2.0, 1.0, 0.5,$ and 2.5 inches) and distance between buttons ($D = 2.0, 4.0,$ and 8.0 inches) was adjusted to provide indexes of difficulty ranging from 1 to 6 bits ($ID = \log_2 [2D/W]$). Participants had to use the mouse's left button to click on the target localized on the left side of the monitor display and then move the mouse cursor as fast as possible to click on the target on the right side. Trials were disregarded when (a) the mouse button was clicked outside the specified target, (b) the mouse button was not clicked, or (c) the mouse cursor trajectory went beyond the second target and was moved back in order to perform the button click. The custom software developed to simulate this task also provided for kinematic analysis of the mouse cursor movements (displacement, velocity, and acceleration). An optical mouse was used (ML-135, Knex, Brazil) with sensitivity set at 50%. A mouse pad (19×23 cm) was provided to improve mouse movement.

The task was performed by all participants with the right hand, with right-handedness confirmed using the Edinburgh Handedness Inventory [30]. The task was performed sitting in a comfortable position in front of the computer. Participants were instructed to perform the movements as fast and accurately as possible.

The participants were tested on three separate occasions as pre-test, post-test, and retention test. In pre-test, post-test, and retention, 12 trials were performed, one in each condition of ID (three distances between targets \times four target widths). Participants began each trial upon hearing an audio cue. A familiarization period was provided where five trials of the experimental task conditions were randomly presented. The pre-test was administered immediately after the familiarization period.

The practice period was performed by the experimental group after the pre-test, in which the task was practiced in three sessions on different days (24 hours between each session). In each practice session, 36 trials were performed (three trials of each combination of tar-

get width and distance between the targets), grouped into blocks of 12 consecutive trials. Between the blocks of trials there was a rest interval of 1 min. None of the subjects reported any kind of fatigue or tiredness after the blocks of practice.

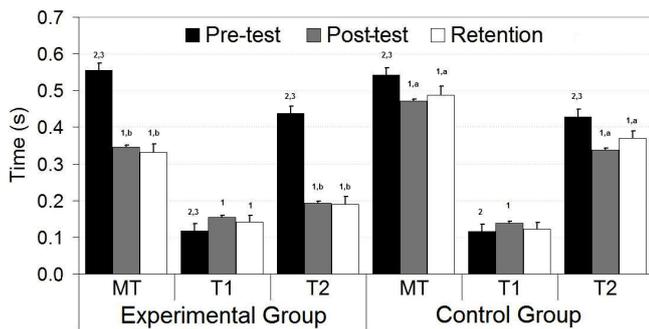
The post-test was performed by all participants immediately after the experimental group finished practice. The retention test was then applied 24 hours after post-test. In all tests, sequences with different target widths and with different distances between targets were pseudo-randomized between subjects (using Williams' design). In each trial, subjects observed the movement time (MT) provided by the software as a form of motivational feedback.

The kinematic dependent variables selected for analysis included mean movement time (absolute), effective error (absolute error calculated from the center of the target), velocity and acceleration peaks, time to peak velocity and time to peak acceleration (absolute and relative), and primary (T1) and secondary (T2) or higher order submovement times (absolute and relative). Submovement was defined according to Meyer et al. [16], in which the linear acceleration profile begins from a null value, becomes a positive value and then a negative value, and, subsequently, returns to a null value, similar in design to a sine wave [16]. For analysis of the speed-accuracy trade-off, the index of difficulty originally established by Fitts was used [1, 2], defined as: $ID = \log_2 (2D/W)$.

The custom-designed software provided the mouse cursor linear position as a function of time at a sample frequency of 100 Hz. Position data were filtered through a Butterworth 4th order recursive filter with a cutoff frequency at 10 Hz. After filtering, velocity and acceleration derivatives were calculated and dependent variables were then extracted. All dependent variables were analyzed by two-way ANOVA in a 2×3 design (Group: experimental \times control) \times (Time: pre-test \times post-test \times retention), with repeated measures for the last factor. Comparisons were made using Tukey's post hoc test. Statistical analysis was performed using Statistica ver. 6.0 software (Statsoft, USA) with the level of significance set at 5% ($p = 0.05$).

Results

The absolute times of MT, T1, and T2, for the experimental and control groups in pre-test, post-test, and retention are presented in Figure 1. The relative times of T1 and T2 for the experimental and control groups in pre-test, post-test, and retention are presented in Figure 2. Movement time (MT) showed a main effect of Group [$F(1, 18) = 12.79, p = 0.0004$], indicating lower MT for the experimental group compared with the control group. The effect of Time [$F(2, 18) = 120.63, p < 0.0001$] suggests that practice provided better performance by scoring lower MTs. There was an interaction effect of Time \times Group [$F(2, 18) = 38.25, p < 0.0001$], in which both the experimental and control

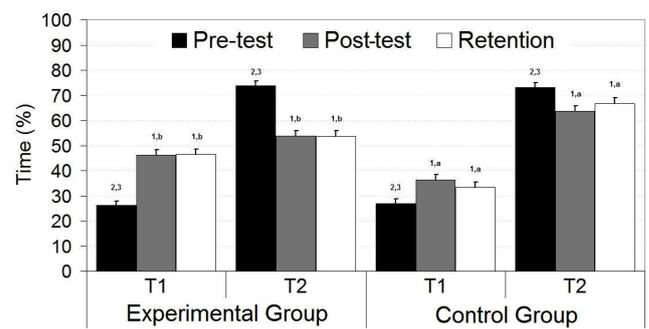


Significant difference ($p < 0.05$) when compared with: ^a experimental group, ^b control group, ¹ pre-test; ² post-test, ³ retention

Figure 1. Means of total movement time (MT), primary submovement time (T1), and secondary submovement time (T2) as a function of group (experimental and control) and time (pre-test, post-test, and retention)

groups presented lower MTs in pre-test in comparison with post-test ($p < 0.05$) and retention ($p < 0.05$). The experimental group also showed shorter movement time in pre-test ($p < 0.05$) and post-test ($p < 0.05$) compared with the control group.

Primary submovement time (T1) showed a main effect for Group for absolute [$F(1, 18) = 7.16, p < 0.008$] and relative [$F(1, 18) = 27.24, p < 0.0001$] times, indicating greater T1 for the experimental group in comparison with the control group ($p < 0.05$). An increase in T1 was also observed in Time for both absolute [$F(2, 18) = 19.64, p < 0.05$] and relative [$F(2, 18) = 104.57, p < 0.0001$] times. There was no interaction between Group \times Time for T1 absolute time [$F(2, 18) = 1.98, p = 0.14$]. However, an interaction effect was found for Group \times Time for T1 relative time [$F(2, 18) = 32.75, p < 0.0001$] for the experimental and control groups, showing increased T1 relative time in pre-test compared with post-test ($p < 0.05$)



Significant difference ($p < 0.05$) when compared with: ^a experimental group, ^b control group, ¹ pre-test, ² post-test, ³ retention

Figure 2. Relative primary (T1) and secondary (T2) submovement time as a function of group (experimental and control) and time (pre-test, post-test, and retention)

and retention ($p < 0.05$). The experimental group demonstrated greater T1 relative time in comparison with the control group ($p < 0.05$).

Secondary submovement time (T2) presented a main effect for Group in absolute [$F(1, 18) = 16.38, p < 0.0001$] and relative [$F(1, 18) = 27.24, p < 0.0001$] times, indicating lower T2 for the experimental group. The effect of Time for absolute [$F(2, 18) = 114.33, p < 0.0001$] and relative [$F(2, 18) = 104.58, p < 0.0001$] times also showed that practice and the tests provided better performance in terms of decreasing T2. The interaction effect of Group \times Time was also verified for absolute [$F(2, 18) = 33.19, p < 0.0001$] and relative [$F(2, 18) = 32.75, p < 0.0001$] times, where in the experimental group T2 decreased in pre-test in comparison with post-test ($p < 0.05$) and retention ($p < 0.05$) values. The experimental group showed lower T2 relative ($p < 0.05$) and absolute ($p < 0.05$) times compared with the control group.

Table 1. Means and standard deviations (in parenthesis) of the dependent variables as a function of group and time

Dependent variables	Experimental group			Control group		
	Pre-test	Post-test	Retention	Pre-test	Post-test	Retention
Effective error (mm)	8.51 (1.29)	8.50 (1.48)	8.76 (1.40)	9.79 (1.29)	9.84 (1.48)	9.50 (1.40)
Peak velocity (mm/s)	1122.52 (67.48) ^{2,3}	1378.81 (66.03) ¹	1343.93 (68.60) ¹	1158.30 (68.34)	1136.42 (66.87)	1111.59 (69.48)
Absolute time to peak velocity (s)	0.15 (0.007) ^{2,3}	0.10 (0.005) ^{1b}	0.09 (0.005) ^{1b}	0.15 (0.007)	0.13 (0.005) ^a	0.13 (0.005) ^a
Relative time to peak velocity (%)	29.56 (1.12) ³	32.59 (1.13)	33.43 (1.21) ¹	28.77 (1.13)	30.01 (1.15)	31.06 (1.23)
Acceleration peak (mm/s ²)	28227.73 (1522.7) ^{2,3}	38275.08 (1589.2) ^{1b}	35868.16 (1558.01) ¹	29625.81 (1542.18)	28864.69 (1609.49) ^a	28364.84 (1577.86)
Absolute time to peak acceleration (s)	0.08 (0.007) ^{2,3}	0.05 (0.004) ¹	0.05 (0.007) ^{1b}	0.09 (0.007)	0.08 (0.004)	0.09 (0.007) ^a
Relative time to peak acceleration (%)	17.10 (1.37)	18.10 (1.10)	19.31 (1.17)	18.97 (1.39)	18.91 (1.11)	20.08 (1.18)

Significant differences ($p < 0.05$) when compared with: ^a experimental group, ^b control group ¹ pre-test, ² post-test, ³ retention

Table 1 shows effective error, peak velocity, acceleration, and time to peak velocity and peak acceleration (absolute and relative) data for the experimental and control groups in pre-test, post-test, and retention. Effective error did not show a main effect of Group [$F(1, 18) = 0.79, p = 0.37$] and Time [$F(2, 18) = 0.001, p = 0.99$], nor an interaction effect between Group \times Time [$F(2, 18) = 0.032, p > 0.97$], suggesting that participants were able to maintain accuracy throughout the experimental conditions. Peak velocity presented a main effect of Time [$F(2, 18) = 5.24, p = 0.006$], indicating that practice provided a greater magnitude of velocity. An interaction effect was also observed for Group \times Time [$F(2, 18) = 8.79, p < 0.0002$] in which the experimental group had greater peak velocity at pre-test in comparison with post-test ($p < 0.05$) and retention ($p < 0.05$). Time to peak velocity showed a main effect for Group [$F(1, 18) = 13.87, p = 0.0002$] and Time [$F(2, 18) = 32.24, p < 0.0001$], indicating a lower time for the experimental group compared with control group. The effect was also observed in the interaction between Group \times Time [$F(2, 18) = 13.97, p < 0.0001$], in which the experimental group decreased time to peak velocity in the pre-test in comparison with post-test ($p < 0.05$) and retention ($p < 0.05$). The experimental group also showed lower time to peak velocity in post-test and retention in comparison with the control group. Relative time to peak velocity showed a main effect only for Time [$F(2, 18) = 6.74, p < 0.05$], indicating an increase in the relative time to peak velocity for the experimental group in the pre-test compared with retention ($p < 0.05$).

Peak acceleration showed a main effect for Group [$F(1, 18) = 7.50, p = 0.007$], indicating a greater magnitude of acceleration in the experimental group compared with the control group. The effect of Time [$F(2, 18) = 11.80, p < 0.0001$] showed an increase in peak acceleration as a result of practice. The interaction effect of Group \times Time [$F(2, 18) = 16.49, p < 0.0001$] indicated greater peak acceleration for the experimental group in the pre-test in comparison with post-test ($p < 0.05$) and retention ($p < 0.05$). The experimental group also showed greater peak acceleration in post-test compared with the control group ($p < 0.05$). Time to peak acceleration showed a main effect for Group [$F(1, 18) = 12.64, p = 0.0005$], indicating lower time to peak acceleration for the experimental group in relation to the control

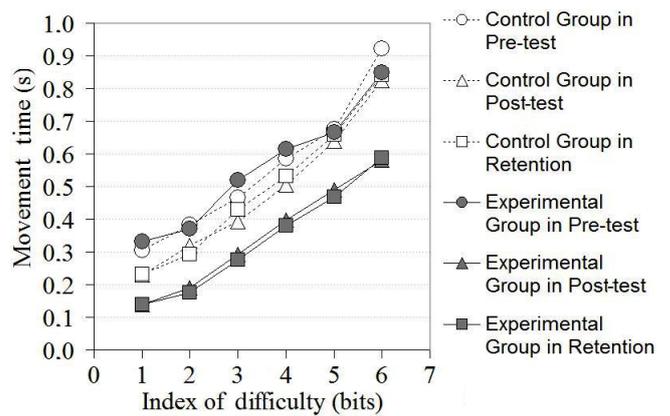


Figure 3. Movement time (MT) \times index of difficulty (ID) for group (experimental and control) as a function of time (pre-test, post-test, and retention)

group. The effect of Time [$F(2, 18) = 10.79, p < 0.0001$] also showed an anticipation (decreased) in the peak of acceleration arising from practice. There was an effect of interaction between Group \times Time [$F(2, 18) = 5.10, p = 0.006$], indicating lower time for peak acceleration in the experimental group in pre-test compared with post-test ($p < 0.05$) and retention ($p < 0.05$). There was also a lower time to peak acceleration for the experimental group compared with the control group. Relative time to peak acceleration did not show a main effect for Group ($p > 0.05$), Time ($p > 0.05$) and the interaction between Group \times Time ($p > 0.05$).

Table 2 showed the relationship between movement time (MT) and the index of difficulty (ID). It was found that Fitts' Law was not rejected as a function of practice (see Tab. 2 and Fig. 3). A relationship was found between MT \times ID [$r > 0.97, R^2 > 0.95, F(1, 4) > 129.03, p < 0.003$]. The coefficient 'a' in the linear predictive equation during regression analysis showed that practice seemed to approximate the MT value to the intersection between the abscissa and ordinate axes for IDs closer to zero (Tab. 2).

Discussion

Practice decreased total movement time, as expected, while maintaining movement accuracy (as assessed by effective error). Other studies also verified improved

Table 2. Coefficients of linear regression analysis for group (experimental and control) as a function of time (pre-test, post-test, and retention)

Group	Time	r	R ²	Equation
Control	Pre-test	0.984	0.969	y = 0.1019x + 0.2022
Control	Post-test	0.976	0.953	y = 0.1167x + 0.1476
Control	Retention	0.985	0.972	y = 0.1156x + 0.0801
Experimental	Pre-test	0.990	0.981	y = 0.1216x + 0.0717
Experimental	Post-test	0.996	0.994	y = 0.0918x + 0.0267
Experimental	Retention	0.991	0.984	y = 0.0926x + 0.0138

movement with increased velocity while accuracy was maintained [20, 23]. An interesting discovery was that, even with increasing velocity, Fitts' Law [1] was not violated as a function of practice. In other words, the prediction of movement time as a function of the index of difficulty (Tab. 2) showed a coefficient of $R^2 > 0.95$ for all test periods (pre-test, post-test, and retention) and for all groups (experimental and control). Thus, Fitts' Law proved to be robust enough to consider the effect of practice on movement performance in the spatially constrained task used in the present study (Fig. 3).

The strategies adopted to explain this decrease in movement time in the present study showed changes in movement phases considered to be predominantly pre-programmed and regulated by feedback. This pre-programmed movement phase has been assumed to underline primary submovements [16]. In this study, it was observed that the primary submovement phase (T1) increased (absolute and relative time) in the experimental group as a function of practice. This result suggests that practice provides better movement pre-programming. Additionally, it seems reasonable to consider that the first phase of the movement is a larger determinant of movement accuracy. Therefore, if added errors occurred in this first phase of movement, more time would be needed for additional feedback adjustments to correct them. This idea has support in studies that verified better feedforward control after practice by a decrease in spatial variability and increase of the distance traveled by primary submovements [31]. These results are also consistent with Meyers et al.'s proposition [16] of the Stochastic Optimized Submovement Model. According to Meyers et al.'s model, better pre-programmed movement would be expected as a result of practice by reducing the need of using feedback with higher orders of submovements. Data provided by the control phase, in which movement is regulated predominantly by feedback (T2), is also in agreement with such a proposition.

Practice also decreased the time (absolute and relative) of T2 in the experimental group. Thus, it seemed that movement before practice was controlled mainly through corrections based on feedback information. Whereas, after practice, the proportional sizes of T1 and T2 were found to be very close. An interesting discovery was the large decrease in the magnitude of T2 absolute time as a result of practice. This suggests that movement time shortened after practice giving less time for feedback adjustments (T2), which demanded better use of feedback for movement corrections. Therefore, even after becoming faster as a result of practice, accuracy was still maintained (effective absolute error) during movement and infers that use of additional feedback information was not necessary [20, 32]. Better movement control appears to have arisen from practice, thus providing a better ability to integrate sensorial feedback information with central motor commands [23, 31]. Hence, in spite of better pre-programming arising from

practice, it is suggested that the efficient reduction in total time occurred mainly as the result of optimizing the movement feedback process.

It is also important to explain the changes verified in the control group during the tests. The control group showed a decrease in movement time and T2 although an increase in T1 from pre-test to post-test and retention. These changes were explained by the number of conditions in each test (12), as it provided participants with a certain amount of practice (total of 36 trials considering all test conditions). Since the task used to analyze the effect of practice on the speed-accuracy trade-off was simple in nature, even a few repetitions were enough to provide an improvement in performance. However, the greater number of trials practiced by the experimental group showed more evident changes in performance after practice compared with the control group for the relative time variables (lower MT and T2 and greater T1).

Movement time decreased in the experimental group by increases in the magnitude of velocity and acceleration. According to some of the models explaining the speed-accuracy trade-off, an increase in velocity/acceleration would lead to lower accuracy. For example, the models of Impulse Variability [18] and Stochastic Optimized Submovement [16] indicate that higher velocity/acceleration warrants greater force generation during movement performance. This greater force generation would be inversely associated with response variability and, consequently, lead to lower movement accuracy [18]. These models are based on the idea that greater force generation causes more noise in the system leading to response variability and lower accuracy. Moreover, decreases in MT, according to the Iterative Corrective Model [15], would also result in greater response variability. Therefore, this model assumes that accuracy is achieved by sensorial-feedback corrections that depend on time in order to be correctly processed [15]. Nevertheless, the present study did not verify greater effective error, as a function of practice, even with higher velocity and acceleration. In all probability, the optimization of pre-programmed primary submovements and the use of sensory feedback provided faster and more accurate movement.

Another possible explanation for maintaining accuracy could stem from the study control variables used to manipulate the tasks' spatial constraints. As spatial constraint was an adjustable variable, by the combination of different target sizes and distances between the targets, it was expected that movement would not exceed certain spatial limits. In this regard, the fact that movement accuracy was maintained showed that the applied spatial constraints were guaranteed in the different conditions analyzed. However, such an explanation by itself would not explain the ability to generate greater velocity and acceleration without leading to lower accuracy.

The paradigm of fast and accurate movements explained by Zelaznik's [17] Triggered Deceleration Time Model has been analyzed in soccer kicks [33], basketball jump shots [34–37], and overarm throwing [21]. These studies showed a strategy of control the instant in which peak velocity occurred in order to maintain movement accuracy. It is believed that such a strategy allows for a lengthening of the movement deceleration phase ordinarily related to the feedback control process. Additionally, this strategy may provide for lower acceleration at the instant of a performance-critical movement such as during release, contact, impact, etc., therefore providing smaller response variability at this critical moment [17, 22, 34]. This strategy adopted by Zelaznik [17] hypothesized that a reduction in MT would be accomplished by greater T2 and a lengthened deceleration phase (diminished time to peak velocity) as a consequence of practice. The reduction in time to peak velocity (considered as the movement acceleration phase) would give the perceptual impression that this strategy was used as a result of practice. However, the constancy found in relative time of peak velocity and acceleration in the present study does not sustain Zelaznik's hypothesis. Instead, it is suggested that such a strategy is used both before and after practice.

Conclusions

In summary, movement time decreased mainly as a function of the reduction in the time used for feedback adjustments. It is suggested that the improvement in performance as a function of practice occurred through the interdependence of programming and the feedback process. Therefore, as the task was practiced, there was a reduced need for feedback due to improved pre-programming of the primary submovement and the use of sensorial feedback information. This strategy and the lengthened deceleration phase can help explain the paradigm of fast and accurate movements arising from practice. Considering the application of these results, it may be suggested that, during practice, it is important to emphasize the perception of the most important aspects of a movement. This would allow for faster development of pre-programming, deemphasize the need of feedback, and allow for better use of the lengthened deceleration phase of the movement. Despite the changes in performance as a consequence of practice, Fitts' Law showed to be robust enough to predict movement time as a function of the index of difficulty. One limitation of the present study is that analysis was based on a task simulated in a virtual environment. It is therefore suggested that future studies analyze more complex motor skills such as those found in sports.

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