Human Movement Science 64 (2019) 142–152

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Oculomotor behavior and the level of repetition in motor practice: Effects on pupil dilation, eyeblinks and visual scanning

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ARTICLE INFO

Keywords:
Motor learning
Sensory processing
Perception
Mental workload
Practice schedule
Working memory

ABSTRACT

The benefits of less repetitive practice in motor learning have been explained by the increased demand for memory processes during the execution of motor skills. Recently, a new perspective associating increased demand for perception with less repetitive practice has also been proposed. Augmented information gathering and visual scanning characterize this higher perceptual demand. To extend our knowledge about mental effort and perceptual differences in practice organization, the association between oculomotor behavior and type of practice was investigated. We required participants to press four keys with different absolute and relative timing goals during the acquisition phase. An eye-tracker captured visual scanning of the skill's absolute and relative information displayed on the screen. Participants were tested 24 h after acquisition by a retention and transfer test. A higher level of both pupil dilation and amount of eyeblinks indicated an increased mental effort in less repetitive practice compared to more repetitive practice. Visual scanning of the skill's relative and absolute information was specific to the type of practice. The findings indicate many differences in oculomotor behavior associated with the practice schedule.

1. Introduction

Practice is the most important factor involved in motor learning, since it provides an active search for the solution of motor problems. A well-documented effect of practice is the advantage of less repetitive practice over more repetitive practice in motor learning (Bonney, Jelsma, Ferguson, & Smits-Engelsman, 2017; Lage et al., 2017; Shea & Morgan, 1979). More repetitive practice involves the execution of only one skill (e.g., constant practice: AAAAAAAAA) or the consecutive execution of all trials of a given skill before the execution of the block of another skill (e.g., blocked practice: AAABBBCCC). Conversely, less repetitive practice involves a non-systematic order of skills' execution (e.g. random practice: ACBCBABAC) or a serial order of execution (e.g. serial practice: ABCABCABC) (Lage et al., 2015). Constant or blocked practice lead to improved practice performance but result in poorer retention and transfer. Conversely, random and serial practice lead to worse performance during practice, but promotes better performance on retention and transfer tests (Buszard, Reid, Krause, Kovalchik, & Farrow, 2017; Lai, Shea, Wulf, & Wright, 2000; Shewokis et al., 2017).

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https://doi.org/10.1016/j.humov.2019.02.001
Received 30 September 2018; Received in revised form 26 January 2019; Accepted 2 February 2019
Available online 05 February 2019
0167-9457/

Explanatory hypotheses regarding the increased benefits of less repetitive practice on motor learning are based on mechanisms associated with greater cognitive effort, which benefits motor learning (Lee & Magill, 1985; Shea & Zimny, 1983). Greater cognitive effort results from the increased demand of memory processes caused by trial-to-trial variations (Lage, Vieira, Palhares, Ugrinowitsch, & Benda, 2006; Song, Sharma, Buch, & Cohen, 2012). Less repetitive practice seems to involve more elaborative processing of information (Shea & Zimny, 1983), higher demand of reconstruction of action plans (Lee & Magill, 1985) or greater abstraction of the movement rules defined as schema (Moxley, 1979). These behavioral hypotheses have been recently strengthened by neurobiological analyses of the neural substrates associated with the type of practice experienced (Lage et al., 2015). For instance, the dorsolateral prefrontal cortex (DLPFC), a cortical area related to working memory function, is more associated with random than constant practice (Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2011).

For almost 40 years, the efforts of investigation have been directed to memory processes (Lee & Magill, 1983; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Shea & Morgan, 1979; Weeks, Reeve, Dornier, & Fober, 1991). However, a new perspective associating perception with practice organization has been recently proposed, which opens a new exciting field of study. Lelis-Torres et al. (2017) proposed a theoretical model, which points out differentiated levels of perceptual processing induced by less and more repetitive practice schedules. This model suggests that less repetitive practice demands greater perceptual effort characterized by increased information gathering, visual scanning, and sustained attention. Two central aspects of trial-to-trial variations were emphasized. First, there is a necessity of performing visual scanning to gather information related to the required goal in each trial. This process feeds the first stage of movement planning. Conversely, the trial-to-trial stability promoted by the consecutive repetition of a task does not require the learner to continuously search for previous information about the goal of the movement to supply the next planning step.

The second aspect considered by Lelis-Torres et al. (2017) is the visual scanning to gather information after movement execution. In discrete sequence-production tasks with two temporal goals to be learned, knowledge of results (KR) is supplied in relation to the absolute and relative timing errors. The hypothesis proposes that learners in less repetitive practice condition direct their attention more to the absolute dimension of the task because they are concerned about the constant change in the absolute dimension. Conversely, during more repetitive practice, attention is focused more in the relative dimension of the task. This hypothesis is based on behavioral findings indicating that constant practice benefits learning of the relative timing of the movement and random practice benefits the learning of the absolute timing, defined as a movement parameter (Lage et al., 2007; Lai & Shea, 1998; Lai et al., 2000).

Three other studies published in the same period as the Lelis-Torres et al. (2017) study have also confirmed the association between brain areas involved in perceptual processing and practice organization (Chalavi et al., 2018; Henz, John, Merz, & Schollhorn, 2018; Thurer, Stockinger, Putze, Schultz & Stein, 2017). Thurer et al. (2017) observed a greater EEG activity of the alpha band in the parietal cortex region during less repetitive practice. Henz et al. (2018) found an increased activity of theta and alpha bands for practice with less repetition in the somatosensory regions of the cortex, indicating a greater perceptual activity in this type of practice. Chalavi et al. (2018) evaluated the neurochemical bases involved in less and more repetitive practice schedules. Magnetic resonance spectroscopy showed differences in GABAergic (gamma-aminobutyric acid) activity in the occipital cortex. Random practice was associated with greater modulation in GABAþ levels, probably because the less repetitive nature of this practice demands greater involvement of visual processing regions. While less repetitive practice schedule requires deeper processing of both the stimulus structure and the movement's visual feedback, more repetitive practice becomes more habitual and without trial-to-trial shifting, since less visual attention needs to be directed to features of the task. Altogether, these studies point out different perceptual requirements when the learner is involved in less or more repetitive practice (Chalavi et al., 2018; Henz et al., 2018; Lelis-Torres et al., 2017; Thurer et al., 2017).

With the specific aim of broaden the understanding about mental effort and perceptual differences in different types of practice schedules, the present study aims to investigate the association between oculomotor behavior and types of practice. This approach can help us understand if the increased mental effort observed in information processing is also observed in ocular behavior. Visual parameters such as pupil dilation and eyeblinks rate have been used as measures of perceptual effort in reading (Hyona & Olson, 1995) and divided attention tasks (Baldock, Kapadia, & van Steenbrugge, 2018). During the execution of cognitive tasks, the level of these measures increases as the task demand increases. If less repetitive motor practice demands greater mental effort than more repetitive practice, we can expect greater pupil dilation and amount of eyeblinks during practice. If trial-to-trial stability does not require from the learners continuous visual search to keep them informed about the movement goals (Lelis-Torres et al., 2017), we can also expect a decreased level of pupil dilation and amount of eyeblinks throughout more repetitive practice. Conversely, the level of these measures should be kept constant during less repetitive practice.

The second aim of this study is to investigate how visual information feeds perceptual processes in more and less repetitive motor practice. If the type of practice influences how attention is directed to different dimensions of the task (Lelis-Torres et al., 2017), we can expect greater amount of visual information gathered throughout practice on absolute task dimension to less repetitive practice compared to more repetitive practice. Conversely, visual gathering on absolute dimension should decrease during practice with more repetition. Finally, we can expect increased focus of visual attention on relative task dimension in more repetitive practice.

2. Method

2.1. Participants

This study included thirty female undergraduate students (mean age of 22.8 ± 4 years). All participants were right-handed, had normal or corrected-to-normal vision and were randomized into two experimental groups: Constant Practice or CP

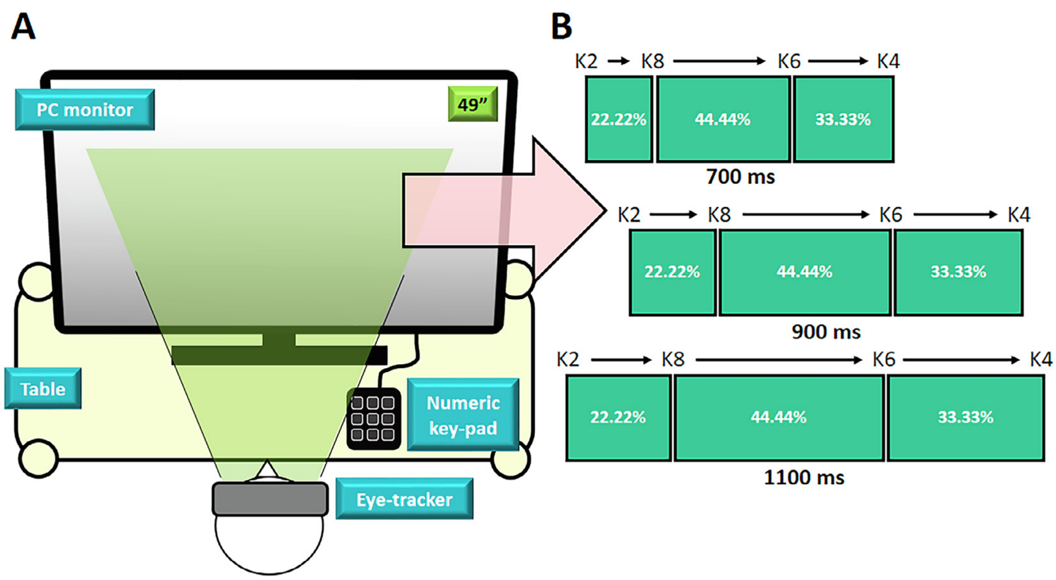

Fig. 1. (A) Apparatus used to apply the motor task, (B) the sequence of keys typed (K2…K4), the relative criterion segment ratios between the keys (22.22%, 44.44% and 33.33%) and the total criterion movement time (700, 900 and 1100 ms).

(23.0 ± 4.8 years) and Random Practice or RP (22.6 ± 4.1 years). All participants were naïve with regard to the motor task.

All participants signed written informed consent after receiving a full explanation of about the study. An ethics committee from a local university approved all procedures, and we conformed to the standards set by the Declaration of Helsinki (2014 version).

2.2. Apparatus

To conduct the experimental task, a 49 in. 4 K/Ultra HD-LED television (LG, Seoul, South Korea) and a numeric keypad were placed on a standard table and connected to a notebook (Fig. 1A). Participants were instructed to perform the task seated on a chair facing the TV, wearing a SMI Eye-tracker (Sensomotoric Instruments, Teltow, Germany) settled at 30 Hz, which was connected to a second notebook. They were also instructed to adjust the position of the numeric keypad to comfortably use it with their right hand. A standard lighting was used, the windows of the room were properly covered by curtains, and no other objects were placed on the environment in order to reduce distraction.

2.3. Experimental procedures

Initially, participants were instructed to quietly stare at a blank gray screen during 60 s to compute a baseline metric to allow discrimination of possible differences in sample selection and calculation of the gain in pupil diameter. The background color of the task/baseline was carefully standardized by light and neutral color (hex #ebebeb) and all feedback forms were white (hex #ffffff) in order to avoid further psychological effects. Both groups received the same task display. The Begaze (SMI) used infrared cameras to monitor the eyes and detect the pupil. The SMI "world camera" video was extracted to identify the gaze and the position of each KR and task goals. To perform the gaze calibration, participants were asked to look at 3 visual points scattered as vertices around the relevant points in the task display.

For the motor task, participants were asked to sequentially press four different keys with their index finger of the right hand (keys 2–8 – 6–4) with a constant relative timing goal (i.e., movement segment ratio between two key presses) of 22.22%, 44.44%, and 33.33% for the first, second and third segments, respectively. The movement time (MT) required to complete each sequence were 700, 900, and 1100 ms for RP and 900 ms for CP (Fig. 1B). This paradigm used was based on previous studies investigating the effects of constant and random practice in the learning of relative and absolute dimensions of the task (Apolinário-Souza et al., 2016; Lage et al., 2017; Lai et al., 2000; Shea, Lai, Wright, Immink, & Black, 2001). Before each trial, the relative timing (RT) and MT goals were presented on the screen (e.g., "22.22%; 44.44%; 33.33% – 900 ms"). Participants were asked to be as accurate as possible regarding both RT and MT.

The experimental design was divided in three moments: acquisition phase, retention test, and transfer test. Participants performed 120 trials during the acquisition phase, After the completion of each trial, knowledge of results (KR) and the next goals were displayed on the screen. The KR included the relative time of each segment performed by the volunteer, the relative error (RE), defined as the sum of the differences between the criterion segment ratio and the ratio performed by the volunteer for each segment, and the MT performed. Six seconds after the KR presentation, the message "Initiate next trial" instructed the participants to start the next sequence of key pressing when they decided to do it. A 12-trial block on the retention and transfer test was administered 24hr

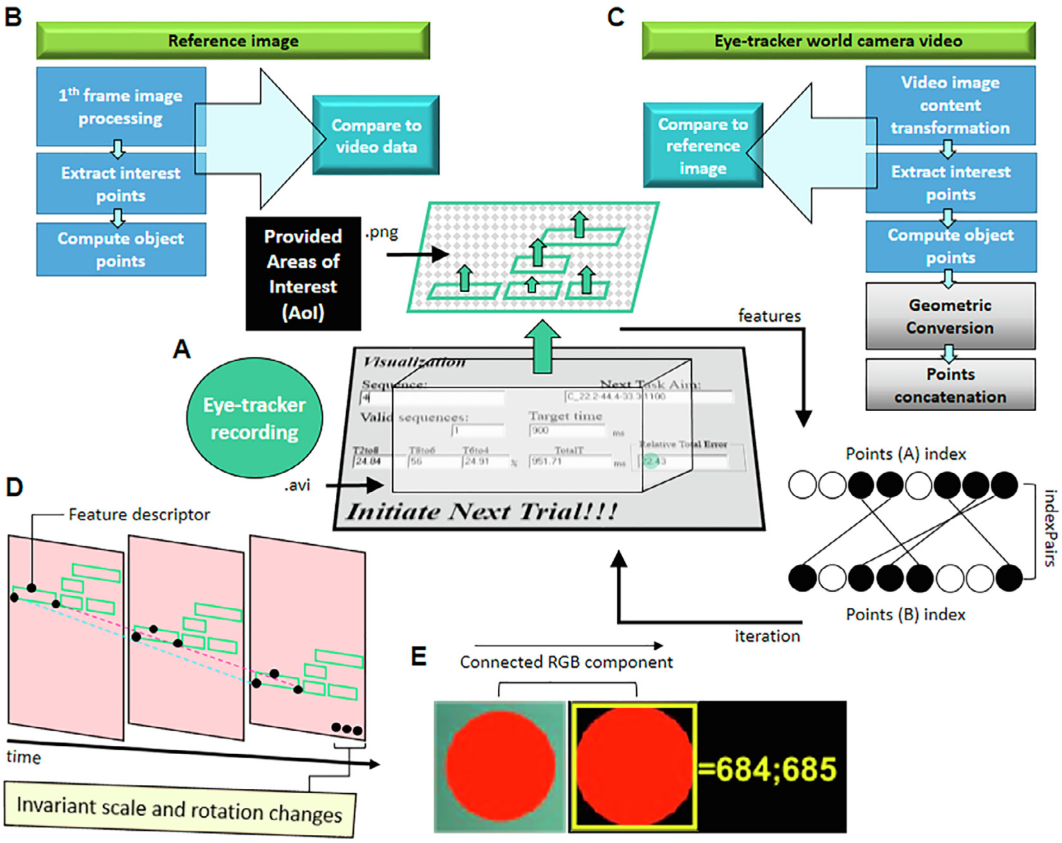

Fig. 2. Schematic representation of the areas of interest recognition procedure built in Matlab language.

after acquisition. On the retention test, participants were instructed to perform the same MT of 900 ms. On the transfer test, participants performed a novel MT of 1300 ms. The RTs required on both tests were the same of acquisition. KR was not provided on both tests.

2.4. Eye tracker signal processing

Artificial system techniques (details in Fig. 2A) were employed with Matlab (The Mathworks Inc., Massachusetts, EUA) to measure the amount of visual information gathered in terms of task goals and KR in both relative and absolute dimensions of the motor skill. All data was computed offline. Thus, there was no processing delay. The recorded eye-tracker "world camera" video of each participant was extracted to identify the position of each KR and task goals in the whole video data. The first image frame was then extracted to provide a reference and comparison image with the world camera video to compute each KR/task goals throughout the whole data (Fig. 2B). This frame went through a process of manipulation of different parameters, such as resolution and hueing (e.g. DPI and RGB color values) and we built a feature matrix addressing the points of interest to parse each KR/task goal (Fig. 2D). These features were compared with the entire video data. Parameters of the video image underwent the same image transformation techniques and point structures were computed throughout the video to build a geometric conversion and a concatenation of the index matrix points with the image of reference (Fig. 2C). To ensure an accurate definition of dynamic areas, deformations of points of interest throughout video data, such as rotation and shape changes, were detected and assigned afterward to a parametric multidimensional adjustment function. Areas of interests (AOI) vectors of each KR and task goals displayed on the screen were then built, establishing the putative targets for calculation of the time spent by the eyes on each feedback form. The analysis of gaze was made by a processing technique that involved the extraction of its RGB values and the metrics of its connected components (Fig. 2E).

2.5. Measurements

The absolute timing error (*AE*) was used as a measure of parameterization proficiency and was computed as the difference between the actual movement time (MT) and the total criterion time.

The relative timing error (*RE*) was used as a measure of proficiency in the relative dimension of the task, informing about the formation of a movement pattern, and was computed as the sum of the absolute difference between the observed and criterion ratio timing for each segment with the following formula:

$$RE = |R_1 - 22.22| + |R_2 - 44.44| + |R_3 - 33.33|,$$

where R_n = (performed timing of segment n/MT) × 100.

Pupil dilation and eyeblinks measures were also processed using Matlab. To estimate the changes in pupil diameter, a subtractive baseline correction was employed, and the signal was artifact-reconstructed by a cubic spline function. The pupil peak dilation was inferred as the gain in pupil peak diameter in each trial on each block of trials. The average of pupil dilation was defined as the gain in averaged signal courses within each trial on each block of trials. A median filter (5th order) was also applied to filter spikes in order to create a reliable signal profile. An automatic clipped reading function of peak values was used to discriminate eye-blinks and to count the pronounced dips in pupil size. To investigate the perceptual effort, the level of pupil dilation and amount of eyeblinks were assessed on the first and last blocks of trials during the acquisition phase. These measures were also analyzed on the retention and transfer tests. Offline learning (Δoffline), characterized by the difference between the retention test block and the last block of acquisition, was analyzed in both oculomotor measures.

To measure the amount of visual information gathered on KR and goals during the acquisition phase, in both relative and absolute dimensions the total dwell time (TDT) on each AOI was computed. The TDT was then normalized into seconds, partitioned into trials/blocks and further segmented into feedback period (FP) and planning period (PP). The FP comprises the 6 s period of visual search that occurs between the last key pressing and the appearance of the message "Initiate next trial" while the PP encompasses the meantime between the appearance of the message and the pressing of the first key of the next trial sequence. During PP, feedback information was also available

2.6. Data analysis

The Shapiro-Wilk test revealed that all measures had a normal distribution. Thus, the data were organized as means and standard deviations (SD) for descriptive analyses. The motor performance measures were organized in blocks of 12 trials. The *RE* and *AE* on the acquisition phase were analyzed using a two-way ANOVA (2 groups × 10 blocks) with repeated measures on the second factor. We conducted t-tests to analyze the retention and transfer tests.

To compare the amount of pupil dilation and eyeblinks in the constant and random groups during the baseline, we conducted Student's t-tests. To analyze the level of both oculomotor measures from the first to the last block of acquisition, we used two-way ANOVAs (2 groups × 2 blocks of acquisition) with repeated measures on the second factor. We analyzed the retention test, transfer test, and Δoffline using independent t-tests.

To investigate the changes in the amount of visual information gathered on KR and task goals from the first to the last block of acquisition, the TDT was analyzed using two-way ANOVAs (2 groups × 2 blocks of acquisition) with repeated measures on the last factor. Thus, we conducted 8 analyses: (1) TDT on relative timing goal: planning period; (2) TDT on relative timing goal: feedback period; (3) TDT on absolute timing goal: planning period; (4) TDT on absolute timing goal: feedback period; (5) TDT on relative timing KR: planning period; (6) TDT on relative timing KR: feedback period; (7) TDT on absolute timing KR: planning period; (8) TDT on absolute timing KR: feedback period.

We used Tukey's *t* test for post hoc analyses when necessary. We set the level of statistical significance at 0.05 for all statistical tests. The effect sizes were calculated using partial eta-squared (η2) for ANOVAs and Cohen's (*d*) for t-tests.

3. Results

3.1. Absolute dimension analysis

We present descriptive analyses in Fig. 3A. On the acquisition phase, the inferential analysis detected a significant main effect for practice condition, $F(1,280) = 247.27$, $p < .001$, $\eta p^2 = 0.46$. Post hoc analysis indicated that absolute timing errors were lower in

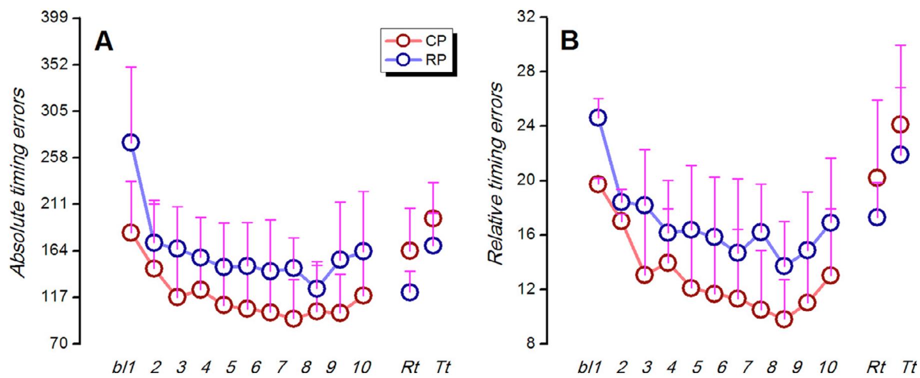

Fig. 3. Mean and + SD values of (A) absolute (ms) and (B) relative timing (%) errors over the blocks of trials during the acquisition phase (bl1…10), retention test (Rt) and transfer test (Tt) of random and constant groups.

CP. The inferential analysis detected a significant main effect for blocks, $F(9,280) = 9.62$, $p < .001$, $\eta p^2 = 0.23$, and the post hoc analysis indicated that first block errors were greater compared with the other blocks. There was no significant group × block interaction, $F(9,280) = 0.36$, $p = .95$, $\eta p^2 = 0.01$.

On retention test, the inferential analysis detected a significant difference between groups, $t(28) = 3.38$, $p < .001$, $d = 1.23$, in which RP promoted less absolute-timing errors than CP. On transfer test, a significant difference was also found, $t(28) = 2.17$, $p = .038$, $d = 0.079$, in which RP promoted less absolute-timing error than CP.

3.2. Relative dimension analysis

Descriptive statistics are presented in Fig. 3B. On the acquisition phase, the inferential analysis detected a significant main effect for practice condition, $F(1,28) = 211.59$, $p < .001$, $\eta p^2 = 0.43$. The post hoc analysis indicated that the relative timing errors were lower in CP. The inferential analysis detected a significant main effect for blocks, $F(9,280) = 5.30$, $p < .001$, $\eta p^2 = 0.14$, and the post hoc analysis indicated that first block errors were significantly greater compared with the other blocks. There was no significant group × block interaction, $F(9,280) = 0.43$, $p = .91$, $\eta p^2 = 0.14$.

The inferential analysis did not detect significant differences between groups on retention, $t(28) = 1.77$, $p = .09$, $d = 0.06$, and transfer test, $t(28) = 1.11$, $p = .27$, $d = 0.04$.

3.3. Amount of pupil dilation and eyeblinks in baseline

The inferential analysis did not detect significant differences between groups in terms of average pupil size, $t(28) = 0.83$, $p = .38$, $d = 0.03$, pupil peak, $t(28) = 0.83$, $p = .40$, $d = 0.30$, and eyeblinks, $t(28) = -0.44$, $p = .65$, $d = 0.01$, during the baseline period.

3.4. Pupil peak dilation

Descriptive statistics are presented in Fig. 4A. The inferential analysis indicated a significant main effect for practice condition, $F(1,56) = 70.86$, $p < .001$, $\eta p^2 = 0.56$. The post hoc analysis indicated a higher level of pupil dilation in RP than in CP. The inferential analysis detected a significant main effect for blocks condition, $F(1,56) = 24.30$, $p < .001$, $\eta p^2 = 0.30$, and the post hoc analysis indicated that pupil dilation decreased from the first to the last block of acquisition phase. The significant group × block interaction, $F(1,56) = 3.96$, $p = .052$, $\eta p^2 = 0.66$, followed by a post hoc analysis indicated a higher level of pupil dilation in RP on both blocks.

The inferential analysis indicated a significant difference between groups on the retention test, $t(28) = -11.32$, $p < .001$, $d = 0.55$, in which RP exhibited a higher level of pupil dilation than CP. Significant difference was also found on transfer test, $t(28) = -6.18$, $p < .001$, $d = 0.55$, in which RP exhibited a higher level of pupil dilation.

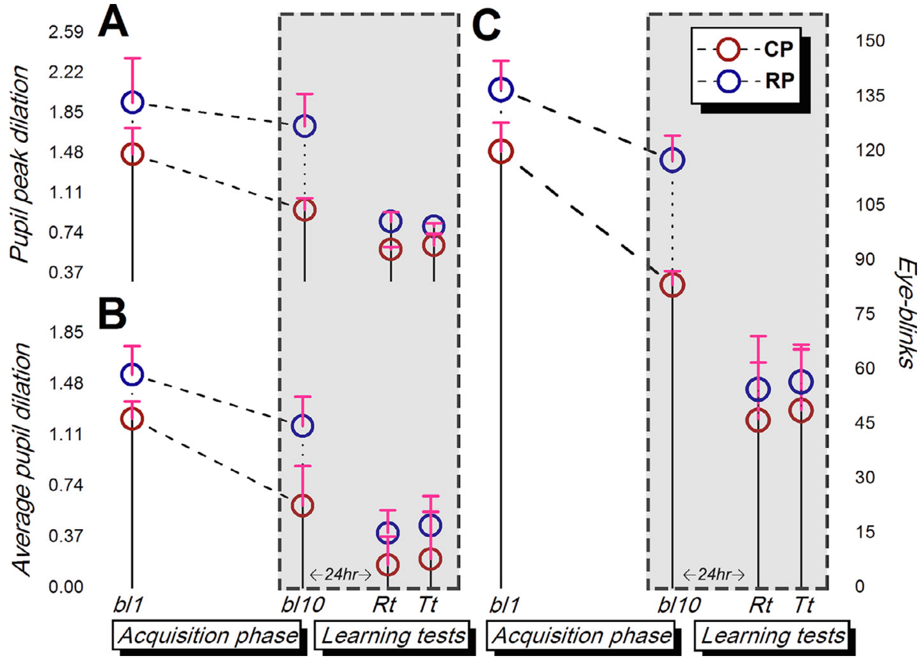

Fig. 4. Mean + SD values of pupil peak dilation (A), average pupil dilation (B) and eyeblinks (C) during the acquisition phase (bl1 and 10), retention test (Rt) and transfer test (Tt) of random and constant practice groups.

3.5. Average pupil dilation

Descriptive statistics are presented in Fig. 4B. On the acquisition phase, the inferential analysis indicated a significant main effect for practice condition, $F(1,56) = 64.43$, $p < .001$, $\eta p^2 = 0.54$. The post hoc analysis indicated a higher level of pupil dilation in RP than in CP. The inferential analysis detected a significant main effect for blocks, $F(1,56) = 80.37$, $p < .001$, $\eta p^2 = 0.59$, and the post hoc analysis indicated that pupil dilation decreased from the first to the last block. The significant group × block interaction, $F(1,56) = 5.39$, p = .024, $\eta p^2 = 0.09$, followed by a post hoc analysis indicated a higher level of pupil dilation in RP on both blocks.

The inferential analysis indicated a significant difference between groups on the retention test, $t(28) = -3.39$, $p = .002$, $d = 1.06$, in which RP exhibited higher level of pupil dilation than CP. Significant difference was also found on transfer test, $t(28) = -2.33$, $p = .027$, $d = 0.87$, in which RP exhibited a higher level of pupil dilation.

3.6. Eyeblinks

Descriptive statistics are presented in Fig. 4C. On the acquisition phase, the inferential analysis indicated a significant main effect for practice condition, $F(1,56) = 214.03$, $p < .001$, $\eta p^2 = 0.79$. The post hoc analysis indicated a higher amount of eyeblinks in RP than in CP. The inferential analysis detected a significant main effect for blocks, $F(1,56) = 257$, $p < .001$, $\eta p^2 = 0.82$, and the post hoc analysis indicated that the amount of eyeblinks decreased from the first to the last block. The significant group × block interaction, $F(1,56) = 24.25$, $p < .001$, $\eta p^2 = 0.30$, followed by a post hoc analysis indicated a higher amount of eyeblinks in RP on both blocks.

The inferential analysis did not indicate significant differences between groups on both retention, $t(28) = 1.53$, $p = .85$, $d = 1.41$, and transfer test, $t(28) = 1.53$, $p = .09$, $d = 2.25$.

3.7. Offline changes in pupil dilation and eye blinks

The inferential analysis on pupil peak dilation, $t(28) = -3.22$, $p < .001$, $d = 1.17$, and average pupil dilation, $t(28) = 3.546$, $p < .001$, $d = 1.10$, indicated a significant higher Δoffline in RP than in CP. Descriptive statistics are presented in Fig. 4A. The inferential analysis on eyeblinks also indicated a significant higher Δoffline, $t(28) = 0.52$, $p < .001$, $d = 5.79$, in the CP than RP. Descriptive statistics are presented in Fig. 4B.

3.8. Total dwell time

3.8.1. Total dwell time on relative timing KR: Planning period

Descriptive statistics are presented in Fig. 5A. The inferential analysis on TDT did not detect a main effect for practice condition, $F(1,56) = 0.56$, $p = .45$, $\eta p^2 = 0.01$, but detected a significant main effect for blocks, $F(1,56) = 49.80$, $p < .001$, $\eta p^2 = 0.47$. The post hoc analysis indicated that TDT decreased from first to the last block of trials. The group × block interaction was not significant, $F(1,56) = 0.06$, $p = .79$, $\eta p^2 = 0.001$.

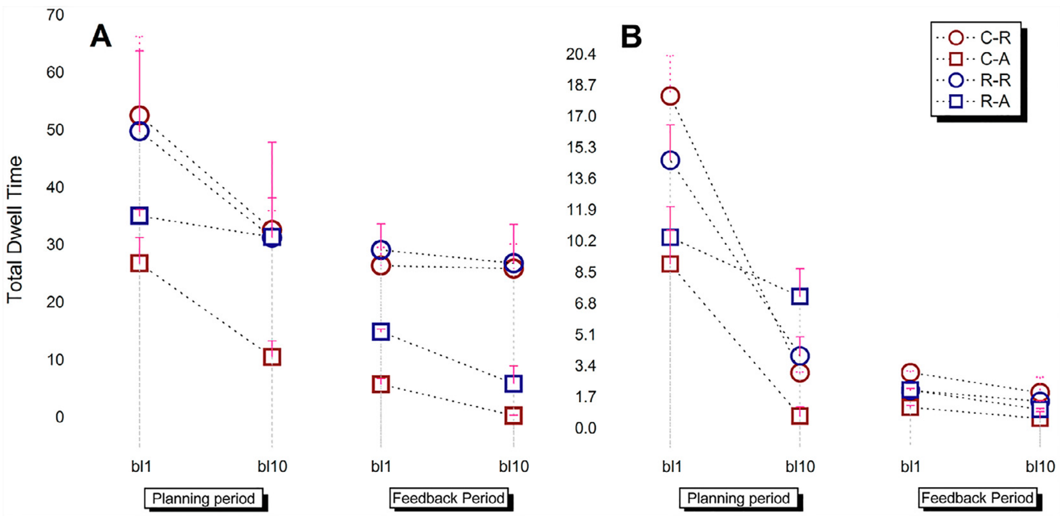

Fig. 5. Mean and ± SD values of total dwell time (TDT) in seconds over relative and absolute information available on the screen for both (A) KR and (B) timing goals. TDT of the first and last blocks were analyzed during both feedback and planning periods on random and constant groups. C-R = constant group *TDT* on relative information; C-A = constant group TDT on absolute information; R-R = random group *TDT* on relative information; R-A = random group *TDT* on absolute information.

3.8.2. Total dwell time on relative timing KR: Feedback period

Descriptive statistics are presented in Fig. 5A. The inferential analysis on TDT did not detect a main effect for practice condition, $F(1,56) = 2.08$, $p = .154$, $\eta p^2 = 0.03$, block condition, $F(1,56) = 1.24$, $p = .26$, $\eta p^2 = 0.02$, or a group × block interaction, $F(1,56) = 0.51$, $p = .47$, $\eta p^2 = 0.00$.

3.8.3. Total dwell time on absolute timing KR: Planning period

Descriptive statistics are presented in Fig. 5A. The inferential analysis on total dwell time indicated a significant main effect for practice condition, $F(1,56) = 299.17$, $p < .001$, $\eta p^2 = 0.84$, in which RP presented a higher TDT than CP. The inferential analysis detected a significant main effect for blocks, $F(1,56) = 291.78$, $p < .001$, $\eta p^2 = 0.79$. The post hoc analysis indicated that TDT decreased from first to the last block of trials. The significant group × block interaction, $F(1,56) = 17.92$, $p < .001$, $\eta p^2 = 0.24$, followed by a post hoc analysis indicated higher TDT on both blocks of acquisition for RP compared to CP.

3.8.4. Total dwell time on absolute timing KR: Feedback period

Descriptive statistics are presented in Fig. 5A. The inferential analysis on Total dwell time indicated a significant differences main effect for practice condition, $F(1,56) = 42.19$, $p < .001$, $\eta p^2 = 0.43$, in which RP presented a higher TDT than CP. The significant main effect for blocks, $F(1,56) = 19.87$, $p < .001$, $\eta p^2 = 0.26$, followed by a post hoc analysis indicated that TDT decreased from the first to the last block. The significant group × block interaction, $F(1,56) = 7.89$, $p < .001$, $\eta p^2 = 0.12$, followed by a post hoc analysis indicated higher TDT on both blocks of acquisition for RP compared to CP.

3.8.5. Total dwell time on relative timing goal: Planning period

Descriptive statistics are presented in Fig. 5B. The inferential analysis on total dwell time indicated a significant main effect for practice condition, $F(1,56) = 10.30$, $p < .001$, $\eta p^2 = 0.15$, in which CP presented a higher TDT than RP. The significant main effect for blocks, $F(1,56) = 1029.21$, $p < .001$, $\eta p^2 = 0.94$, followed by a post hoc analysis indicated that TDT decreased from the first to the last block. The significant group × block interaction, $F(1,56) = 30.38$, $p < .001$, $\eta p^2 = 0.35$, followed by a post hoc analysis indicated higher TDT on the first block of acquisition in CP compared to RP.

3.8.6. Total dwell time on relative timing goal: Feedback period

Descriptive statistics are presented in Fig. 5B. The inferential analysis on total dwell time indicated a significant main effect for practice condition, $F(1,56) = 43.63$, $p < .001$, $\eta p^2 = 0.43$, in which CP presented a higher TDT than RP. The significant main effect for blocks, $F(1,56) = 59.31$, $p < .001$, $\eta p^2 = 0.51$, followed by a post hoc analysis indicated that TDT decreased from the first to the last block. The significant group × block interaction, $F(1,56) = 5.02$, $p = .029$, $\eta p^2 = 0.08$, followed by a post hoc analysis indicated higher TDT on both blocks of acquisition in CP compared to RP.

3.8.7. Total dwell time on absolute timing goal: Planning period

Descriptive statistics are presented in Fig. 5B. The inferential analysis on total dwell time indicated a significant main effect for practice condition, $F(1,56) = 109.67$, $p < .001$, $\eta p^2 = 0.66$, in which RP presented a higher TDT than CP. The significant main effect for blocks, $F(1,56) = 228.98$, $p < .001$, $\eta p^2 = 0.80$, followed by a post hoc analysis indicated that TDT decreased from the first to the last block of trials. The significant group × block interaction, $F(1,56) = 5.022$, $p = .029$, $\eta p^2 = 0.082$, followed by a post hoc analysis indicated higher TDT on both blocks of acquisition in RP compared to CP.

3.8.8. Total dwell time on absolute timing goal: Feedback period

Descriptive statistics are presented in Fig. 5B. The inferential analysis on Total dwell time indicated a significant main effect for practice condition, $F(1,56) = 197.96$, $p < .001$, $\eta p^2 = 0.77$, in which RP presented a TDT time than CP. The significant main effect for block condition, $F(1,56) = 267.44$, $p < .001$, $\eta p^2 = 0.82$, followed by a post hoc analysis indicated that TDT decreased from the first to the last block of trials. The significant group × block interaction, $F(1,56) = 21.15$, $p < .001$, $\eta p^2 = 0.27$, followed by a post hoc analysis indicated higher TDT on both blocks of acquisition in RP than in CP.

4. Discussion

The present study investigated the association between oculomotor behavior and practice schedules. We hypothesized a greater pupil dilation and amount of eyeblinks during less repetitive practice compared to more repetitive practice. We also expected a decreased level of pupil dilation and eyeblinks throughout practice in more repetitive practice. Moreover, the level of these measures should be kept constant during less repetitive practice. Another aim of this study was to investigate how the visual attention is directed to the absolute and relative dimensions of the task. We expected a greater amount of visual information gathered on the absolute dimension in less repetitive practice and greater amount of visual information gathered on the relative dimension in more repetitive practice. Overall, all hypotheses were confirmed, indicating the existence of many differences in oculomotor behavior when the learner engages in practice schedules with more or less repetition.

As expected, less repetitive practice, compared to more repetitive practice, produced higher levels of error in both absolute and relative dimensions of the task during the acquisition phase. Such as expected, an inversion of the groups' performance from acquisition to the learning tests was also observed. Less repetitive practice generated lower levels of absolute timing errors on both retention and transfer tests. This type of behavior is well-documented in the literature, mainly in sequential timing tasks (Lage et al., 2017; Lai & Shea, 1998; Lai et al., 2000; Lelis-Torres et al., 2017). All explanatory hypotheses used to explain this pattern of results are related to the greater cognitive effort produced by less repetitive practice, which promotes worse performance during practice, but favors the strengthening of internal processes related to memory functions. Hence, on the learning tests, a well-developed representation of the task favors the better performance. A strong evidence to this assumption is that even with less practice in the MT of 900 ms (only 33.3% of all trials), less repetitive practice produces better performance on the retention test of 900 ms compared to the practice condition in which this MT was practiced in 100% of the trials. Recently, some studies have presented new explanatory perspectives about the contribution of other mechanisms further than processes involving memory (Chalavi et al., 2018; Henz et al., 2018; Lelis-Torres et al., 2017; Thurer et al., 2017).

Perceptual differences in processing have been found, such as a greater EEG activity of the alpha band in the parietal cortex during less repetitive practice (Thurer et al., 2017). Increased activity of the theta and alpha bands for practice with less repetition was also found in the somatosensory regions (Henz et al., 2018), as well as a greater modulation in GABAþ levels in the occipital area (Chalavi et al., 2018). Despite the growing body of evidence about differences in mental effort involved in more and less repetitive practice, to our knowledge, the results of the present study regarding the differences in oculomotor behavior are novel findings. These differences are related to three aspects: (1) the effort promoted by the level of repetition experienced during practice, (2) the effort involved on the learning tests, and (2) the focus of visual attention during practice.

Only a small number of studies have investigated the effects of motor practice on pupil dilation (White & French, 2017), and our study contributes to the literature with new findings. During practice, the level of pupil dilation was greater to less repetitive practice compared to more repetitive practice. This measure is related to the mental effort imposed by the difficulty of a given task (Baldock et al., 2018; Hyona & Olson, 1995), which strengthens previous results of electroencephalographic studies indicating greater mental effort in less repetitive condition (Chalavi et al., 2018; Henz et al., 2018; Lelis-Torres et al., 2017; Thurer et al., 2017). The offline changes observed from the last block of acquisition to the retention test showed a diminished level of pupil dilation in less repetitive practice. The analyses of the retention and transfer tests indicated that the level of pupil dilation was higher in less repetitive practice. The hemodynamic activation of the cortical structures involved in the planning and execution of skills indicates that less repetitive practice is associated with increased motor area activity at the end of the acquisition phase, but opposite effect is observed during retention test (Lage et al., 2015). The offline changes in pupil dilation observed in our study indicate similar behavior, which can be associated with the neural efficiency phenomenon. That is, from the last block of acquisition to the retention test we observed a decreased pupil activity concomitantly to a better performance on the retention test. Despite the higher offline change of less repetitive practice, the level of pupil dilation was maintained higher on the retention and transfer tests. This finding indicates a higher mental effort to less repetitive practice even during the learning tests. Other physiological parameters are also maintained at high level during the learning tests. For instance, M1 excitability remains increased on learning tests during less repetitive practice (Lin et al., 2011).

Mental effort acts (a) exciting the sympathetic pupil dilator pathway and relaxing the sphincter muscle contributing to the dilation and (b) inhibiting the Edinger-Westphal complex of the oculomotor nucleus, causing the relaxation of the sphincter muscle and consequently, also contributing to dilation (Granholm & Steinhauer, 2004). Remarkably, our findings show that these mechanisms are activated at different intensities by the level of repetition imposed by the practice schedule. Increased mental effort activates the locus coerulus (LC), which subsequently sends inhibitory signals to the Edinger-Westphal complex (Sirois & Brisson, 2014). The LC, a subcortical structure, is the main site for the synthesis of norepinephrine in the brain. The LC and norepinephrine system (LC-NE) are involved in processes related to memory retrieval (Sterpenich et al., 2006) and selective attention (Foote & Morrison, 1987). A new field of investigation could be focused on the association between the LC activation and the level of repetition imposed by practice schedules. The responsivity of cortical neurons are adaptively adjusted by two LC modes (Aston-Jones & Cohen, 2005). While the tonic phase of LC displays a rapid neuronal firing to optimize the focus of attention on a specific task, called the exploitation mode, the tonic mode displays an elevated baseline firing rate in the LC, promoting disengagement from the task and favoring a diffuse exploration mode (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010). Further studies could investigate if the level of motor repetition is associated with the LC modes. Could more repetitive practice be associated with the exploitation mode and less repetitive practice associated with the exploration mode? Is the higher level of pupil dilation on learning tests associated with the exploration mode required mainly on transfer?

Spontaneous eyeblinks also serve as a measure of mental effort and occur during early sensory processing and following sustained information processing (Hyona & Olson, 1995). Our findings showed that less repetitive practice induces higher number of eyeblinks during the acquisition phase, which strengthen the evidences of increased mental effort in this type of practice schedule. The offline changes observed from the last block of acquisition to the retention test showed a diminished amount of eyeblinks in less repetitive practice. On the retention and transfer tests, the amount of eyeblinks were equal between the practice schedules. Similar to the discussion about pupil activity, these findings permit inferences about gains in neural efficiency. Although the exact neural circuitry that controls spontaneous eyeblinks still requires further investigation, a link between spontaneous eyeblinks and dopaminergic activity (DA) in the central nervous system has been studied (Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017). Eyeblinks rate has been used as an indirect measure of DA involved in cognitive functions (den Daas, Hafner, & de Wit, 2013). Indirectly, our findings indicate possible modulation of DA as an effect of the level of repetition experienced during practice. Further studies could investigate this possible association between practice schedule and DA.

Visual scanning and information gathering after movement execution was different between practice conditions. This finding shows that visual scanning is directed by the performance goals of learning the relative and absolute timing of the discrete sequence-production task. Once the movement is finished, two main sources of information are accessed (Lelis-Torres et al., 2017). Information provided by KR about the relative and absolute dimensions is gathered, as well as information about the relative and absolute timing goals. Both types of information gathered, the relative and absolute timing, were analyzed in two periods: the KR period and the planning period. Less repetitive practice showed a higher amount of KR information gathered from the absolute dimension than more repetitive practice. This difference was found in both KR period and planning period. The same results were found for the visual scanning related to the task goals. Less repetitive practice showed a higher amount of goal information gathered from the absolute dimension than more repetitive practice. This difference was also found in both KR period and planning period. These results confirm our hypotheses that the learner in less repetitive practice directs more his/her visual attention to the leaning of the absolute dimension of the task, because the performer is concerned with the constant change in the absolute dimension. This hypothesis was proposed by previous studies (e.g., Lai et al., 2000), but only now confirmed.

During more repetitive practice, attention should be more focused in the relative dimension of the task (Lage et al., 2017). Our results support this view. More repetitive practice showed higher amounts of goal information gathered from the relative dimension than less repetitive practice. This difference was found in both KR period and planning period. Curiously, this type of oculomotor behavior was not found for KR information. Both types of practice showed similar KR visual scanning on the relative dimension. As less repetitive practice induces higher levels of error in both dimensions, learners cannot direct their visual attention to only one dimension. Conversely, more repetitive practice induces lower levels of errors in both dimensions, possibly because leaners direct more their visual attention to the most demanding dimension to be learned, the relative dimension. Lelis-Torres et al. (2017) hypothesized a similar visual scanning of the absolute dimension goal in the early phase of the practice for more and less repetitive practice. However, throughout practice a decreased level of visual scanning for more repetitive practice was expected. Our results showed that both groups diminished the gathering of this information from the first to the last block of the acquisition phase but, differently from the hypothesis proposed by Lelis-Torres et al. (2017), less repetitive practice exhibited a higher amount of information gathering since the first block. Further studies could verify trial-to-trial changes according to the stages of learning, because the visual disengagement of the absolute dimension goal may decrease rapidly.

Taken together, our results indicate many differences in oculomotor behavior associated with practice schedule. Strengthening previous results from studies using other physiological parameters, greater mental effort in less repetitive practice was observed by increased level of pupil dilation and number of eyeblinks. Specific associations between type of information gathered and type of practice schedule were found, confirming the explanatory hypotheses proposed in previous studies. New directions for further studies were proposed, more specifically, the possible associations between type of practice schedule and activation of the LC modes, and the possible relationships between type of practice and DA. Further studies should investigate the oculomotor behavior in other practice schedules, such as blocked and serial practice.

Acknowledgement

This study was supported by Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG: grant APQ-03305-15).

Declarations of conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.02.001.

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