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**Conscious awareness of motor fluidity improves performance and
decreases cognitive effort in sequence learning**

Stefano Ioannucci¹, Arnaud Boutin^{2,3}, Thomas Michelet¹, Alexandre Zenon^{1,**}, &
Arnaud Badets^{1,*,**}

Institution:

¹CNRS, Institut de Neurosciences Cognitives et Intégratives d'Aquitaine (UMR 5287),
Université de Bordeaux, France

² Université Paris-Saclay, CIAMS, 91405, Orsay, France

³ Université d'Orléans, CIAMS, 45067, Orléans, France

*Correspondence: arnaud.badets@u-bordeaux.fr

INCIA - Institut de Neurosciences Cognitives et Intégratives d'Aquitaine
Université de Bordeaux, Bât. 2A- 2ème étage
146 rue Léo Saignat,
33076 Bordeaux cedex

**These authors have contributed equally for this work

Abstract

Motor skill learning is improved when participants are instructed to judge after each trial whether their performed movements have reached maximal fluidity. Consequently, the conscious awareness of this maximal fluidity can be classified as a genuine learning factor for motor sequences. However, it is unknown whether this effect of conscious awareness on motor learning could be mediated by the increased cognitive effort that may accompany such judgment making. The main aim of this study was to test this hypothesis in comparing two groups with, and without, the conscious awareness of the maximal fluidity. To assess the possible involvement of cognitive effort, we have recorded the pupillary dilation to the task, which is well-known to increase in proportion to cognitive effort. Results confirmed that conscious awareness indeed improved motor sequence learning of the trained sequence specifically. Pupil dilation was smaller during trained than during novel sequence performance, indicating that sequence learning decreased the cognitive cost of sequence execution. However, we found that in the group that had to judge on their maximal fluidity, pupil dilation during sequence production was smaller than in the control group, indicating that the motor improvement induced by the fluidity judgment does not involve additional cognitive effort. We discuss these results in the context of motor learning and cognitive effort theories.

Key words:

Motor learning, Conscious awareness, pupil dilation, motor sequence

Introduction

Motor skill learning is critical for survival. For example, efficient acquisition of a new evasive manoeuvre during a flight procedure can be decisive for a military pilot. For a building-worker, effective learning of a dockyard-tool can be critical for safety. Finally, a skilled-surgeon can make the difference between death and life in required situations. Consequently, the cognitive mechanisms at work during learning of many real-world motor skills represent a scientific challenge in our societies (see Harris et al. 2018; Schmidt & Lee, 2011 for reviews). These learning processes are accompanied with subjective, meta-learning percept of performance improvement, and more specifically, about the fluency of the motor skill. Such conscious awareness of the fluency of goal-based movements in turn reinforces future enactments (Boutin et al. 2014). However, little is known about the specific mechanisms at work in this feedback effect of conscious feeling of fluency on learning.

The first empirical evidence on the effect of conscious awareness of action in motor learning comes from a study where participants were required to learn a motor sequence task with the instruction to detect, after each trial, the most maximal fluidity of the motor sequence (Boutin et al. 2014). Specifically, the task in this study was composed of a 12-element motor sequence on a keyboard, cued by on-screen visual stimuli, and participants were requested to press with the right-hand fingers the appropriate response keys as rapidly and accurately as possible. When such regular stimulation is repeated over time (after several trials), it is well known that participants encode the motor sequence by associative learning between keys presses, leading to optimized motor performance (Boutin et al. 2010, Jiménez et al. 2011, Miller, 1956, Solopchuk et al. 2016, see Sakai, Hikosaka, & Nakamura, 2004, for a review). The two main groups of this study were called the “awareness group”, and the “No-judgment control group”. For the awareness group, participants were required to judge after each trial whether their performed motor sequence had attained maximal fluidity; practically, if participants replied “yes” to this question, it meant that she/he believed that she/he was not able to improve motor fluidity further. For participants in the no-judgment group, no judgment was required after each trial, and the instruction emphasized only improving and learning the motor sequence. Results revealed a clear motor improvement for both groups at the end of the learning phase, and most importantly,

that participants in the awareness group outperformed participants of the no-judgment group. For the authors, this is a first piece of evidence that the conscious awareness of the motor fluidity can be categorized as a factor that can influence motor sequence learning positively.

Accordingly to this finding, and as mentioned by Abrahamse, Ruitenberg, de Kleine, and Verwey (2013), motor sequence learning can be deeply improved by explicit sequence descriptions during the instruction. In the same vein, Jaynes, Schieber, and Mink (2016) have revealed that participants who became aware of their motor patterns during the learning phase performed the sequence with greater consistency with regard to their movement kinematics. Finally, Toner and Moran (2014) emphasized that expert sport performers and musicians can improve their performances throughout conscious cognitive activities in deploying for instance attention toward bodily movements.

However, altogether these results say little about the mechanisms at play in this motor learning improvement induced by conscious awareness. One hypothesis is that cognitive effort would be increased in the condition in which participants focus on reaching maximal fluidity of the movement, in turn leading to improved performance. Indeed, it is well known that some experimental factors which emphasize more cognitive effort can in turn improve motor learning (Schmidt & Lee, 2011). For example, it is accepted that practicing several motor tasks in a random practice format during the learning phase (e.g., the randomization of three motor tasks to-be learned), is more beneficial for a long-lasting learning than practicing the same tasks in a blocked format (e.g., with no or less randomization of these tasks). This beneficial effect of randomization for motor learning is known under the name “contextual interference effect” (Shea & Morgan, 1979). Accordingly, Li and Wright (2000) have found greater attentional demand for the motor planning of the task to-be learned during the learning phase of a random practice. To interpret these data, Wright and colleagues (2016, for a review) have recently suggested that encountering a contextual interference “in practice is “more effortful or demanding” due to the need to engage a broader set of cognitive operations needed to execute an action.” (p. 4). For these authors, such additional cognitive efforts can in turn improve the learning of the motor sequence tasks. Consequently, in following this theoretical argument of the cognitive effort effect on motor learning, we could speculate that an additional cognitive effort is at work when

participants are instructed to attain the maximal fluidity of a motor sequence which in turn improves motor encoding.

While this cognitive-effort hypothesis seems well suited to interpret the effect of conscious awareness of action on motor learning, an alternative hypothesis would be that the improvement in sequence learning induced by fluidity judgment is mediated by other mechanisms than increased effort. Indeed, in order to assess the fluidity of their performance after each trial, participants have to mentally rehearse their action. Like an additional feedback on the movement, this additional rehearsal of performance in the fluidity judgment group could be responsible for the specific enhancement in their motor learning process (Aiken, Fairbrother & Post, 2012). Moreover, Wulf and Lewthwaite (2016) showed that focusing attention on the enhancement of future performance outcomes is an important factor for motor learning. For these authors, “enhanced outcome is achieved with less effort, as indicated by reduced muscular activity, heart rate, oxygen consumption, and so forth. Thus, movement efficiency is enhanced as well.” (p. 1401). For example, it is well known that drawing attention on the environmental consequence of a performed action is more beneficial for motor learning than drawing attention on the different movements themselves to produce this action (see Lewthwaite & Wulf, 2017 for a review). Thus, in accordance with this “outcomes” hypothesis, it could be argued that the beneficial effect in drawing attention - at the end of a trial - on the maximal fluidity of an action can have the capacity to improve subsequently the learning of the motor sequence. Both the rehearsal and the action outcome hypotheses lead to predictions of lower effort associated with the fluidity judgment instructions.

The main aim of the present article is to disentangle these alternative hypotheses about the implication of cognitive effort in the effect of conscious awareness of action on motor learning. To that end, we have used the pupillary dilation paradigm, widely accepted as a physiological marker of cognitive effort (see van der Wel & van Steenbergen, 2018; Zenon, 2019, for reviews). In the domain of task learning, pupil size has been shown to decrease across trials (Foroughi, Sibley & Coyne, 2017), an effect interpreted as the signature of decreasing cognitive load induced by learning. In the present study, we recorded pupillary responses in both groups that learned a motor sequence task. Participants of the first “action awareness” group were instructed to execute the motor task (motor task A) as quickly and accurately as possible and to judge

after each trial whether they reached their maximal motor sequence fluidity (Boutin et al. 2014). Participants of the second no-judgment “control” group were only instructed to perform the motor task as quickly and accurately as possible. For both groups, some test trials (motor task B) were inserted across practice blocks. These test trials served as a within-group control condition in order to assess the cognitive load when participants were facing an unpracticed, new motor task. Indeed, as suggested by Foroughi and colleagues (2017), we expected pupil dilation increases for both groups in the test trials.

More importantly, if the conscious awareness effect in motor learning implies increased cognitive effort (Wright et al. 2016), then the expected higher learning rate on motor task A for the awareness group should be associated with increased pupil dilation, in comparison to the control group. In contrast, with respect to both the mental rehearsal and effortless action-outcome hypotheses (Wulf & Lewthwaite, 2016), we expect inverse results during the practice of motor task A. Finally, from the perspective of motor performance, we also expected to replicate the pattern of behavioral results reported by Boutin et al. (2014), that is, a motor learning improvement for the awareness group in comparison to the control group. No difference between groups is expected for the new motor task B, in terms of task performance and pupil dilation.

Method

Participants

30 students from the University of Bordeaux (age = 24.1 ± 3.8 , 13 M) participated in this study. All were naive to the experimental procedure and task. All participants were right-handed and possessed normal or corrected-to-normal vision. Their informed consents to participate was obtained before the experiment, and the study was approved by the Ethical Review Board of the university. The inclusion criteria were the absence of any medical history related to the cognitive domain (e.g. dyslexia, lethargy, neglect, depression, psycho-motor impairments) and normal or corrected-to-normal vision. Participants volunteered for the study and received no compensation for their participation. The sample size was predetermined to be sufficient to detect effect of action awareness on implicit motor learning on the basis of previous work (Boutin et al 2014).

Materials

Participants were comfortably seated in front of a 1280 by 1024 computer screen and a keyboard for the key pressing task. The screen stood at approximately 50 cm from the participants' head, which was placed onto a chin-rest. An Eye-tracker 1000 was placed below the screen (SR Research Ltd., Mississauga, Canada) in order to record variations in pupil size, as volunteers executed the task. The experiment was programmed and implemented with the Psychtoolbox on Matlab software, version 2019a (The MathWorks, Inc., Natick, Massachusetts, United States). Source code is freely available on [<https://github.com/ste-ioan/SeqLearn>]. All data has been made available at <https://zenodo.org/record/4963687> (Ioannucci, 2021).

Procedure

The experimental procedure was carried out in a single session day. During the experiment, four horizontally aligned black squares were presented on the center of the computer screen on a grey background. These hollow squares were 2 cm wide and 2 cm high, with 1 cm distance between them. Imperative stimuli were green square fillings appearing, in sequence, inside any one of the four above-mentioned locations. Participants were instructed to respond as quickly and correctly as possible to the sequentially presented stimuli, by pressing the corresponding response keys with their right-hand fingers. In order to signal the beginning of each new trial, which consisted of a full repetition of a stimuli-response sequence, a 50-ms starting tone (1250 Hz) was played synchronously with the presentation of the four empty squares. The onset of the first stimulus was randomly varied in an interval between 1 and 3s after the aforementioned tone (in 0.5-s steps), while a 5s fixed pause was set between trials. The green target squares would disappear only after a key was pressed by the participant, immediately followed by the next in sequence. Reaction times (RT) were measured as the time between the presentation of an imperative stimulus and the corresponding key press.

Participants were assigned randomly to two experimental groups: the "control" group (N = 15, age = 22.7 ± 3.2 , 6 males), and the "action awareness" group (N = 15, age = 25.4 ± 3.9 , 7 males). All participants underwent the same type of task, which included a training phase and a test phase, distinguished by two different motor sequences; motor

sequence “A” for the training phases and motor sequence “B” for the test phases. Therefore, the structure of the experiment for all participants was the following: 3 pre-test trials (sequence B), 45 training trials (sequence A, first acquisition), 3 mid-test trials (sequence B), 45 training trials (sequence A, second acquisition) and 3 post-test trials (sequence B). Therefore, the training consisted of 90 trials, while the test included 9 trials, for a total of 99 trials. This task design allowed us to attempt at replicating a previous finding that demonstrated a potentiation of sensory-motor learning induced by action awareness (Boutin et al., 2014) and to assess whether group effects would extend into a second acquisition phase. Each trial included one repetition of a 12-element sensorimotor sequence, which as mentioned differed between the test and the training phases, being either sequence “A” or “B”. Specifically, from the four horizontally aligned squares, participants were required to press sequentially the following keys: C V B N. For convenience and ease of read, response keys C-V-B-N were reported as numbers 1-2-3-4, where 1 corresponds to the index and 4 to the little finger. Sequence A consisted in 2-4-2-1-3-4-1-2-3-1-4-3, and sequence B in 2-4-1-3-2-1-4-2-3-4-3-1. Participants were not informed about the two different sequences and their structure. The inclusion of test trials (unpracticed sequence “B”) at different time points subserves the role of quantifying the learning-specific effects of performance evaluation (in terms of both pupil dilation and motor performance), in order to distinguish them from generalized practice performance (Abrahamse et al., 2010).

Importantly, the only experimental variation between the two groups consisted in displaying to participants of the awareness group the following question at the end of the trial: “Maximal fluidity?”. Participants were initially instructed that maximal fluidity corresponded to the moment where they felt they could no longer improve in the execution of the motor task. They were required to respond by pressing on the keyboard with their left hand: 1 for “yes” if they felt that they had performed the task as smoothly and fast as they could, or 2 for “no” if they had the impression they could yet improve sequence performance. More precisely, this fluidity instruction emphasized an ideal motor performance with no interruption between successive key presses. Lastly, after completion of the 99 trials, participants were asked to recall from memory the training sequence by two means. Firstly by attempting 3 times to reproduce the sequence on the keyboard without visual stimuli on the screen (only empty squares were displayed), and secondly by writing down the elements in their sequential arrangement on a sheet of

paper. The outcomes of these procedures were used as an index of implicit and explicit sequence knowledge, respectively.

We kept track of the pupillary responses of participants' as they were engaged in the motor sequence task, extracting the signal from the onset of the first target stimulus to the last key press for each of the 99 trials. Blinks were removed and linearly interpolated. Subsequently, the data was down-sampled and high-pass filtered with 0.05Hz cut-off frequency. Then, an autoregressive model with exogenous inputs was fitted to the pupil signal (Zénon, 2017). This method allowed us to extract the pupillary responses to each individual target onset, thereby taking care of the potential confound induced by the differences in reaction times across groups and sequences. The model was given as input a matrix including five regressors, signaling target onset separately for the five phases of the experiment. This resulted in separate impulse responses to target onset for the 2 phases of training and the 3 phases of test. We then extracted the maximal value of those impulse responses as estimates of pupil peak size of each participant for pre-test, first training, mid-test, second training and post-test. Additionally, to further rule-out the presence of a group-wise difference in the baseline levels of pupil sizes, subject-wise baseline pupil size was estimated for each of the 99 trials in the task, consisting of the average pupil size during the two seconds that preceded the onset of the task stimuli (i.e. during display of trial number), which were then averaged across trials.

Wrong responses and outliers (beyond ± 2 SD), consisting in 8% of the dataset (Wrong: 3.1%, Outlier: 4.96%), were excluded from the behavioral analyses. One participant failed to respond to more than half of the elements of the sequence in 3 trials, the RTs of which were considered unreliable and discarded. First of all, to assess whether the error rate was significantly different between groups, a ranked-sum test between groups was carried out on the sum of errors across participants, for each trial. Then, to evaluate group level differences in the learning of the sequence "A" in both training acquisitions (first 45 trials and second 45 trials), we first assessed if a better fit would be provided by an exponential [$y = a \cdot \exp(b \cdot x)$] or a power function [$y = a \cdot x^b$], given the contention in the literature on the topic (Heathcote et al., 2000). We found a slight advantage of the power law (mean $R^2 = 0.28$) compared to the exponential

function (mean $R^2 = 0.26$). Therefore, we fitted RT data of each participant with a power function to extract an estimate of their rate of learning (Newell & Rosenbloom, 1993) in both training acquisitions. Subsequently, these parameter estimates were tested in a mixed ANOVA, assessing the effects of group, acquisition (first or second set of 45 trials) and their interaction. For the test trials employing sequence “B”, given the lower number of trials and different number of acquisitions, we conducted a separate repeated measures ANOVA on the two groups and the 3-trial RT averages of the 3 tests (pre- / mid- / post-test). To further evaluate sequence-specific effects of the action awareness condition, an additional mixed ANOVA was ran on the difference between the RTs of the two sequences, thus providing indices of an early (mean RT of trials 1 to 3 - mean RT of trials 4 to 6), halfway (mean RT of trials 49 to 51 - mean RT of trials 46 to 48 and 52 to 54) and late (mean RT of trials 97 to 99 - mean RT of trials 94 to 96) learning. The learning phase (early, halfway, late), group (control, awareness) and their interaction were included in the model.

Concerning the pupil measures, we conducted a linear mixed model on the peaks of the pupillary impulse responses, with sequence, group and their interaction as fixed factors, and participant as random variable. The baseline estimates of pupil sizes were tested in a between-subjects rank-sum test.

Results

The rank-sum test on the error rates did not highlight significant group differences in the occurrence of errors between the two groups ($Z = 1.6$, $p = 0.11$, $d = 0.15$). Specifically, the sum of errors of the control group had a mean of 5.8 and a median of 5 errors across all trials, and the awareness group’s sum of errors had a mean of 5.3 and a median of 4 errors across trials. This finding implies that any effect found between the RTs of groups could not be explained by diverging error rates.

The analysis on the participants’ learning curves of the training phases revealed a significant effect at the group level ($F(1, 28) = 4.37$, $p = 0.046$, $\eta^2_p = 0.13$), revealing that the awareness group learned the training sequence “A” faster than the control group, regardless of the acquisition phase. No significant effects were found for the acquisition ($F(1, 28) = 0.54$, $p = 0.47$, $\eta^2_p = 0.02$), nor for the interaction between acquisition and group ($F(1, 28) = 1.84$, $p = 0.19$, $\eta^2_p = 0.06$).

Conscious awareness and cognitive effort

The analysis of the test trials did not reveal a group effect for the sequence “B” ($F(1, 28) = 0.04$, $p = 0.84$, $\eta^2_p = 0.001$), while a general practice effect of acquisition ($F(2, 56) = 4.34$, $p = 0.018$, $\eta^2_p = 0.13$) was found to be significant. A Tukey post-hoc comparison indicated that the pre-test was not significantly different from the mid-test ($p = 0.88$, $d = 0.06$), but was different from the post-test ($p = 0.02$, $d = 0.4$). The difference from the mid-test to the post-test was not significant ($p = 0.06$, $d = 0.31$). Altogether, these results revealed a general improvement from the pre- to the post-test in sequence “B” (502 ± 73 ms, 497 ± 85 ms, 472 ± 76 ms; for the pre-, mid-, and post-test, respectively). The interaction between acquisition and group was not significant ($F(1, 56) = 1$, $p = 0.37$, $\eta^2_p = 0.03$).

On the other hand, the analysis of the difference in RT between trained and novel sequences across the three learning phases highlighted a significant interaction between the learning phase and the group condition ($F(2, 56) = 3.44$, $p = 0.039$, $\eta^2_p = 0.11$). The main effect of learning was also significant ($F(2, 56) = 23.68$, $p < 0.001$, $\eta^2_p = 0.46$), while the group main effect failed to reach significance ($F(1, 28) = 3.71$, $p = 0.064$, $\eta^2_p = 0.12$). A Tukey post-hoc analysis on the learning phase and group interaction showed that the two groups differed significantly in the late learning phase only ($p = 0.036$, $d = -0.85$), but not in the early ($p = 0.9$, $d = 0.18$) and halfway ($p = 0.86$, $d = -0.42$) phases.

Conscious awareness and cognitive effort

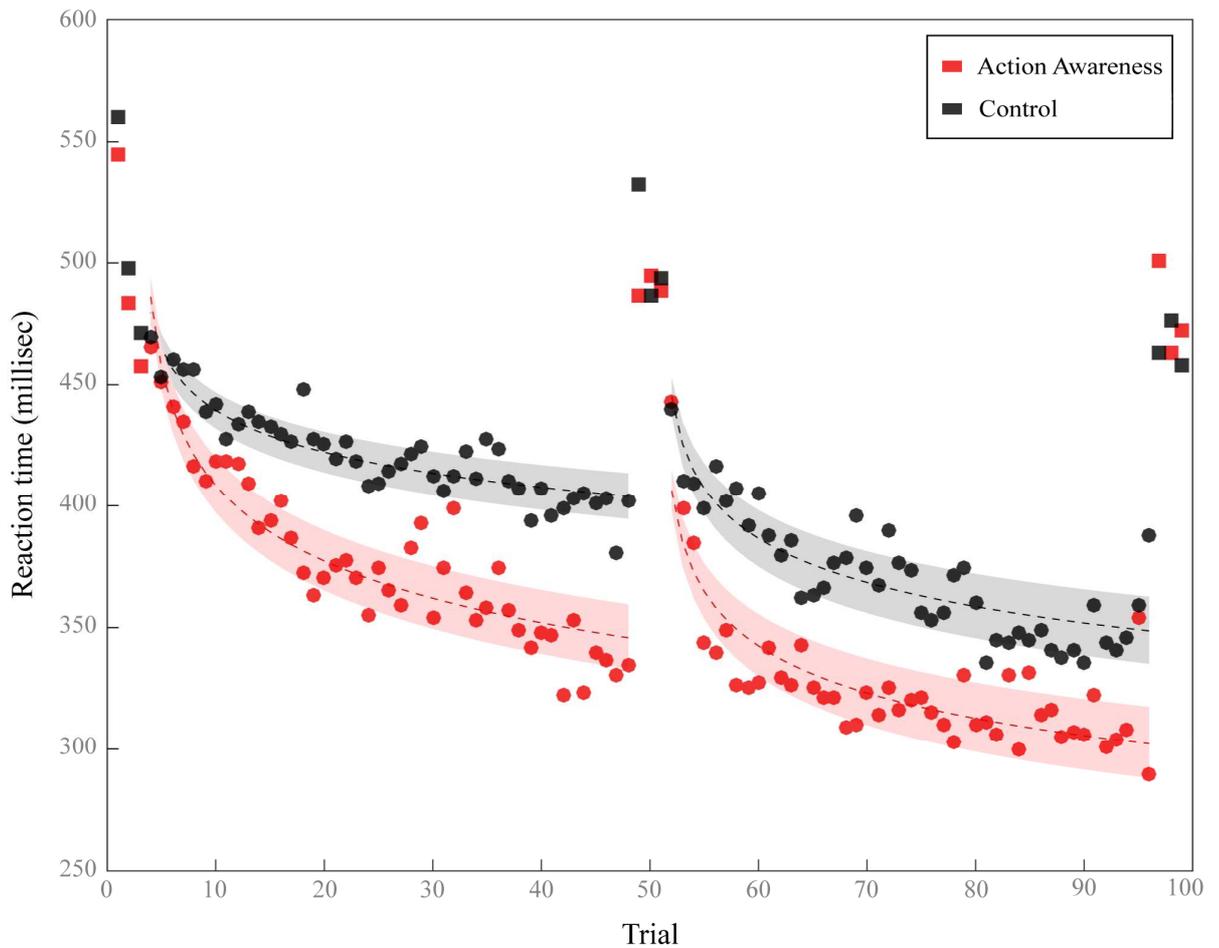


Figure 1: Graphical depiction of average reaction time in the test trials (squares indicating sequence B; trials 1-3, 49-51 and 97-99), and training trials (dots indicating sequence A; trials 4-48 and 52-96) with the power curve fitted on the latter. Symbols in red represent the action awareness group, while symbols in black indicate the control group. Shaded area depicts the standard error.

Concerning the participants' pupil size, sequence ($F(1, 132) = 5.90, p = 0.016, \eta^2_p = 0.04$) and group ($F(1, 132) = 24.59, p < 0.0001, \eta^2_p = 0.15$), were found to have significant medium and large effects, respectively. Indeed, the awareness group displayed a smaller absolute change in pupil size when engaged in the task, regardless of the sequence, and both groups displayed a larger pupil size when presented with the sequence "B" during test trials. No significant interaction was revealed between sequence and group ($F(1, 132) = 1.16, p = 0.28, \eta^2_p = 0.01$).

Conscious awareness and cognitive effort

The rank-sum test ran on the baseline pupil sizes of participants confirmed the absence of group-wise differences [$Z = -0.7$, $p = 0.48$, $d = -0.17$].

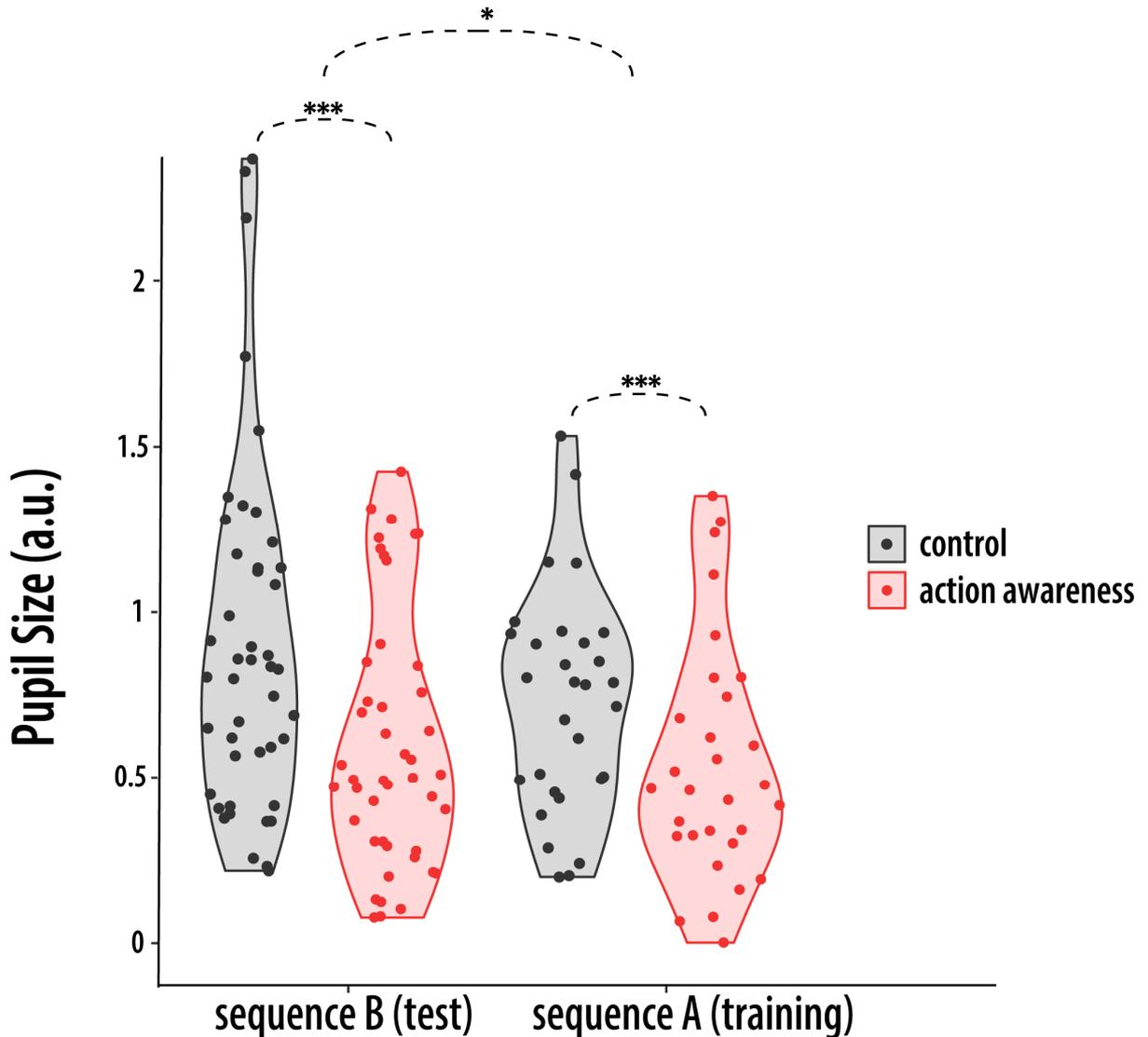


Figure 2: Representation of extracted pupil sizes of both groups, for the test phases (sequence B, left columns, 3 per subject) and the training phases (sequence A, right columns, 2 per subject). For transparency's sake, all the data points are displayed. * $p < 0.05$, *** $p < 0.0001$.

In regard to the explicit recall of the training sequence, 1 participant per group correctly recalled the entire training sequence, while a t-test on the number of explicitly recalled elements of the training sequence "A" confirmed the absence of group-wise differences [$T(28) = 0.11$, $p = 0.91$, $d = 0.04$]. Concerning the implicit recall, 2

participants in the awareness condition recalled correctly the training sequence in all 3 implicit recall trials, while no participant in the control group did so. However, a t-test between groups did not reveal a significant difference in the number of average items implicitly recalled [$T(28) = 0.52$, $p = 0.60$, $d = 0.19$].

Discussion

The main goal of this study was to tease apart two alternative hypotheses regarding the mechanisms at the origin of the effect of conscious awareness of action on motor learning. The cognitive effort hypothesis predicted that improved performance in the “awareness” condition would be associated with dilated pupil size (Wright et al., 2016). In contrast, the mental rehearsal and the action outcome hypotheses, assuming that participants would rehearse more their past actions and/or focus more their attention on action outcome in the awareness group, would predict the opposite pattern of results (Wulf & Lewthwaite, 2016). Our findings are clearly in favor of the latter, with the fluidity judgment leading to decreased pupillary responses in comparison to the control group. Besides, and as expected, motor learning results confirmed earlier findings from Boutin and colleagues, showing that the action awareness group benefitted from the fluidity judgment specifically for the learned motor sequence A, and not for the control sequence B (in exact replication of Boutin et al. 2014). Moreover, the emergence of sequence-specific learning in the late learning phase confirmed the necessity to have a large number of sequence repetitions to see the emergence of sequence learning effects.

Also, we found for both groups that the pupillary response increased when performing the new sequence B, which is interpreted as the marker of additional cognitive effort necessary to perform this new sequence (Foroughi, Sibley & Coyne, 2017; Zénon, Solopchuk & Pezzulo 2019). These results are also in agreement with earlier reports of increased pupillary response to the violation of expected sequences of stimulus presentation, even when partly unconscious (Alamia et al., 2019; Pupil-linked arousal responds to unconscious surprisal). However, to the best of our knowledge, this is the first time that such results are presented in the context of motor sequence learning.

Altogether, these findings revealed that the specific improvement of the motor sequence A induced by the fluidity judgment was not associated with increased

cognitive effort and suggests, on the contrary, that attentional allocation to action outcomes may have improved performance, while concurrently decreasing cognitive effort. Surprisingly though, the action awareness group showed lower pupil dilation during practice of both the trained and untrained sequences. To interpret this sequence-unspecific effect, we suggest that action awareness had a general impact on motivation that, in turn, affected both tasks. Indeed, participants were instructed to judge whether the task was performed with maximal fluidity, and consequently, we could further assume that such strategy afforded a sort of general motivational comfort in performing both tasks. Accordingly, for Eitam, Kennedy, and Higgins (2013), when an action is followed by constant perceptual effects, the participants' motivation to perform this task is improved. For the present study, the detection of the maximal fluidity can be seen as a constant perceptual and expected effect that can reinforce a general motivational mechanism. Importantly though, this general motivational comfort did not impact the performance of the motor sequence B.

For the specific improvement of the motor sequence A related to conscious awareness of action, we agree with Boutin and colleagues (2014) that such positive effect could have its origin at the level of the representation of the sequence. In this view, because the instructions emphasized the expected fluidity effect of the movement, we suggest that an ideomotor mechanism could be at work during this motor learning. Indeed, according to ideomotor theory, the cognitive representation of an action depends much more on the expected effect of the action than on the action movements themselves (see Badets & Osiurak, 2017, for a review; Greenwald, 1970). This interpretation is in agreement with findings on tool use paradigms (see Osiurak & Badets, 2016 for a theory). For example, in using inverse pliers that inversed the relationship between the hand movement toward the tool and the tool movement toward the environment, Osiurak and Badets (2014) have found that actions were easier when processing stimuli that were coherent in terms of their effect on the environment. This finding revealed that during tool use, the cognitive representation of the action is more based on the expected perceptual effect on the environment than on the hand movement toward the tool. For the present data, the expected perceptual effect is the expected maximal fluidity which is processed after each trial that composed the 12-element key press. More precisely, this expected perceptual effect is processed after the entire completion of the motor sequence, but it is also mentally rehearsed by the

participant who has to judge if the maximal effect was reached or not. As suggested by the rehearsal hypothesis (Aiken, Fairbrother & Post, 2012), both actual execution and additional mental rehearsal have probably improved the motor skill learning of the entire motor sequence. However, if the current finding fits well with the ideomotor theory, it does not represent a direct support for its conjectural rationality. More direct experimental evidence is required to link an ideomotor mechanism to conscious awareness of actions.

Finally, our ideomotor interpretation accords at the first glance with Wulf and Lewthwaite (2016; i.e., the outcome hypothesis, but see also Wulf & Prinz, for an ideomotor account of this outcome-attentional effect) who claimed that focusing the attention to the outcomes can improve motor learning. However, while our data clearly dissociate motor sequence performance (specific to sequence A) from the pupillary responses (decreased in both sequences), this outcome-attentional effect theory does not fully support current findings. Nevertheless, it could also be argued that the learning of motor sequence B did not benefit from the conscious awareness effect due to the scarcity of trials on this sequence, which may have shadowed its beneficial learning effects. Indeed, from the seminal finding (Boutin et al. 2014), and the present data, we propose that the conscious awareness of smooth behaviors may be a genuine learning factor that needs sufficient practice to reveal its positive effect in the coding mechanism of new motor tasks. Obviously, additional investigations with different motor tasks are needed to generalize our findings. Nevertheless, Toner and Moran (2014) have revealed that focusing attention toward bodily movements can also improve motor performance in different sports, and consequently, we can hypothesize that the present learning factor could also have positive effects in several behaviors that require fluidity like a tennis service or a boxing sequence.

To conclude, the present findings revealed that when participants are instructed to judge the maximal fluidity of their performed movements, which can be interpreted as conscious awareness of fluent goal-based movements, their motor skill is reinforced for future enactments, and did not transfer to another, new task. This specific effect could come from an ideomotor mechanism at the cognitive level that manages and represents the task. Another cognitive level is also impacted by such fluidity judgement throughout an attentional mechanism which is highlighted by the pupil dilation. However, this attentional mechanism seems completely decorrelated from the motor

mechanism responsible for improving motor learning. Moreover, the generalizability of the results of this work may be hindered by the relatively small samples employed, albeit in line with most of the published literature in the domain. Consequently, the present results should be interpreted conservatively until they have been replicated in a larger sample. Therefore, more studies are needed to explore these new avenues in motor learning throughout the lens of the pupillary response and the possible link with motor sequence representation.

Compliance with Ethical Standards:

Authors declare that they have no conflict of interest.

All procedures performed in this study were in accordance with the ethical standards of the institutional and national research committee, and with the 1964 Helsinki declaration. Finally, informed consent was obtained from all individual participants included in the study.

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