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Acquiring a Novel Coordination Movement with Non-task Goal Related Variability

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Abstract: In two experiments, we tested whether non-task goal related variability, in the form of randomly administered mechanical perturbations during practice, would facilitate the acquisition of a novel two-handed coordination movement. In both experiments, we failed to find beneficial effects of adding non-task related variability in comparison to no-added variability control groups. In Experiment 1, when variability was administered after a period of stabilization, and in the presence of performance enhancing feedback, no differences between a control group and a variability (perturbation) group were found in retention. This was despite significant improvements for both groups and evidence that the perturbations worked to increase movement variability later in practice. In Experiment 2, we increased the amount of practice, changed the feedback, and provided variability throughout practice. Despite these changes, externally added, mechanical perturbations failed to aid learning. We conclude that variability, in and of itself, is not a sufficient variable to bring positive change to performance and learning. Variability has the potential to aid learning when it is internally-generated, dependent on performance and/or task goal related.

Keywords: Practice, motor learning, interference, error-learning.

There is evidence that introducing task-goal related variability into the practice environment can be a beneficial aid to long-term retention of motor skills [1, 2]. Recent extensions of variability research provide reason to believe that adding variation to practice does not need to be related to the task goal and benefits can be derived from practice when the variations are ostensibly of a non-task related nature [3]. Our aim in these experiments was to further test the conditions of practice that are beneficial to motor skill learning through manipulation of variability unrelated to the goal of the task. This was achieved through mechanical perturbations that were added to practice during the acquisition of a novel, dual limb coordination skill.

Task goal related variability has generally been shown to positively impact motor skill retention. This might be variability in how different skills are scheduled (i.e., random vs blocked practice [1]) or variability in practice of the task features of one skill (i.e., variable vs constant practice [2]). The mechanisms underlying the positive effects of variability in these two methods are believed to be due to the cognitive operations experienced during practice and the varied experience of the sensory-motor conditions. Importantly, the encouragement to predict, detect and correct errors in performance, through task variations, is assumed to be important for motor skill learning. There is recent evidence that variability not directly related to the to-be-acquired motor skill can also benefit performance and learning. Using a training program termed "differential training" learning benefits were shown in skilled soccer players for both passing and shooting skills in comparison to traditional practice groups [3, 4]. The differential training group was introduced to non-task related movement components during practice, such as receiving the ball with a stiff stance leg, putting their arms up in the air, in comparison to a traditional practice group who repetitively practiced only the criterion action [3]. Differential learning benefits have also been noted for novices when practicing shot put [5] and there are reported benefits for tennis training [6, 7] and volleyball [6, 8]. These studies support the idea that forcing the learner to adapt and react to new task demands benefits learning, rather than just merely practicing with different variations of the same skill.

Having the learner perform in a changing, dynamic environment can create variability that promotes the discovery of optimal motor solution(s) [3, 9].Variability is assumed to aid in the detection of weaker signals, such as, to-be acquired, new behaviors or movement patterns [3]. There is some laboratory based experimental evidence to support this idea that adding variability unrelated to the primary motor skill aids experience of the task (dynamics). For example, participants adapted to a single, inertial force field environment following either reaching practice in this environment with a robot arm, or following exposure to this environment when a viscous force-field was additionally added [10]. Moreover, this second "added variability" group showed benefits beyond the single force group when tested in the single force environment. This technique is based on learning methods that are founded on the principle of 'error augmentation'. The rationale behind the potential success of this error augmentation method is that errors are more clearly identified and corrections are performed more frequently when variability is intentionally added to performance and self-produced errors are enhanced [11, 12].

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There is also evidence that augmenting the experience of errors early in learning (even on one trial) can actually speed up the rate of acquisition or adaptation. Emken and Reinkensmeyer [13] analyzed treadmill walking adaptations to new viscous force-fields and found that when the magnitude of the force was amplified on the first trial, participants were faster at adapting to the less extreme forces felt on subsequent trials. Accordingly, even transient amplification of errors can aid learning as long as the error causes a change to the motor command on the subsequent movement attempt [14].

In studies of bimanual coordination, it has also been shown that too much stability in movements can cause problems for learning new movement patterns. Learning of new patterns of coordination between the fingers, wrists or arms (such as a relative phasing of 90°, where one limb reverses a quarter of a cycle earlier than another) requires a 'break-away' from existing stable movement patterns or attractors (such as the tendency to temporally couple the joints at reversal points [15-18]). In repeated studies it has been shown that new coordination patterns can be acquired and eventually stabilized given the right feedback conditions and that variability might play a role in aiding learning and mediating the effects of feedback [19-21]. For example, retention performance was found to be positively related to self-produced within trial variability demonstrated by participants early in learning [15]. Between trial variability in the scheduling of movements during the acquisition of 2 or 3 different task variations has also been shown to be beneficial for learning of novel coordination movements [22, 23]. Maslovat *et al* also showed that random practice (what we have termed task-goal related variability) even facilitated rate of acquisition, not just retention, again suggesting that early variability might be beneficial for these types of tasks [23]. However, in this study participants were given a number of familiarization trials before practice began.

In other research, variability in the scheduling of practice has been shown to be of more benefit to retention and transfer performance of novel motor skills when it is added later rather than earlier. This has been attributed to the learner's need to stabilize the movement before variability can have any beneficial effects [24]. This is thought to allow the learner time to understand the skill early when the task is challenging, and then increase the level of challenge and encourage more (cognitive) effort at a later point to aid in retention [25, 26].

Based on the above, there is cause to believe that added within trial variability, unrelated to the task goal, will potentially aid learning. Variability added later in practice, following a period of acquisition without additional variability, is expected to aid the later recall and retention of the movement through the cognitive processes and experience of the task dynamics encouraged through later variability. In addition, this type of variability might potentially assist in breaking away from intrinsically stable, yet undesired movement patterns or attractors. Transitions to new patterns (either as a result of perturbations, a change in constraints such as increased speed, or learning) are preceded in these types of tasks by increased variability in the current level of performance [17, 27]. Therefore, benefits to learning in terms of breaking away from attractors, created from this natural unintentional variability, could be enhanced by adding non-task goal related variability to the skill during practice. In the following experiments we created this variability by adding small mechanical perturbations at various times during a movement trial and tested its effects when it was added late in practice (Experiment 1) and throughout practice (Experiment 2).

EXPERIMENT 1

Introduction

In Experiment 1, two groups were compared. One group received mechanically-induced perturbations to one of their arms after a period of stabilization in comparison to a second control group who did not receive any externally-added variability. Based on mechanisms underpinning task-related variability [24], variability in practice was expected to be beneficial for retention when given later in practice, once the 'general idea' of the movement had been acquired. The added variability was expected to create a general type of interference impacting physically on skill production, providing a greater experience of the perceptual-motor workspace, as well as cognitively, requiring corrections to errors and enhanced cognitive effort. These processes were expected to aid retention.

Methods

Participants &Groups

Eighteen participants were tested (14 F, M = 21.3 yr, SD = 4.1 yr) who were all self-declared right-handed. They were pseudo-randomly assigned into the Perturbation and Control (no perturbation) groups, controlling for gender. Participants were recruited from the University community and were remunerated $8 per hour. The study was conducted in accordance with the ethical guidelines of the University.

Task & Apparatus

The goal was to make continuous, bimanual movements that were out-of-phase by 90°. Participants sat in a chair with their lower-arms resting on manipulanda with their hands pronate on adjustable hand platforms. The elbow joint was aligned with the axis of rotation of the manipulanda. Instructions were given to constrain movements to a range of ~40° about the elbow joint (20° flexion/towards the body and 20° extension away from the body, additionally alerted by markers on the table). The task goal was specified by a real time displacement-displacement plot of the right-limb against the left-limb, forming what is referred to as a Lissajous plot (e.g., [16]). When performing the correct 90° relative phase (RP) pattern a circle trace is formed and hence the task goal is represented by the completion of approximately one circle per second, during a 20 second trial.

Perturbations were added to the right limb during practice using a DC torque motor (Mavilor MT-600) and a motion control card (Tech-80 model 5638). Perturbations were generated by the torque motor using a dampening value of 200 units on the servo card. The resulting viscous field is similar to the experience of moving through a thick liquid, with the forces acting to oppose the direction of movement for ~1-2 seconds. Measurement of angular rotation was captured using an optical encoder.

Procedure

The experiment took place over 2 sessions, 24 hours apart (see Table **1**). Before testing on Day 1 participants were given six trials (at 0° and 180° RP) to familiarize themselves with the apparatus and amplitude and fluidity goals.

Practice and Experimental Manipulations

Practice consisted of 80 trials at the 90° RP pattern with a 5 minute break halfway through testing. All trials lasted 20 seconds and included knowledge of results (KR) as well as Lissajous feedback. Terminal KR was visually displayed, in terms of mean constant error (CE) and standard deviation (SD). Participants were told that these numbers represented overall trial accuracy (CE) and consistency (SD). It was also explained that they should try to get these numbers close to zero.

Lissajous feedback consisted of a circular template projected on the computer screen. Feedback from the participants' movement was superimposed over the template (60 Hz refresh rate), which showed the participant's current position (and the previous 67 ms of movement) in a real-time, orthogonal displacement-displacement plot of the two limbs. The left manipulandum produced vertical movements of the on-screen cursor and the right manipulandum produced horizontal movements. A tracer line moving around the Lissajous figure at 1 Hz frequency specified the required cycle time for the trials.

The Perturbation group experienced mechanical perturbations to movements of their right arm. These were only administered in the second half of practice (last 40 trials), and not at all for the Control group. Perturbations were applied three times during each 20 s trial (i.e., for ~30% of the trial). They were pseudo-randomly administered, with the constraint that perturbations would not begin during the first or last 2 s of the trial and that they would occur between 4 to 7 s of each other (to allow recovery). Perturbations were only applied on 80% of the trials in the second half of practice, pseudo-randomly scheduled such that 1 in 5 trials were criterion trials. These criterion trials allowed us to make comparisons in practice with the Control group. Participants were not told whether a trial would include perturbations.

Post-tests (Retention & Transfer Assessment)

Post-tests were conducted 24 hours after practice and consisted of three conditions (see Table **1**). No KR was given and all tests were performed at 1 Hz. Three retention tests of the 90° pattern were first performed with no Lissa-

Table 1. Experiment 1: Experimental Conditions and Their Associated Manipulations

Day	Condition	# of trials	Stimulus	KR	Perturbations
1	Familiarization	6	Lissajous	No	none
	Practice Block	40	Lissajous	Yes	none
	Practice Block	40	Lissajous	Yes	4 out of 5*
2	Retention	3	None	No	none
	Retention (stimulus)	3	Lissajous	No	none
	Perturbation Left	3	Lissajous	No	Yes

* Only the Perturbation group received perturbations.

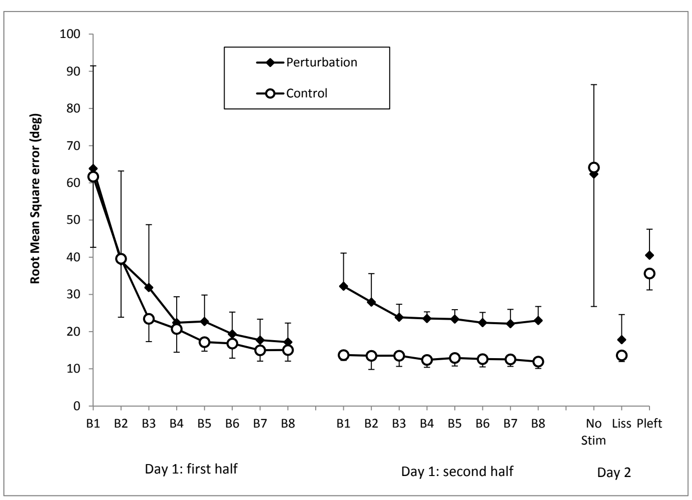

Fig. (1). Experiment 1: Mean RMS error (and between subject SD) across Practice, as a function of Condition (first half/second half of practice) and Block (B), and in retention (without feedback, no stimulus trials, and with Lissajous feedback) and left-hand perturbation transfer conditions (PLeft).

jous feedback (no stimulus), to get an indication of how well the 90° pattern was retained and then for 3 trials with Lissajous feedback. There then followed 3 trials of the 90° pattern with perturbations applied to the opposite, left hand (and with Lissajous feedback).

Data Analysis

For analysis, the first and last 2 s of each trial were not used. Data were collected at 500 Hz, and relative phase (RP) was calculated at 100 Hz (or every 1/5th point). A phase angle for each hand was calculated, based on a single data point's position and velocity using the arcsine function. To get RP, we subtracted the left hand phase angle from the right (see [28] for similar methods). Using these data, we calculated absolute CE (i.e., the unsigned value of observed RP minus required RP and variable error within the trial (i.e., SD of CE). A combined measure was also calculated to give an overall measure of performance, referred to as root-mean-square error (RMS error, e.g., [29]).

Statistical Analysis

Practice

Practice data were analyzed in a 2 Group x 2 Condition (First & Second Half) x 8 Block repeated measures (rm) ANOVA. Separate analyses were conducted on the criterion trials in a 2 Group x 8 Trial rm ANOVA.

Retention & Transfer

For retention, groups were compared in a 2 Group x 2 Feedback Type (with and without Lissajous feedback) rm ANOVA. A 2 Group x 2 Test rm ANOVA was used to compare the left arm perturbation condition to the retention test (both with Lissajous feedback).

Effect size measures (partial eta squared, η_p^2) are reported for all significant effects and power calculations (1-β) for non-significant effects. When there were violations to sphericity for repeated measures the Greenhouse Geisser correction was used.

Results

Practice

The RMS data as a function of condition and block are shown in Fig. (**1**). Both groups improved during practice (i.e., reduced error) as indicated by a main effect of block, F(2.5,40.6)= 55.99, $p< 0.001$, $\eta_p^2 = 0.78$. Perturbations in the second half of practice increased overall error as indicated by a group effect, F(1,16) = 12.52, $p< 0.01$, $\eta_p^2 = 0.44$, and Group x Condition interaction, F(1,16) = 5.57, $p = 0.031$, $\eta_p^2 = 0.26$. As shown in Fig. (**1**), the Perturbation group increased error during the second part of practice. This was due to a large increase in variable error (SD) for the Perturbation group as indicated by the Group x Condition interaction for this metric, F(1,16)= 10.86, $p< 0.01$, $\eta_p^2 = 0.40$. Therefore, the manipulation had its intended effect. No other group related effects were observed.

We also analyzed performance on criterion trials (i.e., no perturbation trials) for the perturbation group which were compared to matched trials for the control group. For RMS there was no group, F(1,16)= 1.44, $p = 0.25$, 1-β= .204, nor trial, F(7,112)= 1.64, $p = 0.13$, 1-β = .65 effect, and no interaction, F < 1. However, inspection of ACE showed that the Control group was more accurate (M = 3.04°, SD = 2.03°) than the Perturbation group (M = 5.96°, SD = 5.07°) despite the fact that neither group was receiving perturbations, F(1,16)= 4.40, $p = 0.052$, $\eta_p^2 = 0.22$, 1-β = .504. There was no Group x Trial interaction for ACE, F(3.7, 59.7) = 1.39, 1-β = .39. No differences in variability were observed, opposite to what we saw in the non-criterion trials.

Retention and Transfer

Both groups performed more accurately in retention when Lissajous feedback was given (M_{RMS} = 15.71°, SD = 4.21°) compared to when there was no feedback (M_{RMS} = 63.24°, SD = 30.71°), F(1,16) = 45.82, $p< 0.001$, $\eta_p^2 = 0.74$ (see Fig. **1**). This effect was also seen for ACE and SD (both ps< 0.001). Contrary to our predictions, there were no group related effects.

Comparison of the left-hand perturbation condition to the retention test for RMS yielded a main effect of group, F(1,16) = 7.09, $p = .017$, $\eta_p^2 = 0.31$ and test condition, F(1,16) = 140.52, $p< 0.011$, $\eta_p^2 = 0.90$, but no interaction, F < 1 (see Fig. **1**). Opposite to our predictions, the Control group showed less error overall on both tests, even though both groups showed an increase in error on the left-hand perturbation test. These differences were mainly a result of less variability (SD) for the Control group in comparison to the Perturbation group ($p< 0.05$), as well as reduced variability and accuracy in retention compared to the perturbation condition (ps< 0.05).

Discussion

Two groups of participants practiced a novel phase relation between their hands with non-task goal related variability (i.e. mechanical perturbations) added later in practice for one of the groups. Although our procedures were successful in teaching this new pattern to the participants; as evidenced by a reduction in error during practice for both groups and relatively low errors in retention when feedback was provided, the perturbations did not facilitate learning or transfer. This was despite the fact that the procedures did work to increase variability (i.e., within trial SD) for the Perturbation group in the second half of practice. Indeed, it was the Control group that showed a trend to perform better in the retention tests when feedback was provided, even in the face of added variability (i.e., left hand perturbations). Therefore, externally added, non-task goal related variability in practice did not facilitate learning.

Although it is possible that this type of added variability is not a useful practice technique, at least for the acquisition and retention of a new coordination movement, there were three methodological concerns. These were related to the type and amount of feedback provided, the amount of practice and the addition of perturbations (i.e., added variability) only later in practice.

There was significant evidence that participants in our study were heavily reliant on the Lissajous feedback for performance. This type of feedback has been shown to be a significant guiding source of information for learning tasks of this nature [15, 19, 30, 31]. When it is removed, participants often show little evidence of learning (i.e., that the movement pattern has been internalized [18]). Further, when it is available it significantly eases performance, potentially stabilizing performance rather than promoting learning [31]. Therefore, it is possible that the feedback we provided both made the task too easy when it was available, preventing the detection of group differences, as well as too difficult when it was withheld.

A second factor to be considered with this manipulation was the duration of the practice session in conjunction with the feedback. Due to the fact that participants were able to acquire the required phasing relatively quickly in practice, we decided to limit practice to one day and provide the perturbations after an initial period of acquisition. It is possible, especially if Lissajous feedback is reduced, that more practice trials or practice distributed over a couple of days would help the stability of the acquired movement and potentially decrease the reliance on feedback. Related, perturbations were administered only after the participants had received practice and had arguably acquired the movement. In other research, task-related variability has been shown to be most useful once a person has first practiced under constant practice conditions [24]. However, there is also evidence that variability provides a benefit early in acquisition, as a potential aid in breaking from stable or undesired behaviours [16, 19]. Finally, because we restricted our manipulation to only half of the practice trials, it is possible that any potential effects of the manipulation were reduced.

In view of these considerations, a second experiment was conducted with several methodological changes. Two groups of participants practiced over 2 days, with retention and transfer tests on a third day. We restricted the amount of Lissajous feedback, and instead presented oscillating pendula on the majority of trials, corresponding to the desired motions of the left and right hand. Perturbations were also given throughout practice (as opposed to just later in practice). This also allowed us to determine whether there were any potential benefits to be gained from early variability, potentially speeding up the acquisition process by aiding in breaking away from more stable, yet undesired, symmetrical movements (i.e., in- and anti-phase). A second transfer test was also included in this experiment that was designed to bring about increased variability in the movement in the form of increased stress. We were interested to see whether the addition of externally-added variability during practice acts to ward off negative consequences associated with internal stressors induced during a later test phase. Van Gemmert and Van Galen [32] proposed that both physical and mental stressors share a common mechanism, where both types of stressors increase the level of neuromotor noise or variability. If participants are accustomed to performing with additional variability during practice, then we might expect that they will more readily compensate for additional variability derived from these stressors.

EXPERIMENT 2

Methods

These were the same as Experiment 1 except where noted below.

Participants& Groups

Twenty new, self-declared right handed participants were tested (12 F, M = 21.8 yr, SD = 3.2 yr) and were again pseudo-randomly assigned into either a Perturbation or Control (no perturbation) group.

Task & Apparatus

The task goal (i.e, 90° RP) was now primarily specified by two moving inverted pendula presented on a computer monitor (40.5cm x 30.5cm, Viewsonic G810). These were two green vertical lines that oscillated at 1 Hz. *Via* manipulations to the time lags between the two pendula it was possible to dictate the required RP. Participants were required to track the left and right pendula with their arms.

Procedure

The experiment took place in 3 separate days, over an 8-day period (see Table **2**).

Practice and Experimental Manipulations

Practice consisted of 160 trials at the 90° RP pattern spread over 2 consecutive days (80 trials /day). Based on other research [28, 33] two procedures were implemented to additionally encourage learning. Movement speed was reduced early in practice and gradually increased, and Lissajous feedback was sparingly provided, such that it replaced pendula stimulus for three blocks of practice (2 blocks on day 1; t21-25; t46-50 and one block on day 2; t21-25). Stimulus (pendula) frequency gradually increased from 0.75 Hz (25 trials) to 0.85 Hz (25 trials) to 1Hz (30 trials) on day 1. Day-2 started at 0.85 Hz (25 trials), and the remainder of the trials were performed at the criterion speed, 1Hz. Different to Experiment 1, perturbations were administered throughout practice for the Perturbation group.

Post-tests (Retention & Transfer Assessment)

Day-3 was delayed 6-days from practice on day-2, and consisted of five conditions (Table **2**). No augmented feedback was given and all tests were performed at 1 Hz. Three retention trials of the 90° RP pattern were performed with no visual assistance (i.e., no pendula stimulus). This was followed by 3 trials of the 90° RP pattern where the pendula disappeared from the computer screen after 5 s but the participant was required to continue moving (faded stimulus trials). Participants then completed 6 trials with perturbations administered to either their right or left arm. They were unaware whether the trial would consist of left or right arm perturbations. The schedule was pseudo-random, such that all three trials for one arm would not occur consecutively. Finally, participants performed 3 trials under conditions designed to increase stress (for similar methods, [34]). Participants were told that there was an opportunity to earn extra performance based remuneration. An external observer was also brought in during these trials whose task ostensibly was to evaluate performance.

Data Analysis

See Experiment 1.

Statistical Analysis

Practice

Practice data were analyzed in a 2 Group x 2 Day x 14 Block (5 trials/block) rm ANOVA (due to Lissajous feedback, blocks 5 and 10 on each day were excluded from

Table 2. Experiment 2: Experimental Conditions and Their Associated Manipulations

Day	Condition	# of Trials	Stimulus	KR	Frequency (Hz)	Perturb
1	Familiarization	6	Lissajous	No	1	none
	Practice	70	Pendula	Yes	0.75-1	4 out of 5*
	Practice	10	Lissajous	Yes	0.75-0.85	4 out of 5*
2	Practice	75	Pendula	Yes	0.85-1	4 out of 5*
	Practice	5	Lissajous	Yes	0.85	4 out of 5*
3	Retention	3	No Stimulus	No	1	none
	Faded Stimulus	3	Pendula	No	1	none
	Perturbation	6	Pendula	No	1	Left and Right
	Stress	3	No Stimulus	No	1	none

* Only the Perturbation group received perturbations.

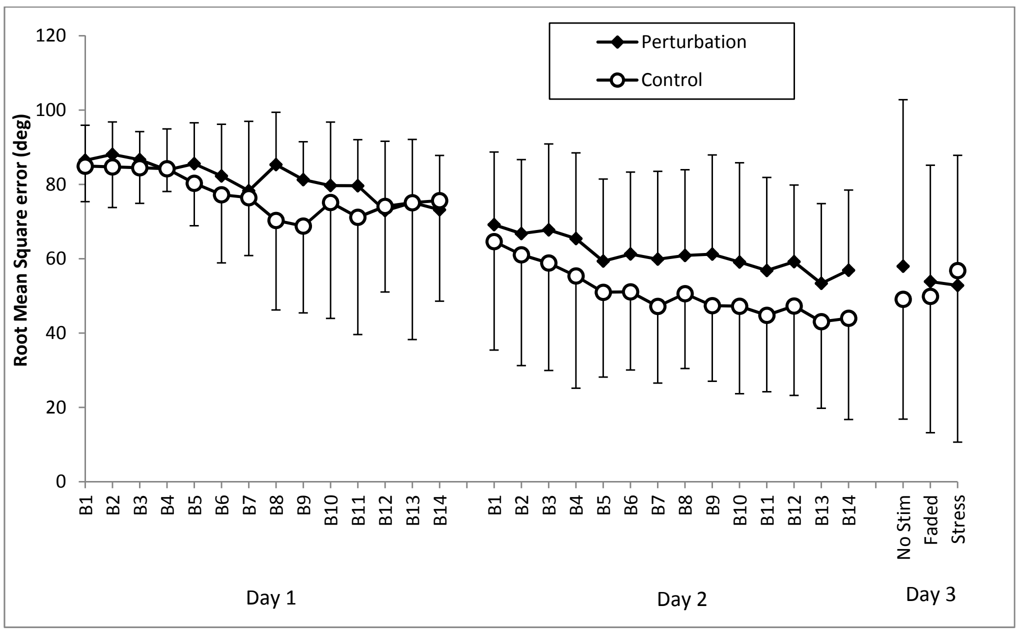

Fig. (2). Experiment 2: Mean RMS error (and between subject SD) across Practice, as a function of Day and Block (B), and in retention (without feedback, no stimulus trials, and with faded stimulus) and stress conditions.

analysis). Separate analyses were conducted on the criterion trials (every 5 trials) in a 2 Group x 2 Day x 14 Trial rm ANOVA.

Retention & Transfer

A 2 Group x 2 Feedback Type (no and faded stimulus) rm ANOVA was used to analyze retention data. A comparable 2 Group x 2 Test (no stimulus and stress) ANOVA was conducted to evaluate effects of the stress condition. Comparisons were also made across the two types of perturbations, left and right in a 2 Group x 2 Side (Left and Right) analysis.

Results

Practice

Both groups improved during practice, showing reduced error (RMS) as indicated by a block effect, F(4.9,88.8) = 10.07, $p< 0.001$, $\eta_p^2 = 0.36$. These data are illustrated in Fig. (**2**). Despite the fact that the Perturbation group received perturbations throughout practice, there was no Group effect for this measure, F(1,18) = 1.01, $p = 0.33$, 1-β = 0.16. Although the Perturbation group (M_{SD} = 45.64°, SD = 16.63°) showed more variability than the Control group (M_{SD} = 37.16°, SD = 18.94°), we did not find a statistically significant difference, F(1,18) = 3.01, $p = 0.10$, 1-β = 0.38. No other group related effects were significant for either of these measures or for ACE.

We also analyzed performance on criterion trials (i.e., no perturbation trials) and compared these to the average for the same block from the control group. For our overall measure of performance (RMS) there was again a main effect of block, F(6.2,112.2) = 6.80, $p< 0.001$, $\eta_p^2 = 0.27$ which had a significant linear component due to the incremental decrease in error (p = .04), but there was no group, F < 1, nor Group x Block interaction, F(6.24, 112.2) = 1.06, p = .40, 1-β = .41. No group related effects were seen in any of our other measures.

Retention

We expected that the Perturbation group (M_{RMS} = 55.93°, SD = 37.69°) would perform with less error in retention than the Control group (M_{RMS} = 49.50°, SD = 33.63°) on both the Faded stimulus and No stimulus tasks, but this was not the case for any of the dependent variables (all Fs< 1). There was also no effect of Feedback or Group x Feedback interaction, Fs< 1 (see Fig. **2**).

Transfer

Although the Perturbation group (M_{RMS} = 52.8°, SD = 35.0°) performed with less error than the Control group (M_{RMS} = 56.8°, SD = 46.2°) under stress-inducing conditions in comparison to no stimulus retention where they performed with more error than the Control group, the group effect was not significant (F < 1). Neither the test (F < 1) nor the Group x Test interaction, F(1,18) = 1.39, p = 0.25, β = 0.20 were significant. None of the other variables showed significant effects.

In our comparison of perturbations to the left hand and right hand, although the Perturbation group was generally less variable (M_{SD} = 46.07°, SD = 14.12°) than the Control group (M_{SD} = 55.60°, SD = 21.61°), F(1,18) = 1.59, 1-β= .22, there were no differences between the two groups for RMS or ACE (both Fs< 1). Perturbations to the right hand (M_{RMS} = 66.86°, SD = 29.23°) were performed with less error than to the left hand (M_{RMS} = 72.72°, SD = 23.98°), F(1,18) = 5.10, p = 0.04, η_p^2 = 0.22 as a result of increased variability in the left hand, SD, F(1,18) = 10.15, p< 0.01, η_p^2 = 0.36, rather than decreased accuracy (ACE, F < 1). There was no Group x Hand interaction for any of the measures, RMS and SD, Fs< 1, ACE, F(1,18) = 1.12, β = 0.17.

Discussion

We expected four key findings; the variability manipulation should result in increased variability during practice, both groups were expected to show improvements over practice, with early variability aiding acquisition rate for the Perturbation group, and the groups were expected to be different in retention/transfer, with the Perturbation group showing less error/variability than the Control group.

Against our predictions, and contrary to Experiment 1, although the Perturbation group did perform with more variability during practice, we did not see a significant increase in variability (SD, p = .10) or overall error (RMS, p = .33). Therefore, our variability manipulation had diminished effects in this experiment compared to Experiment 1. There was evidence that the procedural protocol we had chosen for this task was able to bring about performance improvements and learning as evidenced by an improvement over practice blocks as well as relatively low errors in retention. Despite improvements in practice, there was no evidence that added variability early in practice facilitated acquisition (*cf*., [6, 16]). There remains strong evidence that in these tasks variability precedes a change in relative phase [27] and Schöllhorn and colleagues [6] have argued that learning *via* differential methods is preceded by a variability-induced bifurcation. To further investigate the potential benefit of introducing variability early, we pilot tested two additional groups (n = 4/group), who received perturbations either exclusively early or late in practice. However, again no group differences were evidenced and there was no indication that early variability aided acquisition.

Finally, beyond just performance improvements, we expected that the Perturbation group would perform with less error than the Control group in retention and transfer tests. Again, however, we found no evidence to support this major hypothesis. When performing with perturbations to the right or left arm in transfer testing, although the Perturbation group was less variable than the Control group, this difference was not statistically significant and there were no differences with respect to accuracy. Similarly, a non-significant advantage was also noted for the Perturbation group under the stress conditions. These were the only slight advantages associated with this method of practice and, hence, we would be extremely cautious in extrapolating positively from these findings.

GENERAL DISCUSSION

In two experiments we tested for learning benefits which could be attributed to the addition of non-task goal related variability. Similar types of ‘unrelated’ variability have had some success when used in applied domains, under the heading of “differential learning” [3,9]. However, under controlled laboratory conditions, in two experiments, we failed to find an advantage for this type of variability. Although we found that the groups with added variability were still able to acquire the motor skill (i.e., 90° RP pattern), in contrast to expectations, any beneficial effects in retention were mostly limited to the Control group (Exp. 1).

Task Properties

One possible explanation for our failure to find group differences could be related to the type of task. We had a novel and relatively difficult task to teach, but one where acquisition is possible over a short time and a task where variability is thought to be important for acquisition. Despite these variables which support the choice of task, there was still only a finite task solution (i.e., a specific relative phasing in addition to limited degrees of freedom available to produce the desired movement pattern). In contrast to sport skills, such as kicking or throwing, the opportunity for the learner to develop an ‘optimal solution’ is not present and hence although task exploration is encouraged (i.e, variability in how a task solution is reached), no individual solution, as such, is possible.

It is worth referring back to the studies on task-related variability, which have been conducted with these types of movement skills, in order to help understand how variability in general might potentially aid learning of these novel coordination movements [22, 23]. Although benefits have been seen for random in comparison to blocked practice for this task [22], these results were limited to the more extreme comparison of a blocked versus a random group, where skills changed across days, rather than within a day for the former groups. This may indicate that this type of task is not as robust at showing benefits from added variability (regardless of the type), or perhaps that only a small amount of (task related) variability is optimal for retention benefits. Furthermore, benefits of variable practice have generally been limited to absolute features of a movement and not the relative features (such as relative timing between the limbs, [35]). Therefore, perhaps in part because of the inherent variability of these types of coordination tasks, particularly when Lissajous feedback is not provided, any type of externally-induced variability (task or non-task related) is likely to be moderated, either leading to an attenuated or null effect.

Externally vs. Internally-generated Variability

With this type of bimanual coordination task, we were able to control the size, frequency and duration of the perturbations (variability). In past research, variability has been encouraged mostly through verbal instructions and some manipulations to external parameters, such as ball size [3]such that variability would not be consistent across participants or studies. However, our failure to show benefits from this variability brings up the possibility that the learner needs to be the agent of their variability for benefits in learning to be seen or that the amount of added variability was not sufficient to aid learning. There is some evidence that self-generated error is more advantageous for skill acquisition than externally-produced error [36]. Using a beam-walking task, externally-induced errors failed to aid balance control, but there was a positive relationship between self-induced error in torso variability and accuracy. However, if non-task related variability is expected to be beneficial because it forces the learner to adapt to continuously changing situations and encourages exploration of task dynamics, then it perhaps should not matter if the movement is self-generated. With respect to the amount of variability, it is possible that the perturbations were not significantly large enough to benefit learning. We chose the degree of perturbation based on a need to optimize safety with the torque motors whilst being confident that participants were required to adapt and compensate for changes to their movement. In Experiment 1, these forces were sufficient to increase variability (i.e., the desired intent), but in Experiment 2, these forces were potentially not significant enough to compensate for the self-induced variability inherent from performing in the absence of Lissajous feedback. It might well be the case that optimal amounts of variability are learner dependent.

Performance-dependent Variability and Engagement

Error augmentation shares some commonalities with differential learning, in that both serve to create more errors in practice. However, error augmentation techniques are typically performance dependent and errors are usually related in some way to the task goal. For example, Emken and Reinkensmeyer [13] showed that early error enhancement benefited performance on subsequent trials during novel reaching movements. The errors we created with opposing forces in our Experiments were not proportionally related to the task goal nor dependent on current performance levels. Further we did not reduce the magnitude of the forces as practice progressed. That said, it is likely that variability added to the task can potentially benefit learning, but that the types of errors induced need to be carefully structured depending on the person. Indeed, it is quite possible that one potential mechanism behind benefits of self-induced variability or performance-dependent variability is that it serves to keep participants motivated and more (cognitively) engaged in the learning process.

Summary and Conclusion

In conclusion, in two experiments, we failed to find evidence that externally-added, non-task goal related variability, provided a beneficial effect for skill acquisition. Therefore, some caution is recommended in using this type of technique to enhance the skill acquisition process. Although there are some potentially promising results from the differential learning literature and the error-augmentation literature, the evidence is somewhat sparse and mostly limited to one group of researchers, at least in the former case [3]. Moreover, in terms of error-augmentation, the variability is performance dependent whereby errors are ‘augmented’ or increased, rather than added in a random fashion, independent of current performance (as was the case with our methods and differential learning techniques). Finding the optimal amount of variability to include in practice is likely mediated by more than just exploring a dynamic workspace, and should include factors such as motivation, task difficulty, and skill level of the participant.

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CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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