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Practicing Elements vs. Practicing Coordination: Changes in the Structure of Variance

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Abstract

We explored effects of practice of a two-finger accurate force production task on components of finger force variance quantified within the uncontrolled manifold (UCM) hypothesis, V_{UCM} that had no effect on total force and V_{ORT} that affected total force. A variable task with graded instability was designed to encourage use of variable solutions. Two groups of subjects ($n = 9$ each) were tested prior to a 1.5-hour practice session, after the session, and two weeks later (retention test). Group-1 practiced one finger at a time, while Group-2 practiced the task with two fingers (index and middle) pressing together. Both groups showed comparable improvements in the performance indices. Both groups showed a decrease in V_{ORT} , while only Group-2 showed an increase in V_{UCM} . These effects persisted during the retention test. The results show that practicing elements and practicing redundant groups of elements may lead to similar changes in performance, i.e. in the variability of the total force produced by the set of fingers, accompanied by dramatically different changes in the structure of variance: A drop in V_{UCM} after the single-finger practice and an increase following the two-finger practice. The strong retention effects promise applications of the method to rehabilitation.

Keywords

practice; coordination; finger; variance; force; uncontrolled manifold

INTRODUCTION

Practicing a motor task can lead to changes in performance variables directly related to the task formulation (their average across trials characteristics and variability; reviewed in Newell 1991) as well as in coordination among redundant sets of elements (cf. Bernstein 1967) involved in the production of voluntary movements. The changes in coordination with practice has been notoriously hard to address, although important progress has been achieved in studies within the dynamic systems approach (Scholz and Kelso 1989; Buchanan et al. 2007). Recent progress in analysis of apparently redundant systems has led to the formulation of the principle of abundance (Gelfand and Latash 1998; Latash 2012), leading to an operational definition of multi-element synergies, and a method to quantify synergies within the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999; reviewed in Latash et al. 2007).

Within this framework, variance in a multi-dimensional space of elemental variables (those produced by elements such as muscles, joints, digits, etc.) may be viewed as consisting of

two components, “good” and “bad”. The “good” component (V_{UCM}) lies within the UCM and leads to no changes in a potentially important performance variable, while the “bad” component (V_{ORT}) lies in the orthogonal to the UCM sub-space and affects that performance variable. Two factors make V_{UCM} “good”. First, in real life all the elements of our body are typically involved in more than one task and have to contribute to stabilization of more than one variable. Large amounts of V_{UCM} with respect to one of such performance variables create a large sub-space where the same elemental variables may vary to produce and stabilize other variables. If V_{UCM} is small, any secondary task would require finding new solutions for the first task as well. Second, performance of any task is associated with unpredictable changes both within the body and in the environment (“noise”). Large V_{UCM} creates space for the effects of such noise factors to be channeled into. There is experimental support for an important role played by both factors (Scholz et al. 2000; Zhang et al. 2008; Gera et al. 2009; Mattos et al. 2011).

In general, $V_{UCM} > V_{ORT}$ signifies a synergy stabilizing the performance variable. Several studies have suggested that the purpose of strong synergies (high V_{UCM}) may be two-fold: 1). Stabilizing performance in the presence of expected perturbations (Scholz et al. 2000; De Freitas et al. 2007; Mattos et al. 2011); and 2). Performing secondary tasks by the same set of elements without affecting performance of the original task (Zhang et al. 2008; Gera et al. 2009; Klous et al. 2010).

Several studies explored changes in the two variance components with practice of tasks that required accurate performance by a redundant system (Domkin et al. 2002, 2005; Latash et al. 2003; Kang et al. 2004; Yang and Scholz 2005; reviewed in Latash 2010). Typical observations involved a drop in total variance while V_{UCM} and V_{ORT} (computed with respect to that variable) could show disproportionate changes. Two stages of the effects of practice were described: If the task was unusual and complex, during the first stage V_{ORT} dropped at a higher rate as compared to V_{UCM} . Later, during the second stage, when performance became very accurate, V_{ORT} had little room for further decline, while V_{UCM} continued to decrease.

So far, no study has documented an increase in V_{UCM} with practice, while such an increase could potentially benefit performance if the task were performed in unstable conditions or in the presence of unexpected perturbations (cf. De Freitas et al. 2007). In this study we tested a hypothesis (Hypothesis 1) that practice of a variable task with graded instability could lead to higher V_{UCM} (and lower V_{ORT}). We also hypothesized (Hypothesis 2) that such effects could only be observed when a redundant system was practicing the task, not when elements of the task are practiced individually. To test the hypotheses, we designed a task with graded instability (described later) and compared the effects of practice of a redundant system with those of practice of each of its elements individually.

METHODS

Subjects

Eighteen right-handed healthy male subjects participated in the experiment. Their age, height and mass were respectively (mean $\pm$ SD): 28.8 ± 4.6 years, 1.78 ± 0.06 m, 78.4 ± 7.9 kg. Subjects were randomly divided into two groups, nine subjects each. None of the subjects reported a previous history of neuromuscular disorder or trauma to their upper extremities. Prior to the testing all subjects signed the consent form according to the procedures approved by the Office for Research Protection of the Pennsylvania State University.

Apparatus

Four force sensors (Nano 17, ATI Industrial Automation, Garner, NC) were used to measure downward finger forces. The sensors were placed on the panel ($140 \times 90 \times 5$ mm) with four slots, which allowed adjusting sensor position to fit the individual hand's anatomy. The panel was fixed to the table. Data were collected by a PC at 100 Hz, with a 12-bit resolution using a customized Labview program. Experimental tasks were displayed on a 17" computer monitor located 0.75 m away from the participant.

The subjects sat in front of the computer monitor; their right forearm was placed into the wrist-forearm brace and fixed with Velcro straps. The subjects placed the four fingertips on individual sensor centers and kept the fingertips in contact with the sensors at all times. Memory foam was placed underneath the subject's right palm and forearm to ensure a constant anatomical configuration of the hand and fingers. The subjects were free to select a comfortable thumb position.

Procedures

The experiment consisted of two sessions. The first session included three parts (pre-test, practice, and post-test), and two weeks later a retention test was performed. The pre-test included three tasks: maximal voluntary contraction (MVC), ramp force production, and the main "tube-task" (described later). The practice part involved only the "tube-task". The post-test and retention tests were identical to the pre-test.

MVC tasks—After a short familiarization period, the participants were required to produce MVCs by each of the four fingers (MVC_I , MVC_M , MVC_R , and MVC_L ; I – index, M – middle, R – ring, L – little) and by the I and M fingers pressing together (MVC_{IM}). Subjects were asked to keep all the fingers on the sensors and pay no attention to possible force production by other fingers of the hand. Two 5-s trials were recorded for each finger combination (in a random order), and the value of the highest peak force produced by the task finger(s) was used to normalize target forces in the following tasks. There was at least a 30-s interval between trials.

Ramp force production tasks—In these tasks, the participants were shown a template consisting of 5% of MVC for the first 2 s followed by a slanted line from 5 to 45% of MVC over the next 4 s. In each trial, the participants were instructed to produce a force profile matching the template on the screen with one of the fingers while not paying attention to possible force production by the non-task fingers. Only the force produced by the instructed finger was shown as feedback. Two trials were performed by each finger in a random order. There was at least a 30-s interval between trials.

The "tube-task"—The participants were shown a template consisting of fourteen half-cycles of sine-like patterns concatenated into a "tube". The template (Figure 1) showed the central line (F_{TASK}) with permissible error margins. The template involved four standard half-cycles, hidden at random times among at least ten randomly created half-cycles. The initial force level was set at 15% of MVC. Further, randomly created half-cycles were concatenated starting from the initial force level. These half-cycles were selected from a normal distribution with the amplitude of $7 \pm 2\%$ of MVC and the period of 3 ± 0.2 s. The width of the "tube" was always 4% of MVC. In each trial, the participants were asked to produce a force profile matching F_{TASK} as accurately as possible. The task could be performed by the I finger alone, by the M finger alone, and by both fingers pressing together. Only the force produced by the instructed finger(s) was used for the feedback. The feedback signal (F_{FB}) was computed as: $F_{FB} = F_{ACT} + G \times \text{sign}(F_{ACT} - F_{TASK}) \times (F_{ACT} - F_{TASK})^2$, where F_{ACT} stands for the actual force produced by the subject, G is a constant

(gain). When $G = 0$, the feedback corresponded to the actual force produced by the subject; changing G led to amplification of the deviation from F_{TASK} as if the subject were moving over the ridge of a concave surface with variable slope. This allowed grading the degree of task instability. We used $G = 0.02$ in all pre-, post-, and retention tests to make them moderately challenging; in those tests, each subject performed 12 trials in a row. Based on pilot experiments, this value of G was selected to ensure that the subjects performed initially with many errors and needed to practice to achieve good performance. After each trial, two indices were provided to the subject, the root-mean-square error score (RMS_{ES}) computed with respect to F_{TASK} and total time spent outside the “tube” (T_{OUT}). The duration of one trial was 26-s; 4-s prior to the entrance into the “tube” plus 22-s of the “tube”. There was at least a 30-s interval between trials. To get familiar with the task, subjects performed 12 trials with the target representing a perfect sine wave with the period of 3 s and amplitude of 7% MVC.

Practice protocols

The subjects were randomly assigned to two experimental groups. The *two-finger* group practiced with I and M fingers together for 6 blocks $\times$ 6 trials (total 36 trials), while the *one-finger* group practiced I finger and M finger separately, 2 fingers $\times$ 6 blocks $\times$ 6 trials (36 trials with I and 36 trials with M, in total 72 trials). The amount of practice per finger was matched in the two groups, which resulted in twice as many trials in the *one-finger* group.

The initial G value was adjusted based on the initial level of performance (the lowest T_{OUT}). If $T_{OUT} < 0.5$ s, $G = 0.025$ (more challenging); for $0.5 \text{ s} < T_{OUT} < 1$ s, $G = 0.02$ (as in the pre-test); for $1 \text{ s} < T_{OUT} < 5$ s, $G = 0.015$, and for $T_{OUT} > 5$ s, $G = 0.01$. After each block of six trials, if the subjects improved their performance (i.e., if at least one of the T_{OUT} scores was under 0.5 s), the G value was increased by 0.005. The subjects had at least 30-s rest periods between trials, and 1-min breaks between blocks.

Data Processing

The data were processed using a customized program created in Labview. Individual finger forces were used to compute the following indices:

From *MVC tasks*, peak force (MVC) was measured at the time when the force produced by the task finger(s) peaked.

The enslaving matrix (**E**) reflects the unintentional force production by non-task fingers when an instructed finger produces force (Zatsiorsky et al. 2000). We used *Ramp force production tasks* to estimate **E**. For each single-finger ramp trial, linear regressions of the forces produced by each finger against total force (F_{TOT}) over the 4-s ramp time interval were computed. The regression coefficients in $F_{i,j} = f_i^0 + k_{i,j} \cdot F_{TOT,j}$ were used to construct the

$$\mathbf{E} = \begin{bmatrix} k_{I,I} & k_{I,M} & k_{I,R} & k_{I,L} \\ k_{M,I} & k_{M,M} & k_{M,R} & k_{M,L} \\ k_{R,I} & k_{R,M} & k_{R,R} & k_{R,L} \\ k_{L,I} & k_{L,M} & k_{L,R} & k_{L,L} \end{bmatrix}$$

enslaving matrix, where $i = \{I, M, R, L\}$ and $j = \{I, M, R, L\}$; j represents a task finger. $F_{i,j}$ and $F_{TOT,j}$ indicate the individual i -finger force and F_{TOT} , respectively, when j -finger was the task-finger. An overall index of enslaving, $|E|$ was computed as the sum of the off-diagonal numbers in **E**.

The analysis of two-finger synergies stabilizing the force profile during the two-finger “tube-task” was performed in the framework of the UCM hypothesis (Scholz and Schöner 1999; Latash et al. 2002, 2007). Since individual finger forces co-vary because of the phenomenon of enslaving, variance analysis was performed in the space of finger modes, **m**

$= \mathbf{E}^{-1}\mathbf{F}$, where $\mathbf{F}$ is the finger force vector (Latash et al. 2001; Danion et al. 2003; Zatsiorsky et al. 1998). Since $\mathbf{E}$ could change with practice (for details see the Results), we processed data in both *mode* and *force* spaces. The standard half-cycles were aligned by their initiation, and variance was computed across these half-cycles for each time sample. The variance across trials was quantified separately in two sub-spaces for each time sample. The first sub-space (UCM) corresponded to no changes in F_{TOT} ; it was estimated as variance within the null-space of the Jacobian of the system. The second sub-space was the orthogonal complement (ORT) to the UCM; variance within ORT changed F_{TOT} . In order to investigate the effects of practice on the structure of variance in the *mode* space, variance in the UCM space (V_{UCM}) and variance in the ORT space (V_{ORT}) were normalized by the total variance (V_{TOT}) observed during the pre-test.

Statistical analysis

Standard descriptive statistics were used; the data are presented as means $\pm$ standard error (SE). Two-way mixed analyses of variance (ANOVAs) with the factors *Group* (*one-finger* and *two-finger*) and *Test* (pre, post, retention) were used to explore how indices of performance (RMS_{SE} and T_{OUT}), indices of enslaving ($|E|$), and variance components (V_{UCM} and V_{ORT}) changed with practice. Two-way mixed ANOVA with *Group* and *Block* (6 practice blocks) was performed on the G values applied during practice. To ensure normality, data were log-transformed when needed. A Greenhouse-Geisser adjustment was used in case of violation of the sphericity condition. Significant effects were further analyzed with Tukey's HSD multiple comparisons. Statistical significance was set at $p < 0.05$. All statistical tests were performed using SPSS 19.0 (SPSS Inc, Chicago, IL).

RESULTS

Typical trials before and after practice performed by a representative subject from the *one-finger* group are illustrated in Figure 1. The total force trajectory produced by the subject before practice (during the pre-test, panel A) deviated from the task force substantially. After practice (during the post-test, panel B), all subjects in both groups showed considerable improvements in both performance scores.

The G value increased with improved performance (see Methods). As shown in Figure 2, the G value increased similarly for the two groups (on average, from 0.011 to 0.027 for the *two-finger* group, and from 0.009 to 0.026 for the *one-finger* group). A two-way ANOVA *Block* (6 levels) $\times$ *Group* (2 levels) confirmed a main effect of *Block* ($F_{[5, 80]} = 87.14$, $p < 0.001$) with no other effects. Pairwise contrasts confirmed that G increased significantly after each block.

Performance score

In both groups, practice significantly improved the performance scores (Table 1), confirmed by the results of two-way ANOVAs *Test* (3 levels) $\times$ *Group*. The main effect of *Test* was significant for both RMS_{ES} ($F_{[2, 32]} = 25.5$, $p < 0.001$) and T_{OUT} ($F_{[2, 32]} = 25.8$, $p < 0.001$), while neither *Group* (RMS_{ES} : $F_{[1, 16]} = 0.11$, $p = 0.74$; T_{OUT} : $F_{[1, 16]} = 0.42$, $p = 0.53$) nor *Test* $\times$ *Group* effects (RMS_{ES} : $F_{[2, 32]} = 0.25$, $p = 0.67$; T_{OUT} : $F_{[2, 32]} = 0.20$, $p = 0.70$) reached significance. Pairwise comparisons showed that both performance scores significantly decreased from the pre-test to the post-test ($p < 0.001$) with no difference between the post-test and retention test.

Enslaving

After practice, the index of involuntary force production, $|E|$, increased in the *two-finger* group from 0.075 ± 0.10 in the pre-test to 0.92 ± 0.12 in the post-test, and 1.01 ± 0.16 in the

retention test. In contrast, $|E|$ stayed basically unchanged in the *one-finger* group (0.79 ± 0.18 , 0.74 ± 0.10 , and 0.73 ± 0.12 for the pre-, post-, and retention test, respectively). Two-way mixed ANOVA showed no main effects, while the *Test* $\times$ *Group* interaction was close to the level of significance ($F_{[2, 32]} = 3.10$, $p = 0.06$).

Structure of Variance

Mode space analyses—Practice had different effects on one of the two variance components (V_{UCM}) in the two groups. V_{UCM} in the *two-finger* group increased after practice and the increase was even higher in the retention test. In contrast, V_{UCM} dropped with practice in the *one-finger* group. V_{ORT} dropped after practice in both groups and stayed at the lower level during the retention test. Figure 3 illustrates V_{UCM} and V_{ORT} in *mode* space, normalized by total variance in the pre-test, averaged across subjects within the groups.

These observations were confirmed by two-way ANOVAs *Test* $\times$ *Group* on V_{UCM} and V_{ORT} . Analysis of V_{UCM} showed significant effects of *Test* ($F_{[2, 32]} = 3.32$, $p < 0.05$), *Group* ($F_{[1, 16]} = 21.86$, $p < 0.001$), and *Test* $\times$ *Group* interaction ($F_{[2, 32]} = 10.86$, $p < 0.001$). Tukey's HSD tests revealed that V_{UCM} in post and retention tests was significantly different between the two groups ($p < 0.005$). Specifically, V_{UCM} increased in the *two-finger* group but decreased in the *one-finger* group. The effects of *Test* ($F_{[2, 32]} = 18.26$, $p < 0.001$), *Group* ($F_{[1, 16]} = 10.94$, $p < 0.005$) and *Test* $\times$ *Group* ($F_{[2, 32]} = 3.37$, $p < 0.05$) were also confirmed for V_{ORT} . Tukey's HSD tests showed that V_{ORT} decreased significantly after practice ($p < 0.001$), and the decrement was more pronounced in the *one-finger* group than in the *two-finger* group while there was no difference between the post- and retention tests.

Force space analyses—Analysis in the force space was performed to explore possible effects of the changes in the enslaving with practice on the structure of variance in the mode space. Overall, the effects of practice were similar in the force and mode spaces. Figure 4 illustrates variance components (V_{UCM} and V_{ORT}) in the *force* space; note the qualitative similarity of the effects to those illustrated in Figure 3. Two-way ANOVAs *Test* $\times$ *Group* on V_{UCM} and V_{ORT} confirmed the effects of *Test* ($F_{[2, 32]} = 5.45$, $p < 0.01$), *Group* ($F_{[1, 16]} = 15.12$, $p = 0.001$), and *Test* $\times$ *Group* ($F_{[2, 32]} = 7.32$, $p < 0.005$) for V_{UCM} . The interaction reflected different effects of practice on V_{UCM} in the two groups (Tukey's HSD test; $p < 0.01$). Significant main effects of *Test* ($F_{[2, 32]} = 17.10$, $p < 0.001$) and *Group* ($F_{[1, 16]} = 6.12$, $p < 0.05$) were observed for V_{ORT} , without a significant interaction ($F_{[2, 32]} = 1.26$, $p = 0.30$). Tukey's HSD tests showed that V_{ORT} in the *force* space decreased significantly after practice ($p < 0.001$).

DISCUSSION

Both hypotheses formulated in the Introduction have been confirmed in the experiment. Indeed, practicing the task with two fingers simultaneously (a redundant system) resulted in an increase in V_{UCM} and a drop in V_{ORT} (Hypothesis-1). In contrast, practicing the same task by individual fingers led to a drop in both V_{UCM} and V_{ORT} (Hypothesis-2). Note that the effects of practice were present after a relatively brief practice time and retained for two weeks.

Within the UCM hypothesis, separation of variance into “good” and “bad” depends on the selected set of elemental variables. As in earlier studies (Latash et al. 2001; Scholz et al. 2002; Kang et al. 2004), we used modes as elemental variables to remove the effects of enslaving (Zatsiorsky et al. 2000) on finger force co-variation. Note that enslaving leads to co-variation of finger forces that is not specific to particular tasks and can affect the relative amounts of V_{UCM} and V_{ORT} . In our experiment, the enslaving changed with practice, and

the changes differed between the two groups. In principle, these changes could lead to contrasting changes in the V_{UCM} and V_{ORT} components. To explore this possibility, we analyzed the data in both the finger *mode* and *force* spaces. Qualitatively similar results in both spaces indicate that the effects of practice on the variance components were robust across the two methods of analysis. Therefore, we conclude that the contrasting effects of practice on the two variance components in the two groups were not simple reflections of the changes in the enslaving.

The design of our practice session had two features to encourage large V_{UCM} , which has no effect on variance of the task variable (total force) and seems irrelevant for the task performance. First, the subjects were presented with a somewhat different “tube” in each trial. Second, we used a method of subject-specific graded instability to increase task complexity without changing the mechanical conditions. While benefits of variable practice may be viewed as well established (Sherwood 1996; Welsh and Elliott 2000), including studies of multi-finger synergies (Latash et al. 2003), the second feature, to our knowledge, has never been implemented. It encouraged the subjects to use more V_{UCM} when the practiced task was performed by a redundant system (by the *two-finger* group). This effect was not observed in the *one-finger* group presumably because these subjects practiced the same task in the absence of redundancy, when V_{UCM} did not exist.

Note that in the two-finger tests V_{UCM} was much higher than V_{ORT} in both groups, both prior to and after practice; in other words, there were strong force-stabilizing synergies (cf. Latash et al. 2001). As a consequence, an increase in V_{UCM} and a drop in V_{ORT} after practice in the *two-finger* group resulted in an increase in the total variance mostly driven by V_{UCM} changes. This result is rather unique: Practicing a task of accurate production of a performance variable (total force) led to an increase in the variance of the elements contributing to the task. Note that indices of task performance (i.e., T_{OUT} and RMS_{ES}), which were affected by V_{ORT} only, changed similarly in the two groups. It remains to be seen whether this unusual effect of practice can be documented for other tasks and transferred to more ecologically valid tasks.

The observed retention effects make us cautiously optimistic with respect to the possibility of developing this method for motor rehabilitation. Indeed, decreased indices of multi-finger synergies have been reported for populations with impaired hand dexterity such as persons with Down syndrome (Latash et al. 2002a), healthy elderly (Shim et al. 2004) and patients with Parkinson's disease (Park et al. 2012). Brief practice led to better performance and increased synergy indices in Down syndrome persons (Scholz et al. 2003) while healthy elderly showed correlated changes in hand dexterity tests and synergy indices after six weeks of hand strength-training (Olafsdottir et al. 2008). Overall, these optimistic observations suggest that multi-finger synergies can change quickly, and these changes can be accompanied by better hand performance. Our current study suggests a specific protocol to encourage flexible involvement of fingers (larger V_{UCM}). This method can be readily applied to hand training in neurological patients. The idea of using subject-specific adjustments in stability can also be developed for a wide range of motor tasks, such as reaching movements, postural tasks and locomotion.

The definition of synergy accepted in this work is tightly linked to the notion of action stability (Martin et al. 2009). Most natural actions are performed in conditions of unpredictable changes in variables produced by both the environment and the body. Hence, ensuring adequate stability is a necessary prerequisite for any action. According to a recent model (Latash et al. 2005), control of movement is associated with specification of two groups of control variables produced by the controller: The first group (CV1) defines patterns of performance that can be seen in averages across repetitive trials while the other

group (CV2) defines stability properties of the action seen, in particular, in the structure of variance estimated across repetitive trials. Several studies have shown that CV1 and CV2 can change independently of each other (reviewed in Latash 2010).

Our study provides a new line of evidence that changes in indices of motor performance and its stability may proceed independently. Indeed, both groups showed comparable improvements in the indices of performance accuracy and showed similar changes in V_{ORT} (similar changes in CV1). However, the changes in V_{UCM} were in opposite directions after practice, an increase in the *two-finger* group and a drop in the *one-finger* group (different changes in CV2). Note that over the week between the post-test and retention test, V_{UCM} continued to increase in the *two-finger* group, while it recovered to about the pre-practice level in the *one-finger* group. Given the relatively small group size and large variability across subjects, we would be cautious in interpreting this enticing phenomenon.

To conclude, our study shows that practicing elements and practicing redundant groups of elements may lead to similar changes in performance. However, the changes in the structure of variance are dramatically different: A drop in V_{UCM} after practicing elements and an increase in V_{UCM} after practicing groups. Note that our groups were matched by the amount of practice per finger, which led to twice as many trials performed by the one-finger group. This may be an important factor to be disentangled in future studies.

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Figure 1.

A typical trial for the “tube” task (A) before practice (pre-test) and (B) after practice (post-test) in a moderately challenging condition with $G = 0.02$. The gray line represents the force target, the dash gray lines are the permissible error margins, and the black line shows the force produced by the typical subject. After each trial, root mean square error, RMS_{ES} and time outside the “tube”, T_{OUT} were displayed on the screen as performance indices.

Figure 2. Averaged G values across subjects in each block for the *one-finger* group (dashed line) and *two-finger* group (solid line) over the practice time. The error bars show the standard errors.

Figure 3. Normalized “good” and “bad” variance (V_{UCM} and V_{ORT} , panels A and B respectively) computed in the *mode* space, averaged across subjects for each group for the pre-, post-, and retention tests. Solid lines show the data for the *two-finger* group while dashed lines show the data for the *one-finger* group. V_{UCM} and V_{ORT} were normalized by the total variance during the pre-test. The error bars show the standard errors.

Figure 4. Normalized “good” and “bad” variance (V_{UCM} and V_{ORT} , panels A and B respectively) computed in the force space, averaged across subjects for each group for the pre-, post-, and retention tests. Solid lines show the data for the *two-finger* group while dashed lines show the data for the *one-finger* group. V_{UCM} and V_{ORT} were normalized by the total variance during the pre-test. The error bars show the standard errors.

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Table 1

The Performance Scores

Group	RMS _{ES} (%MVC)			T _{OUT} (s)		
	Pre-Test	Post-Test	Retention	Pre-Test	Post-Test	Retention
One-finger	1.99 ± 0.31	1.14 ± 0.10	1.11 ± 0.13	4.36 ± 0.96	1.84 ± 0.38	1.56 ± 0.38
Two-finger	1.97 ± 0.28	1.23 ± 0.12	1.27 ± 0.11	4.70 ± 0.95	2.25 ± 0.49	2.37 ± 0.46

Root mean square error index (RMS_{ES}) and time outside the “tube” index (T_{OUT}) averaged across trials and subjects for each group are presented (± SEM) for the three tests.