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Improving Finger Coordination in Young and Elderly Persons

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Abstract

We studied the effects of a single practice session of a variable task with subject specific adjustments of task difficulty (instability) on indices of multi-finger coordination in young and elderly persons. The main hypothesis was that practicing such a task would lead to contrasting changes in the amounts of two components of variance estimated across repetitive trials within the uncontrolled manifold (UCM) hypothesis: V_{UCM} that had no effect on total force and V_{ORT} that affected total force. In addition, we also expected to see strong transfer effects to a different task. A variable task with graded instability was designed to encourage use of variable solutions during the accurate production of total force with two fingers. The subjects practiced with the index and middle fingers pressing on individual force sensors. Overall, the older subjects showed lower indices of performance and higher indices of both V_{UCM} and V_{ORT} . After about one hour of practice, both groups showed an increase in the index of involuntary force production by non-task fingers (enslaving). Both groups improved the indices of performance. The two variance indices showed opposite effects of practice: V_{ORT} dropped with practice while V_{UCM} increased leading to an increase in the total amount of variance in the space of commands to fingers and in the index of force-stabilizing synergy. Performance in a simpler, non-practiced task improved, but there was no transfer of the changes in the structure of variance. Specifically, both variance components, V_{ORT} and V_{UCM} , dropped in the non-practiced task. The results show that the neural system responsible for synergies stabilizing important features of performance is highly adaptable to practice of tasks designed to encourage use of variable solutions. We view the results as highly promising for future use in populations with impaired coordination characterized by low synergy indices.

Keywords

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

Introduction

Older adults show reduced rates of skill learning, and their performance level, even after extended practice, does not reach that of younger persons (Harrington and Haaland 1992; Pratt et al. 1994; McNay and Willingham 1998; van Hedel, Dietz 2004; Voelcker-Rehage and Alberts 2005; Seidler 2004, 2007). There are also reports on age-related decrements in sensorimotor adaptation (Fernandez-Ruiz et al. 2000; Butch et al. 2003, McNay and Willingham 1998; Seidler 2006) and in corticomotor plasticity (Rogasch et al. 2009). On the other hand, several studies produced a more optimistic message including the ability of older persons to optimize postural control (Kubicki et al. 2012), improve smoothness of muscle

contraction (Connelly et al. 2000), learn balance tasks similarly to younger persons (van Ooteghem et al. 2010), and demonstrate the ability to learn new skills (Seidler 2007).

In this study, we address effects of practice on motor coordination, an issue that has been notoriously hard to study because of the lack of a commonly accepted method to quantify coordination. A few studies addressed changes in motor coordination patterns in older persons with practice. In particular, older people have been reported to have problems with learning challenging coordination (Sparrow et al. 2005). Besides, improved finger coordination was observed in a study of the effects of strength training of hand muscles (Olafsdottir et al. 2008).

All natural actions involve redundant sets of elements (muscles, joints, digits, etc.) leading to the famous problem of motor redundancy (Bernstein 1967). The principle of abundance (Gelfand and Latash 1998; Latash 2012) views the problem of motor redundancy as seeming, not real. It considers apparently redundant elemental variables (degrees-of-freedom) not as a source of computational problems but as a crucial feature of the design that allows ensuring stability of performance and performing several tasks simultaneously. Neural organizations that produce families of trajectories that stabilize important performance variables have been termed synergies. A method to quantify synergies developed within the uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999; reviewed in Latash et al. 2007) compares two components of variance in the space of elemental variables, one of which has no effect on a selected performance variable (variance within the UCM, V_{UCM}), while the other one does (variance orthogonal to the UCM, V_{ORT}). The relative difference between V_{UCM} and V_{ORT} has been used as an index of synergy (ΔV) stabilizing the performance variable.

For example, in a task of accurate total force production by two effectors (e.g., two index fingers) pressing on individual force sensors, forces of the fingers may be viewed as elemental variables while total force is an important performance variable. If, across trials, the two finger forces show some variability in the absence of co-variation, $V_{UCM} = V_{ORT}$, and this case will fail to qualify as a synergy ($\Delta V = 0$). If the two forces co-vary negatively, $V_{UCM} > V_{ORT}$, and one may claim that the two fingers are united into a force-stabilizing synergy ($\Delta V > 0$). Stronger negative co-variation would correspond to a stronger synergy.

Aging is associated with major changes in the neuro-muscular system accompanied by a decline in hand dexterity and strength (Boatright et al. 1997, Giampaoli et al. 1999, Hackel et al. 1992) that contributes to the decline in the activities of daily living (Hughes et al., 1997; Rantanen et al., 1999; Francis and Spirduso, 2000). Weaker multi-finger synergies documented in older persons in accurate force and moment-of-force production tasks (Shinohara et al. 2003, 2004; Olafsdottir et al. 2007) may be related to these functional changes.

In this study we focus on the ability of young and older adults to change the multi-finger synergies after a single session of practice of a variable task with graded instability. Such a task encourages using variable solutions and developing stronger synergies. The first study involving young adults has documented an increase in V_{UCM} after a 1.5-hour practice session when the subjects practiced the task with a redundant set of fingers; in contrast, V_{UCM} dropped in a group that practiced the task with one finger at a time (Wu et al. 2012). These effects persisted two weeks later, during the retention test.

In this study, we asked two main questions. First, can older persons show an improvement in an index of a multi-finger synergy after a brief practice of a similar task? Second, do practice-induced changes transfer to a different task? Given the demonstrated benefits of variable practice (Sherwood 1996; Welsh and Elliott 2000) and the results of the mentioned

study of young adults (Wu et al. 2012), we expected affirmative answer to the first question. While V_{UCM} , by definition, has no effect on performance, several studies have suggested that high V_{UCM} values may help stabilize performance in the presence of perturbations (Scholz et al. 2000; De Freitas et al. 2007; Mattos et al. 2011) and perform secondary tasks by the same set of elements (Zhang et al. 2008; Gera et al. 2009; Klous et al. 2010). Hence, we hypothesized that the expected increase in V_{UCM} with practice would help subjects adapt to changed task conditions and show strong transfer effects to a different task.

Methods

Subjects

Twenty-six healthy subjects participated in the experiment. The *elderly* group consisted of four females and six males, while six females and ten males formed the *young* group. The ages (mean $\pm$ SD) for the *elderly* and *young* groups were: 76.1 ± 5.6 years and 26.9 ± 4.9 years, respectively. All the subjects were right-handed according to their natural hand use during writing and eating. None of the subjects reported a previous history of neuromuscular disorder or trauma to their upper extremities. All subjects had their vision normal or corrected to normal. 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

Finger forces were measured by four force sensors (Nano 17, ATI Industrial Automation, Garner, NC). An adjustable panel ($140 \times 90 \times 5$ mm) was placed on a table and used for mounting the sensors. Data collection was performed using a LabView based program at 100 Hz with a 12-bit resolution. Experimental tasks were displayed on a 17" monitor located 0.75 m away from the participant.

The subjects sat in front of the monitor; their right forearm was placed into the wrist-forearm brace and fixed with the Velcro straps. The subjects placed the four fingertips on the centers of individual sensors 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 position of the thumb.

Procedures

The testing session included three parts (*pre-test*, *practice*, and *post-test*). The *pre-test* involved four tasks: maximal voluntary contraction (MVC), ramp force production, the "SINE" task, and the "TUBE" task (described later). The *practice* part involved only the "TUBE" task, while the "SINE" task was used to explore transfer effects. The *post-test* was identical to the *pre-test*. Before the *pre-test*, a short familiarization session with the "SINE" task was given to all subjects consisting of 3–5 trials. This was sufficient to make them feel comfortable with the main tasks.

MVC tasks—The MVC tasks were used to normalize task force levels for individual subjects. The participants were required to produce MVC 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 non-task fingers of the hand. Two 5-s trials were recorded for each finger combination (in a random order), and the highest peak force magnitude 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—The purpose of these tasks was to estimate the enslaving matrix (see later), which was used in the analysis of multi-finger synergies. 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 paying no 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 “SINE” and “TUBE” tasks—The participants were shown a template consisting of fourteen concatenated half-cycles of sine-like patterns (Figure 1 and 2). For both tasks, the initial force level was set at 15% of MVC. The template for the “SINE” task was a perfect sine wave with the amplitude of 7% of MVC and the period of 3 s. The template of the “TUBE” task involved four standard half-cycles (two with force increase and two with force decrease) identical to the half-cycles used in the “SINE” task, hidden at random times among at least ten randomly generated half-cycles. These standard half-cycles were used for the analysis of synergies as described later. The randomly generated half-cycles were created using amplitude and period parameters selected at random from normal distributions with $7 \pm 2\%$ of MVC and 3 ± 0.2 s respectively. The width of the permissible error margins was always 4% of MVC for both tasks. In each trial, the participants were asked to produce a force profile matching the template (F_{TASK}) as accurately as possible while never going outside the margins. The tasks were performed by the I and M fingers pressing together while other fingers stayed on the sensors. 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 I and M fingers together, and G is a constant (gain). When $G = 0$, the feedback corresponded to the actual force produced by the two fingers; positive G led to amplification of the deviation from F_{TASK} as if the subject moved over the ridge of a concave surface with the slope defined by G . Hence, we view higher values of G as corresponding to higher instability of the task. We used $G = 0.02$ in all *pre*- and *post*-tests to make them moderately challenging (based on the earlier study, Wu et al. 2012 and pilot observations on elderly participants). Each subject performed three trials for the “SINE” task and 12 trials for the “TUBE” task. 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 error margins (T_{OUT}). The duration of one trial was 26 s; 4 s prior to the entrance into the half-cycles plus 22 s of the “SINE” or “TUBE” template. There was at least a 30-s interval between trials.

Practice protocol

Both *elderly* and *young* groups practiced for 6 blocks $\times$ 6 trials (total 36 trials) of the “TUBE” task. The initial G value was adjusted based on the initial level of performance (the lowest T_{OUT} observed at the *pre-test*). If the lowest $T_{OUT} < 0.5$ 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 6 trials, if at least one of the T_{OUT} score was 10% lower than the best T_{OUT} score recorded in the previous block, the G value was increase 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.

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. 1998). 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 enslaving matrix,

$$\mathbf{E} = \begin{bmatrix} k_{I,I} & k_{I,M} & k_{I,R} & k_{I,L} \\ k_{M,I} & k_{M,M} & k_{M,R} & k_{M,L} \\ k_{R,I} & k_{R,M} & k_{R,R} & k_{R,L} \\ k_{L,I} & k_{L,M} & k_{L,R} & k_{L,L} \end{bmatrix}$$
, 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 index represents the average force exerted by the non-instructed (enslaved) fingers per 1 N of the total finger force.

The analysis of two-finger synergies stabilizing the force profile during the two-finger “SINE” and “TUBE” tasks was performed within the framework of the UCM hypothesis (Scholz and Schöner 1999; Latash et al. 2002b, 2007). Since individual finger forces co-vary because of the phenomenon of enslaving, variance analysis was performed in the space of finger modes, $\mathbf{m} = \mathbf{E}^{-1}\mathbf{F}$, where $\mathbf{F}$ is the 2×1 (I and M) finger force vector (Zatsiorsky et al. 1998; Latash et al. 2001; Danion et al. 2003). In order to compare variance indices across groups, both components of $\mathbf{F}$ were normalized by MVC_{IM} . The standard half-cycles were aligned by their initiation without further normalization since their amplitudes and periods were identical.

All F_{ACT} half-cycles were screened in two steps with the criteria determined for each subject and each task. First, the half-cycles of F_{ACT} with values outside the range of 3 standard deviations of the mean F_{ACT} trajectory were rejected. Second, the mean area between F_{ACT} and F_{TASK} of the remaining half-cycles and its standard deviation was computed as the criterion. If the area between F_{ACT} and F_{TASK} for one half-cycle from the original half-cycle set (i.e., 24 for the “TUBE” and 21 for the “SINE” task) was outside the range of 2 standard deviation of the mean area, the half-cycle was considered as outlier and removed. These criteria resulted in accepting 92.0% of the half-cycles for the *elderly* group and 94.4% of the half-cycles for the *young* group.

Further, variance indices in the $\mathbf{m}$ space were computed across the accepted half-cycles for each time sample. The variance in the $\mathbf{m}$ space across trials (V_{TOT}) was decomposed into two components, within the UCM corresponding to no changes in F_{TOT} (V_{UCM}) and orthogonal to it (V_{ORT}), for each time sample. The UCM was computed as the null-space of the Jacobian of the system. The index of synergy (ΔV) was computed as: $\Delta V = (V_{UCM} - V_{ORT}) / V_{TOT}$. Note that all the variance indices were computed per dimension in the corresponding sub-spaces, 1 for V_{ORT} , 1 for V_{UCM} , and 2 for V_{TOT} . The index ΔV is computed in such a way that $\Delta V = 0$ corresponds to no covariation across half-cycles in the $\mathbf{m}$ space, while $\Delta V > 0$ corresponds to co-variation reducing the total force variance (force-stabilizing synergy). For statistical analysis, modified Fisher’s z-transformation was applied to ΔV with the boundaries of -2 and 2 .

Statistical analysis

Standard descriptive statistics were used; the data are presented as mean $\pm$ SE. The Aligned Rank Transform (ART) procedure (Wobbrock et al. 2011) with two-way mixed-effects analyses of variance (ANOVA) was used to explore how G -values differed between the two groups and changed over practice blocks. The factors were *Age* (*elderly* and *young*) and *Block* (6 levels). Three-way mixed ANOVAs with the factors *Age*, *Task* (“TUBE” and “SINE”) and *Test* (*pre-test* and *post-test*) were used to explore how indices of performance (RMS_{ES} and T_{OUT}). A two-way ANOVA was used to test whether the index of enslaving (I) was affected by age and practice. Three-way mixed ANOVAs with the factors *Age*, *Task* (“TUBE” and “SINE”), and *Test* were used to explore how variance indices (V_{UCM} , V_{ORT} , and V_{TOT}), and the synergy index (ΔV) were affected by age and practice as well as the transfer effects from the practiced task (“TUBE”) to the non-practiced task (“SINE”). To ensure normality, data of variance indices were power-transformed when needed (Osborne 2010). Pair-wise comparisons with Bonferroni corrections were used to explore significant effects, while post-hoc ANOVAs were performed to explore interaction effects in the three-way analysis (Bruin 2006). Statistical significance was set at $p = 0.05$. All statistical tests were performed using SPSS 19.0 (SPSS Inc, Chicago, IL).

Results

The tasks were perceived as challenging, particularly by the elderly subjects. Single trials performed by representative subjects from both groups before and after practice for both “TUBE” and “SINE” tasks are illustrated in Figures 1 and 2. For both tasks, multiple corrections can be seen in all panels. Practice of the “TUBE” task led to a gradual improvement in both performance scores, T_{OUT} and RMS_{ES} , in both groups. As T_{OUT} improved, the task was made more challenging (unstable) by an increase in the G value (see Methods). The G value increased similarly for both groups (median: from 0.010 to 0.025 for the *elderly* group, and from 0.015 to 0.030 for the *young* group) as shown in Figure 3. Because G values had discrete values, non-parametric tests were used. A two-way mixed (*Age* $\times$ *Block*) ANOVA with ART procedure (see Methods) showed only a significant effect of *Block* ($F_{[2.68, 64.3]} = 118.49$, $p < 0.001$). Pair-wise comparisons with Bonferroni adjustments confirmed that G increased significantly after each block except between the last two blocks.

Performance score

Elderly subjects performed both tasks less accurately reflected in the higher RMS_{ES} and T_{OUT} values. In both groups the error indices dropped with practice. The “TUBE” task showed higher RMS_{ES} values than the “SINE” task in both groups, while the T_{OUT} scores were similar between the two tasks. The average values across the groups for T_{OUT} and RMS_{ES} for both tasks are illustrated in Figure 4; note the lower indices in the *post-test* and the higher RMS_{ES} in the *elderly* group. These results have been confirmed by a three-way mixed (*Age* $\times$ *Task* $\times$ *Test*) ANOVA. All main effects were significant for RMS_{ES} (*Age*: $F_{[1, 22]} = 25.75$, $p < 0.001$; *Task*: $F_{[1, 22]} = 22.38$; *Test*: $F_{[1, 22]} = 142.45$, $p < 0.001$) with the only significant *Age* $\times$ *Test* interaction ($F_{[1, 22]} = 5.54$, $p < 0.05$). The interaction reflected a larger improvement in RMS_{ES} in the *young* group compared to the *elderly* group. For T_{OUT} , the main effects of *Age* and *Test* ($F_{[1, 22]} = 48.36$, $p < 0.001$; $F_{[1, 22]} = 96.23$, $p < 0.001$, respectively) and *Task* $\times$ *Test* interaction ($F_{[1, 22]} = 13.29$, $p < 0.001$) were observed. Post-hoc tests confirmed that the practice effects were more prominent on T_{OUT} in the “SINE” task than in the “TUBE” task ($F_{[1, 22]} = 14.53$, $p < 0.001$). In summary, there was strong transfer of the practice effects to the non-practiced (“SINE”) task.

Enslaving

Practice led to an increase in the index of unintentional force production by non-task fingers (index of enslaving, $|E|$). Elderly subjects showed a tendency towards lower enslaving indices both before and after practice. The average values of $|E|$ in the elderly before and after practice were 0.71 vs. 0.94 while in the young they were 0.81 vs. 0.95. Although the *elderly* group showed a slightly higher increase in $|E|$ with practice, a two-way mixed ANOVA, $Age \times Test$, confirmed only a significant main effect of $Test$ ($F_{[1, 24]} = 23.7$, $p < 0.01$).

Structure of Variance

The amount of variance in the mode space (see Methods) was higher in the *elderly* group across tasks and tests. In addition, there was also a major difference in the effects of practice on variance indices in the “TUBE” and “SINE” tasks. While both groups before practice showed similar amounts of variance in the two tasks, after practice they showed much higher amounts of total variance (V_{TOT}) in the “TUBE” task as compared to the “SINE” task. Practice led to a drop in V_{ORT} (which affected total force) in both groups in both practiced (“TUBE”) and non-practiced (“SINE”) tasks. Figure 5 illustrates V_{UCM} , V_{ORT} , V_{TOT} , and ΔV averaged across subjects within age groups for the two tasks (“SINE” and “TUBE”), before and after practice.

Both groups showed much higher proportion of total variance in the finger *mode* space confined to the UCM sub-space. This was true for both tasks, “TUBE” and “SINE”, both before and after practice. In other words, $V_{UCM} > V_{ORT}$ (or, equivalently, $\Delta V > 0$) reflecting a force-stabilizing two-finger synergy across tasks, tests, and groups. These effects are illustrated in Figure 5A and 5B (note the different scales for V_{UCM} and V_{ORT}).

Since most variance was within the UCM (V_{UCM} that did not affect total force), effects of age and practice were similar for V_{TOT} and V_{UCM} (compare Figures 5A and 5C). Specifically, both variance indices were significantly higher in the *elderly* than in the *young* group. Three-way mixed ANOVAs ($Age \times Task \times Test$) on both V_{TOT} and V_{UCM} showed significant main effects of Age ($F_{[1, 24]} > 11.16$, $p < 0.01$) and $Task$ ($F_{[1, 24]} > 18.17$, $p < 0.01$), as well as $Task \times Test$ interactions ($F_{[1, 24]} > 7.45$, $p < 0.01$).

After practice, both groups showed an increase in V_{TOT} and V_{UCM} in the “TUBE” task. Note that these effects were not transferred to the “SINE” task: In the “SINE” task these variance indices remained the same or even decreased slightly. To analyze the transfer effects on the variance indices, two-way ($Task \times Test$) ANOVAs for individual groups were performed. These ANOVAs revealed significant main effects of $Task$ ($F_{[1, 24]} > 7.40$, $p < 0.01$) for both groups. The $Task \times Test$ interaction was significant in the *young* group ($F_{[1, 24]} > 4.50$, $p < 0.05$) but not in the *elderly* group ($F_{[1, 24]} < 3.0$, $p > 0.10$) possibly due to the higher within-group variability in the elderly subjects.

V_{ORT} in both groups dropped after practice for both tasks, while the *elderly* group showed higher V_{ORT} than the *young* group (Figure 5B). So, in contrast to the described effects on V_{UCM} , the practice effect on V_{ORT} was transferred to the “SINE” task. A three-way ($Age \times Task \times Test$) ANOVA confirmed significant effects of all three factors: Age ($F_{[1, 24]} = 47.75$, $p < 0.01$), $Task$ ($F_{[1, 24]} = 26.52$, $p < 0.01$) and $Test$ ($F_{[1, 24]} = 29.67$, $p < 0.01$). There were no interactions.

The index of synergy (ΔV) in both groups increased after practice with no significant differences between the groups. On average, after practice ΔV increased in both tasks, although the increase was significant for the “TUBE” task only (Figure 5D). Note that the values in parentheses in Figure 5D show the original ΔV values while the height of the

columns shows averaged across subjects z-transformed values with standard error bars. Since the transformation was nonlinear, the non-transformed values could be underestimated. The effects of practice and transfer were explored by a three-way ($Age \times Task \times Test$) ANOVA on ΔV_Z (z-transformed ΔV). The main effects of $Test$ ($F_{[1, 24]} = 13.6, p < 0.01$) and $Task$ ($F_{[1, 24]} = 4.88, p < 0.05$) were significant, as well as the $Task \times Test$ interaction ($F_{[1, 24]} = 5.35, p < 0.05$). The interaction reflected the fact that ΔV in the “TUBE” task increased after practice while the changes in ΔV after practice were not significant in the “SINE” task. Two-way ANOVAs ($Test \times Age$) for individual tasks revealed only significant effects of $Test$ ($F_{[1, 24]} > 16.4, p < 0.01$) for the “TUBE” task with no significant Age and interaction effects.

Discussion

The first question formulated in the Introduction was: Can older persons show an improvement in an index of a multi-finger synergy after a brief practice of the variable task with graded instability (modified by changes in G)? The results suggest an affirmative answer. The analysis of the structure of variance in the space of hypothetical commands to fingers (*modes*, Zatsiorsky et al. 1998; Latash et al. 2001) has confirmed an increase in the component of variance, V_{UCM} that had no effect on the total force produced by the index and middle fingers (F_{IM}). In contrast, the component of variance that led to changes in F_{IM} dropped with practice. These effects were observed in both *young* and *elderly* groups. The changes in the structure of variance could be interpreted as strengthening (increasing the index, ΔV) of the two-finger synergy stabilizing F_{IM} .

The second question was: Do practice-induced changes transfer to a different task? We used the “SINE” task to quantify the transfer effects. While both groups showed an improvement in the performance of the “SINE” task, the effects of practice on the two variance components were different from those observed in the practiced “TUBE” task. Both variance components estimated for the “SINE” task dropped; as a result, no major changes in the synergy index were observed. So, transfer effects were seen in the indices of performance but not in the synergy index.

Further, we discuss implications of these results for the issues of learning novel motor coordination by young and older persons and changes in the structure of variance in redundant tasks. We believe that these observations carry a highly optimistic message that promises direct applications of this approach to motor rehabilitation in a variety of disorders characterized by impaired coordination.

Is aging associated with a decrement in the ability to learn novel tasks?

The current literature is ambiguous with respect to this question. Several studies emphasized positive effects of practice on such characteristics of motor action as smoothness of muscle contraction (Connelly et al. 2000) and better postural control (Kubicki et al. 2012). Other studies, however, reported problems with learning challenging coordination by older persons (Sparrow et al. 2005), possibly related to diminished corticomotor plasticity (Rogasch et al. 2009), as well as quantitatively smaller effects of practice in older persons (Etnier, Landers 1998; Seidler-Dobrin, Selmach 1998). Several studies linked motor learning to cerebellar and striatal thalamo-cortical pathways (reviewed in Seidler 2010), and age-related decline in the functioning of these pathways has been reported in several studies (Moreno-Baylach et al. 2008; Fathi et al. 2009; Clark and Taylor 2011).

The “TUBE” task used in our study may be viewed as rather unusual and challenging. Nevertheless, while the *elderly* group showed lower indices of performance, T_{OUT} and RMS_{ES} , in this task, the ability of the older subjects to improve these indices with practice

was comparable to that of the *young* group (Figure 4). The finding that we view as particularly exciting (and unexpected) was the increase in the synergy index in the *elderly* group, which was even larger than the increase in this index in the *young* group (although the group difference did not reach significance, Figure 5D). We feel safe to claim therefore that, in the used task, elderly and young participants showed comparable abilities to improve with practice.

One of the effects of practice may be seen as undesirable. As in earlier studies (Olafsdottir et al. 2008; Wu et al. 2012), we observed a consistent practice-related increase in the index of unintended force production by fingers that were not instructed to produce force (enslaving, Zatsiorsky et al. 1998, 2000). While the terms “enslaving” and “lack of individuation” (Schieber and Santello 2004) carry negative connotation, we would like to emphasize that a certain amount of enslaving may be beneficial for multi-digit tasks. First, indices of enslaving are decreased in older persons as compared to younger persons (Shinohara et al. 2003; Kapur et al. 2010). This may signify a shift from synergic control of the hand to element-based control with aging. Second, natural patterns of enslaving were shown to facilitate stabilization of the total rotational action of the four fingers (Zatsiorsky et al. 2000). Since, accurate rotational actions are a very important part of the everyday motor repertoire (e.g., drinking from a glass, using tools and implements, etc.), an increase in the index of enslaving may in fact mean improved conditions for the control of the hand action.

Practice that encourages more “good variance”

Most everyday tasks are performed by systems with more elements than the number of constraints imposed by the tasks leading to the famous problem of motor redundancy introduced by Bernstein as the central problem of motor control (Bernstein 1967). Recently, this problem has been reconsidered based on the principle of motor abundance (Gelfand and Latash 1998; Latash 2012). According to this principle, the neural controller does not try to eliminate the redundancy but takes advantage of it. In particular, the apparent redundancy (better addressed as abundance) allows performing tasks accurately while having relatively high variance of the elements. Such “good variance” (V_{UCM}) has no effect on important performance variables, while it helps with performance of secondary tasks (Zhang et al. 2008; Gera et al. 2009; Klous et al. 2010) and with handling unexpected and/or unusual perturbations (Scholz et al. 2001; Yang et al. 2010; Mattos et al. 2011).

Several recent studies have documented a drop in the relative amount of V_{UCM} (quantified using a synergy index, ΔV) in the total variance in older persons (Shinohara et al. 2004; Olafsdottir et al. 2007) and in patients with neurological disorders (Park et al. 2012). A study of the effects of strength training of hand muscles documented correlated changes in accuracy of performance of hand tasks and indices of synergy stabilizing the total force (Olafsdottir et al. 2008). These observations suggested to us that practicing a task that introduces instability in a subject-specific, graded way (by changing G in our experiment) may encourage the subjects to increase the amount of “good variance” leading to stronger multi-finger synergies.

Changes in the G factor within the practice schedule were designed to emphasize the importance of stability of performance by a redundant (two-finger) system. Important features of the task were using different tasks in each trial and adjusting the level of instability (with the G factor) based on individual subject’s performance. Based on the first study (Wu et al. 2012), we hoped to see higher amount of V_{UCM} in the practiced task in the *young* group. Whether older persons can show a similar counter-intuitive increase in V_{UCM} was an open question. The experiment confirmed that older persons were as able as younger ones to show an increase in V_{UCM} with such practice in the “TUBE” task.

Our analysis of multi-finger synergies and variance components was performed in the space of hypothetical commands to fingers (modes, Danion et al. 2003). The mentioned increase in enslaving with practice could potentially affect the results by itself. To confirm that the main results were not due to the changed enslaving, we re-analyzed the data in the space of finger forces. We are not presenting the results of this analysis (but see Wu et al. 2012) because they show the same main effects and interaction effects as the described analysis in the space of modes. So, we feel safe to conclude that the non-trivial changes in the components of variance were not due to the changes in the enslaving index.

Both prior to and after practice the amount of V_{UCM} was much higher than the amount of “bad variance” (V_{ORT}) (i.e., $\Delta V > 0$). As a result, an increase in V_{UCM} resulted in an overall increase in the total variance in the space of commands to fingers. This result is far from being trivial: Practicing a task that required accurate force production resulted in HIGHER amounts of variance in the space of finger modes (and in the space of finger forces). This was associated with an increase in the synergy index; so, as a result, variance of total force dropped. Note that effects of practice on the synergy index in the *elderly* group tended to be as strong as in the *young* group for the same amount of practice. So, these results do not confirm the earlier conclusion that older persons need extended practice to show effects comparable to those in younger persons (Voelcker-Rehage and Alberts 2005).

Transfer of performance vs. transfer of coordination

Practicing the “TUBE” task showed different transfer effects on performance and synergy indices. Performance indices, T_{OUT} and RMS_{ES} , measured in the non-practiced “SINE” task showed a significant improvement with practice in both groups. However, changes in the two variance components and the synergy index were very different in the two tasks. Indeed, we observed strong transfer effects when these were quantified using indices of performance (T_{OUT} and RMS_{ES}) and no significant transfer of practice related changes in the multi-finger synergy stabilizing total force. Actually, there was an increase (on average, by 16%) in the synergy index in the “SINE” task after practice, but the increase was under the significance level (Fig. 5D).

Variance that affected accuracy of performance (V_{ORT}) dropped with practice in both groups and in both “TUBE” and “SINE” tasks similarly. In contrast, V_{UCM} increased significantly in the “TUBE” task but dropped significantly in the “SINE” task. These results look somewhat unexpected. Note that the transfer task (“SINE”) was simpler than the practiced task. Therefore, it is possible that it did not require large amounts of V_{UCM} (cf. Domkin et al. 2002). Also the subjects could feel more comfortable with the “SINE” task, which was not associated with exaggerated deviations from the template, and did not perceive the need to facilitate stronger synergies. Whether stronger synergies can be transferred to more challenging and more ecologically valid tasks remains to be seen.

Practical implication and conclusions

The observed practice effects in the older adults make us cautiously optimistic with respect to the possibility of developing this method for future use in populations with impaired coordination characterized by low synergy indices. Using a variable task with adjustable stability conditions encouraged flexible involvement of the fingers (larger V_{UCM}). Note that the task itself was always 100% stable and safe (isometric force production), while the apparent stability conditions were manipulated using the software and visual feedback. In a way, the task represented a computer game that encouraged variable involvement of the elements (fingers). This method can be readily applied to hand training in the field of motor rehabilitation, in particular in disorders that affect the hand function such as stroke and Parkinson’s disease. The idea of using subject specific adjustments in task stability can also

be developed for a wide range of motor tasks, such as reaching movements, postural tasks and locomotion. To make the approach practically useful, however, one has to overcome the apparent limitation in the transfer of the effects of practice on synergies that we saw in our study.

To conclude, our study shows that practicing redundant groups of elements may lead to improvement in both motor performance (RMS_{ES} and T_{OUT}) and force-stabilizing synergies in both young and older adults. The two variance indices computed within the framework of the UCM hypothesis showed opposite effects of practice: V_{ORT} dropped with practice while V_{UCM} increased leading to an increase in the index of synergy stabilizing total force. The transfer effects were ambiguous: Performance in the non-practiced task (“SINE”) improved, but there was no transfer of the effect of practice on the structure of variance: Both variance components, V_{ORT} and V_{UCM} , showed a drop. The next step would be to explore these effects using more ecologically relevant tasks that would involve all four fingers and manipulation of hand-held objects.

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Figure 1.

Typical performance of a representative subject from the *elderly* group in the “TUBE” and “SINE” tasks before practice (pre-test, A,C) and after practice (post-test, B,D) in a moderately challenging condition with $G = 0.02$. The gray dashed lines show the force target, the gray solid lines show the permissible error margins, and the black trace shows the actual force. After each trial, root mean square error score (RMSE_S) and time outside the permissible error margins (T_{OUT}) were displayed on the screen as performance indices.

Figure 2.

Typical performance of a representative subject from the *young* group in the “TUBE” and “SINE” tasks before practice (pre-test, A,C) and after practice (post-test, B,D) in a moderately challenging condition with $G = 0.02$. The gray dashed lines show the force target, the gray solid lines show the permissible error margins, and the black trace shows the actual force. After each trial, root mean square error score (RMS_{ES}) and time outside the permissible error margins (T_{OUT}) were displayed on the screen as performance indices.

Figure 3. Median G values across subjects in each block for the *elderly* group (dashed line) and *young* group (solid line) over the practice time.

Figure 4. Indices of performance, RMS_{ES} and T_{OUT}, in the “TUBE” and “SINE” tasks prior to (Pre) and after (Post) practice. Means with standard error bars are shown for the elderly (open bars) and young (black bars) groups.

Figure 5.

Variance within the UCM (V_{UCM}), variance orthogonal to the UCM (V_{ORT}), total variance (V_{TOT}), and z-transformed index of synergy (ΔV_Z) are presented in panels A, B, C, and D, respectively. The variance indices were normalized by MVC² to facilitate across-subjects comparisons. The values in parentheses in panel D represent means of non-transformed ΔV values. All values are averaged across subjects for each group in the pre- and post-test. The error bars show the standard errors.