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RESEARCH ARTICLE

Control of Movement

Repeated context-specific actions disrupt feedforward adjustments in motor commands in younger and older adults

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Abstract

The flexibility of the motor system to adjust a planned action before or during the execution of the movement in response to sensory information is critical for preventing errors in motor control. As individuals age, this function declines, leading to an increased incidence of motor errors. Although sensory processing and cognitive decline are known contributors to this impairment, here, we test the hypothesis that repetition of context-specific planned actions interferes with the adjustment of feedforward motor commands. Younger and older participants were instructed to grasp and lift a T-shaped object with a concealed, off-sided center of mass and minimize its roll through anticipatory force control, relying predominantly on predictive model-driven planning (i.e., sensorimotor memories) developed through repeated lifts. We selectively manipulate the number of trial repeats with the center of mass on one side before switching it to the other side of the T-shaped object. The results showed that increasing the number of repetitions improved performance in manipulating an object with a given center of mass but led to increased errors when the object's center of mass was switched. This deleterious effect of repetition on feedforward motor adjustment was observed in younger and older adults. Critically, we show these effects on an internal model-driven motor planning task that relies predominantly on sensorimotor memory, with no differences in sensory inputs from the repetition manipulation. The findings indicate that feedforward motor adjustments are hampered by repetitive stereotyped planning and execution of motor behavior.

NEW & NOTEWORTHY Adjusting planned actions in response to sensory stimuli degrades with age contributing to increased incidence of errors ranging from clumsy spills to catastrophic falls. Multiple factors likely contribute to age-related motor inflexibility, including sensory- and cognition-supporting system declines. Here, we present compelling evidence for repetition to disrupt feedforward adjusting of motor commands in younger and older adults, which suggests increases in stereotypy as a deleterious potentiator of motor control errors.

aging; anticipatory force control; feedforward motor adjustment; motor flexibility; repetition

INTRODUCTION

An important hallmark of the human motor system is the ability to flexibly adjust a planned action before or during the execution of the movement in response to sensory information, referred to as motor flexibility. Critical errors of motor control such as falls are a rarity rather than the norm in part due to the flexibility of the motor system, for example, to adjust a gait pattern in response to an unexpected icy surface. Adjusting planned actions in response to sensory stimuli degrades with age, increasing the incidence of errors that range from clumsy spills and slips that affect daily functioning and independence to catastrophic falls that are the leading cause of injury in this age cohort (1–3). There are likely multiple contributors to age-related motor inflexibility (4–6) including known declines in sensory processing (5, 6) and cognitive function (2, 7, 8) that are driven by structural and functional changes in motor-dependent nodes in central and peripheral nervous systems (see Ref. 2, for a review).

Preliminary evidence in young adults suggests repetition of context-specific planned actions as another potential contributor to age-related degradation of motor flexibility. In an

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object manipulation task relying predominantly on internal predictive-driven motor planning, repeatedly lifting a symmetrically shaped object with an asymmetric center of mass (CoM) will result in the successful generation of a compensatory torque force that counters the external torque of the object (9, 10). During early sensorimotor learning, the beneficial effects of repetition are context-specific, implying that what is learned through repetition may not easily transfer to different situations. For example, learning to generate a compensatory torque to counter a left CoM will not initially transfer to success when the object is rotated such that the CoM is on the right (9–11). Instead, the forces and digit positions are copied from the trial preceding the object rotation (i.e., anterograde interference), and as a result, there is a failure to generate a torque of appropriate magnitude and direction. Preliminary evidence, mostly from reach-to-target paradigms, suggests that such anterograde interference effects might be exacerbated by repetition. The more one repeats a particular task, the more challenging it can become to learn a completely different or opposite task afterward (9, 12–16). Thus, even though "practice makes perfect" such that increased repetition improves the performance of the practiced task in motor, auditory, and visual domains (17–20), repetition of context-specific planning and execution of actions might impede motor flexibility.

In this study, we investigated whether repeatedly planning and executing a context-specific hand-object interaction interferes with feedforward adjustments in motor commands in younger and older adults without mild cognitive impairment. Participants were tasked to minimize the roll of a symmetrically shaped object with an asymmetric mass distribution (9, 10, 21–24). Success in this object manipulation task requires feedforward anticipatory force control and generating a compensatory torque at lift through a combination of digit position, grip force, and lift force. Feedforward force control relies predominantly on visual cues of object properties when available and internal predictive models built from prior experiences with the same or similar object (i.e., referred to as sensorimotor memories hereafter) (9, 10, 24). As visual cues of object properties were irrelevant in this task, current trial task success here relies predominantly on sensorimotor memories from repeated lifts. In a critical manipulation of this task, we selectively varied the number of trial repetitions in planning and generating the same force and torque control for an object with a given mass distribution before we switched the mass distribution to the other side. There was no difference in sensory processing inputs as a function of the preswitch trial repeat manipulation. Thus, any observed motor switch cost effects of repeatedly planning and executing a context-specific action were not driven by differential demands on sensory processing.

Consistent with our hypothesis, increasing the number of trials in manipulating an object with a given mass distribution refined performance (i.e., successful generation of compensatory torque) but increased errors on the trials following a mass distribution switch (i.e., unsuccessful generation of compensatory torque). This deleterious effect of repeatedly planning and executing a context-specific action was observed in younger and older healthy adults. We show these effects on postswitch performance that relies predominantly on sensorimotor memory, with little to no input from sensory systems during the planned action. Manipulating repetition also did not change the contribution, if any, of sensory processing to task success. Together, these results suggest that motor control errors due to motor inflexibility can arise from repetitive stereotyped motor planning and execution of motor behavior independent of sensory-processing deficits, both of which are typically observed with advancing age.

MATERIALS AND METHODS

Participants

Thirty healthy right-handed younger adults (median age: 23 and range: 18–35; 20 females) and 30 older adults (median age: 71 and range: 59–85; 16 females) participated in this study. The Montreal Cognitive Assessment (MoCA) (21) was administered to older participants as a cognitive screening tool. Older participants with a score under 26, indicating mild cognitive impairment, were excluded from the study ($n = 2$), with the final sample size of 30. This study and all its procedures were approved by the University of Oregon Institutional Review Board, and all participants gave written informed consent.

Materials, Design, and Procedure

Participants used their right thumb and index finger to reach, grasp, and lift an inverted T-shaped object with a concealed off-centered mass that switched between the left and right sides. The task goal was to minimize object tilt. The number of preswitch trials was selectively varied to examine the effect of repetition of context-specific planned action on feedforward motor flexibility (i.e., generating the correct compensatory torque of appropriate magnitude and direction).

The T-shaped object was 3-D printed with chopped carbon fiber containing nylon (Onyx, Markforged). The inverted T-shaped object's vertical column (height: 9.0 cm; width: 5.0 cm; depth: 3.2 cm) had elongated grasp surfaces attached on either side (height: 7.4 cm; width: 4.5 cm; depth: 0.8 cm; between grasp distance: 8.2 cm). The depth dimensions of the grasp surfaces were marginally greater than the diameter of the transducer surfaces (limiting the opportunity to cause torque in a yaw direction). A lead cylinder (height: 4.5 cm; diameter: 3.8 cm; mass: 490 g) was concealed in the horizontal base (height: 5.6 cm; width: 4.9 cm; depth: 18.3 cm). The total mass of the object was 936 g with an external torque of 260 Nmm.

Participants sat in a chair at a comfortable height and distance such that their right forearm and upper arm made a right angle while resting on the table. They were instructed to keep their left arm from resting on the table. At the start of each trial, participants pressed a keyboard button with their right index finger to capture reach onset. An audio cue would say "left," if the object was heavier on the left and "right," if the object was heavier on the right. A beep occurred 1.25 s after the left/right side audio cue instructing the initiation of the participant to reach, grasp, and lift the object (20 cm from the button). The object was lifted to a height marker (11 cm). A second beep (2.50 s after the first beep) instructed setting down the object in its original start position and returning the right index finger to its start position on the keyboard button. Participants were told to complete the object-lifting task at a natural pace and to attempt to lift the object without tilting it to the weighted side. Participants were informed that they could grasp the object anywhere along the elongated grip surfaces.

We manipulated the number of trial repeats (1–5 trials) in lifting the object with a given mass distribution before we switched the CoM to the other side (Fig. 1). Participants experienced 1, 2, 3, 4, or 5 preswitch trials that were followed by a single postswitch trial. Participants were exposed to each condition five times. We evaluated the switch cost of repeatedly planning a context-specific action by varying preswitch trial numbers by focusing on performance of the trial after the CoM switch (i.e., the postswitch trial). The entire experiment comprised 100 trials (75 preswitch lifts and 25 postswitch lifts, 5 for each repetition condition). One-minute breaks were provided after every 20 trials. Participants completed the task twice over 2 days, with the CoM starting on the left or right counterbalanced between subjects. In one session, each of the repetition ensembles (i.e., set of preswitch trials and their postswitch trial) was repeated sequentially (blocked version), whereas in the other session, the repetition ensembles were distributed randomly (mixed version). By examining the repetition effect in both blocked and mixed trials, we can evaluate whether the hampering effect of repetition depends on how many trials before the CoM switch or how many iterations of trials before the CoM switch. The sessions were counterbalanced between starting in the blocked or mixed condition. Most participants completed the blocked and mixed sessions within a 24-h time window, except two older adults and five younger adults who had greater than 24 h between sessions. Results are unchanged excluding participants who had more than a 24-h gap between sessions.

Data Processing

Grip forces and torque applied to the grip surfaces were recorded at a frequency of 500 Hz through force/torque transducers (Mini27 Titanium, ATI Industrial Automation, NC) attached between each grip surface and the vertical column of the T-shaped object. These transducers measured grip force, load forces, and torque, with resolutions of 0.03 N, 0.015 N, and 0.375 Nmm. To track the object's vertical height, we used a three-camera motion tracking system (Precision Point Tracking System; Worldviz) with a frame rate of 150 Hz (camera resolution: 1,280 × 1,024 VGA). The system's spatial accuracy within a 3 × 3 × 3 m volume was ≤ 1 mm. To monitor the object's vertical position, two near-infrared light-emitting diode (LED) markers were securely affixed to the covers on the horizontal base of the object. Data were filtered using a fourth-order low-pass Butterworth filter, applying a cutoff frequency of 5 Hz. Lift onset was defined as the point at which the vertical position of the object went above 1 mm and remained above this value for 20 samples. The force/torque transducers were used to obtain outcome measures on both the thumb and index finger sides:

1) Compensatory moment or torque (M_{Com}) at lift onset is the anticipatory torque generated by the digits measured in Newton millimeters (Nmm) in response to the external torque of the object. This was computed using the formula:

$$M_{Com} = (LF_{diff} \times (d/2)) + (GF_{mean} \times COP_{diff})$$

where d is the width between both grip surfaces (8.20 cm). A positive M_{Com} indicated a clockwise moment and a negative M_{Com} indicated a counterclockwise moment.

2) Grip force mean (GF_{mean}) is the instantaneous average in grip force of each digit in Newtons (N). This was calculated using a numerical averaging method:

$$GF_{mean} = (GF_{thumb} + GF_{index}/2)$$

3) Lift force (LF) difference at lift onset is the difference between the tangential component of the force produced by each digit (N).

$$\text{Lift force difference } (LF_{diff}) = LF_{thumb} - Lf_{index}$$

A higher thumb than index finger lift force shows positive values and a higher index finger than thumb lift force

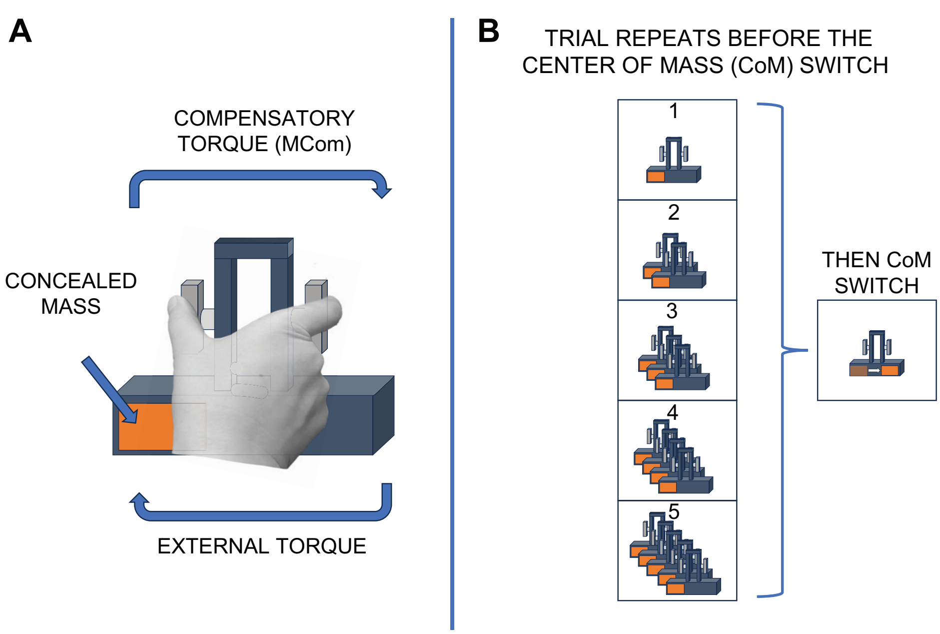

Figure 1. Task and design. Illustration of the T-shaped object with a concealed center of mass (CoM), with the task goal of minimizing tilt via generating a compensatory torque (MCom) in the opposite direction of the object's external torque (*A*). We experimentally manipulated the number of preswitch trial repeats (1–5) with the CoM on a given side (*left*, in the example) before switching the CoM to the other side (*right*, in the example) (*B*).

shows negative values. Larger absolute values indicate a more asymmetric lift force sharing pattern, whereas a zero value indicates a symmetric lift force sharing pattern.

4) Center of pressure (COP) is the measure of digit position defined as the point of contact of each digit on the grip surface relative to the center of the transducer (in mm). This was computed using the formula:

$$\mathrm{COP_{digit}} = \left(Tx_{\mathrm{digit}} - \left(\mathrm{LF_{digit}} \times \text{grip surface thickness}\right)\right)/\mathrm{GF_{digit}}$$

where Tx_{digit} is the digit torque in the frontal plane (Nmm). The difference between thumb and index finger placement was used to identify grip configuration:

$$\text{Center of pressure difference}(\mathrm{COP_{diff}}) = \mathrm{COP_{thumb}} \pm \mathrm{COP_{index}}$$

Positive values indicate higher thumb than index finger COP and negative values indicate higher pointer finger than thumb COP. Larger absolute values indicate a more asymmetric, noncollinear grip configuration, whereas a zero value indicates a symmetric, collinear grip configuration.

5) Load phase is defined as the time from net lift force exceeding 0.2 N and continues to increase for 20 samples to lift onset.

6) Reach phase is defined as the time from releasing the keyboard button to when the subject grasps the object.

Data Analyses

Our main analyses focused on comparing the effect of repetition of context-specific planned actions on feedforward adjustment of motor commands. We examined the effect of preswitch trial repetition and age on M_{Com} and its contributors (GF_{mean}, LF_{diff}, and COP_{diff}) and metrics of efficiency (reach phase and load phase) on the postswitch trial following a CoM switch using 2 × 2 ANOVAs (age factor: young vs. older; preswitch trial repetition number: 1 vs. 5). We also measured the effect of preswitch trial repetition and age on M_{Com} on the trial preceding the switch. Participants either initiated the object manipulation task with the CoM moving *1*) from the left to the right or *2*) from the right to the left. In (1), the left trials were the preswitch trials, and in (2), the right trials were preswitch trials. In this way, none of these "preswitch" trials were included in any of our main postswitch trial analyses to match the number of postswitch observations (for a given CoM) for each repetition condition. For participants who began the task with the CoM on the right, M_{Com}, LF_{diff}, and COP_{diff} values were multiplied by −1 to avoid the statistical complication caused by different signs of M_{Com} when manipulating an object with a left versus a right CoM (22). In this way, a positive M_{Com} that nears or matches the object's external torque on preswitch trials exhibits successful torque generation, resulting in a minimal roll. A negative M_{Com} that nears or matches the object's external torque on postswitch trials exhibits successful torque generation, resulting in a minimal roll.

RESULTS

We tested the hypothesis in younger and older participants that repetition of context-specific planned action interferes with the feedforward adjustment of motor commands in younger and older adults. We did so by manipulating the number of preswitch trial repetitions in lifting an object with a given CoM before the mass distribution is switched to the other side. The task goal was to minimize roll by generating an M_{Com} of appropriate magnitude at lift onset. We then evaluated the effect of preswitch repetition on postswitch task success (M_{Com}), tactics used to complete the task successfully [contributors of M_{Com}: mean digit grip force (GF_{mean}), digit position (COP_{diff}), and the digit lift force (LF_{diff})], and the rate with which reach phase and forces are generated (load phase).

Effect of Repetition on Feedforward Motor Flexibility

Figure 2 shows that preswitch trial performance, quantified by M_{Com}, improved with increasing trial repeats of manipulating an object with a given CoM in both groups in both mixed and blocked sessions. There was a significant effect of repetition in both mixed [$F(1, 58) = 196.10$, $P < 0.0001$, $\eta_p^2 = 0.77$] and blocked [$F(1, 58) = 98.12$, $P < 0.0001$, $\eta_p^2 = 0.63$]. There was no effect of age and no interaction (all P values > 0.05).

Figure 3 shows worse behavioral performance, quantified as M_{Com} on the trial following a CoM switch, as a function of increasing the number of trial repeats preceding a CoM switch. The effect of pre-CoM switch trial repetition on M_{Com} following the CoM switch was significant for both mixed [$F(1, 58) = 22.30$, $P < 0.0001$, $\eta_p^2 = 0.28$] and blocked [$F(1, 58) = 17.15$, $P < 0.0001$, $\eta_p^2 = 0.23$] conditions. There was no effect of age or interaction (all P values > 0.05). The deleterious effects of preswitch trial repeats on postswitch performance were similarly present in median split subgroups of older participants aged 59–70 yr and participants aged 71–85 yr in mixed [$F(1, 28) = 11.69$, $P = 0.0019$, $\eta_p^2 = 0.29$] and blocked task versions [$F(1, 28) = 17.72$, $P = 0.0002$, $\eta_p^2 = 0.39$], with no effect of subgroup or interaction (P values > 0.05). This suggests that the effects of repetition on postswitch performance as was measured here are not magnified as a function of age within the older adult group.

To check the extent to which cognitive function contributes to repetition-induced performance differences on postswitch trials, we correlated each older participant's difference score between postswitch performance after five preswitch lifts and postswitch performance after one preswitch lift with their MoCA score (we did not have MoCA scores for the younger group). There was little to no relationship between the postswitch performance difference as a function of preswitch trial repeats and cognitive function (blocked version: $r = -0.12$, $P = 0.53$, mixed version: $r = 0.04$, $P = 0.82$).

Effect of Repetition and Age on Contributors to Feedforward Force Torque Generation

COP$_{diff}$.

Figure 4*A* shows that increasing the number of trials before a CoM switch had a marked effect on the extent to which symmetric thumb and index finger positioning (COP_{diff}) was adopted and contributed to torque generation on postswitch trials. Specifically, an increase in preswitch trial repetitions before a CoM switch resulted in a more default collinear grip strategy on postswitch trials in both age groups and both mixed [$F(1, 58) = 15.38$, $P = 0.0002$, $\eta_p^2 = 0.21$] and blocked

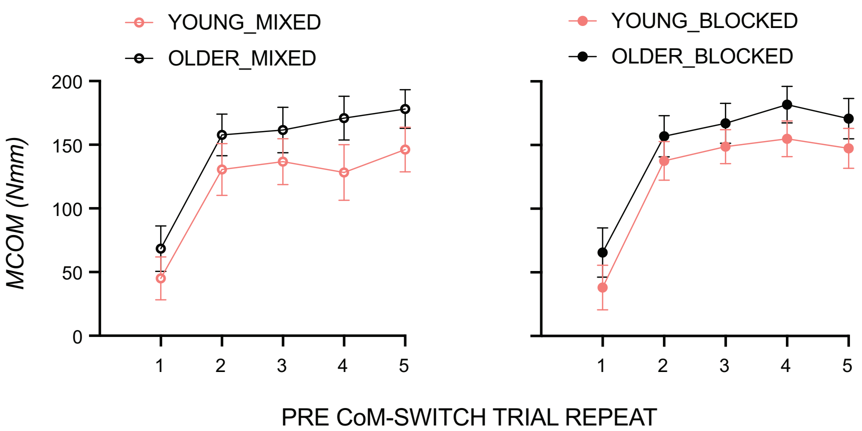

Figure 2. Preswitch performance. Performance, quantified as the group mean compensatory torque (M_{Com}, with error bars ± 1 SE) in younger (pink line) and older (black line) participants on the preswitch trials improved with increasing trial repeats in both mixed (*left*, open circles) and blocked (*right*, solid circles) iterations of the task.

conditions [$F(1, 58) = 5.20$, $P = 0.026$, $\eta_p^2 = 0.082$]. Older adults generally showed increased digit position collinearity and more so with preswitch trial repetition, whereas younger adults tended to adopt an appropriate grip configuration suggestive of positive transfer effects (i.e., higher digit position on the weighted side). However, the effect of age or an interaction did not reach significance (P values > 0.05). These differences indicate that participants adjusted their finger positions toward a default, symmetrical grip on postswitch trials, which is less force efficient (i.e., requiring larger digit lift force partitioning differences), as a function of increased trial repeats preceding the CoM switch.

LF_{diff}.
Figure 4*B* shows a significant interaction in the blocked condition between age and repetition [$F(1, 58) = 4.51$, $P = 0.04$, $\eta_p^2 = 0.07$]; however, there was no effect of repetition or age (P values > 0.05). There was little modulation of lift force sharing patterns by the thumb and index finger (LF_{diff}) due to age or repetition in the mixed condition (P values > 0.05). The interaction in the blocked condition reflects that, in contrast to younger participants, the older group generated more collinear lift forces on postswitch trials as a function of increasing preswitch trials.

GF_{mean}.
Figure 4*C* shows that the mean grip force (GF_{mean}) was generally larger in the older cohort than in the younger cohort in both mixed and blocked conditions [$F(1, 58) = 5.90$, $P < 0.0001$, $\eta_p^2 = 0.09$ and $F(1, 58) = 9.78$, $P < 0.003$, $\eta_p^2 = 0.14$]. In the mixed condition, a small repetition effect was observed on GF_{mean}, with a marginal decrease in grip force on the postswitch trials as a function of increasing preswitch trial repeats, but this effect was small [$F(1, 58) = 6.28$, $P = 0.015$, $\eta_p^2 = 0.01$], with no effect on interaction (P values > 0.05).

Effect of Repetition and Age on Metrics of Efficiency

Reach and load phase.
Figure 5*A* shows generally slower reach phases in the older than in the younger groups in both mixed and blocked iterations of the task on postswitch trials. In the mixed task iteration, a significant interaction effect suggests slower postswitch reach phases in older than in younger participants with increasing preswitch trial repeats [$F(1, 58) = 7.25$, $P = 0.0093$, $\eta_p^2 = 0.11$], with no age or repetition effect (P values > 0.05). In the blocked iteration of the task, older participants were slower than younger participants [$F(1, 58) = 5.85$, $P = 0.014$, $\eta_p^2 = 0.09$] irrespective of preswitch trial number, with no repetition effect and no interaction (P values > 0.05). Figure 5*B* shows marginally slower load phases in the older group than in the younger group, but the effects were not significant in either blocked or mixed task versions. Repetition had little [$F(1, 58) = 6.45$, $P = 0.014$, $\eta_p^2 = 0.10$] to no effects on postswitch load phase in the blocked and mixed versions, respectively. There were no interaction effects (P values > 0.05).

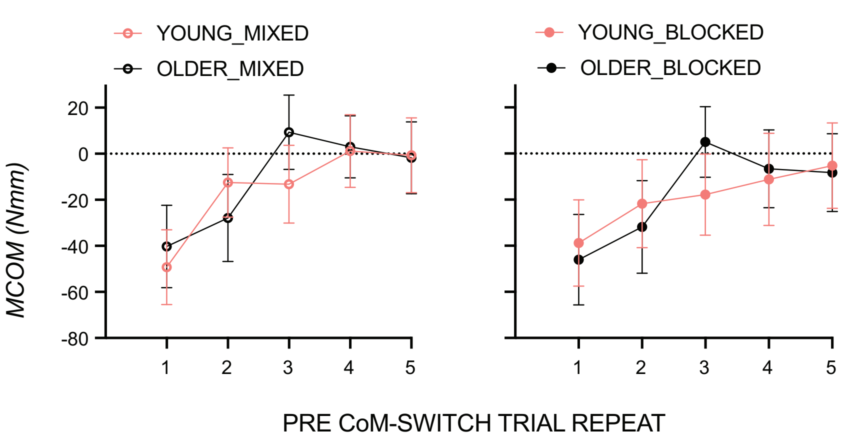

Figure 3. Effect of preswitch trial repeat on postswitch performance. Increasing the number of trials lifting an object with a given center of mass (CoM) before switching it to the other side deleteriously affected postswitch behavioral performance (group mean compensatory torque, M_{Com}, with error bars ± 1 SE) in younger (pink line) and older participants (black line) in both mixed (*left*, open circles) and blocked (*right*, solid circles) iterations of the task.

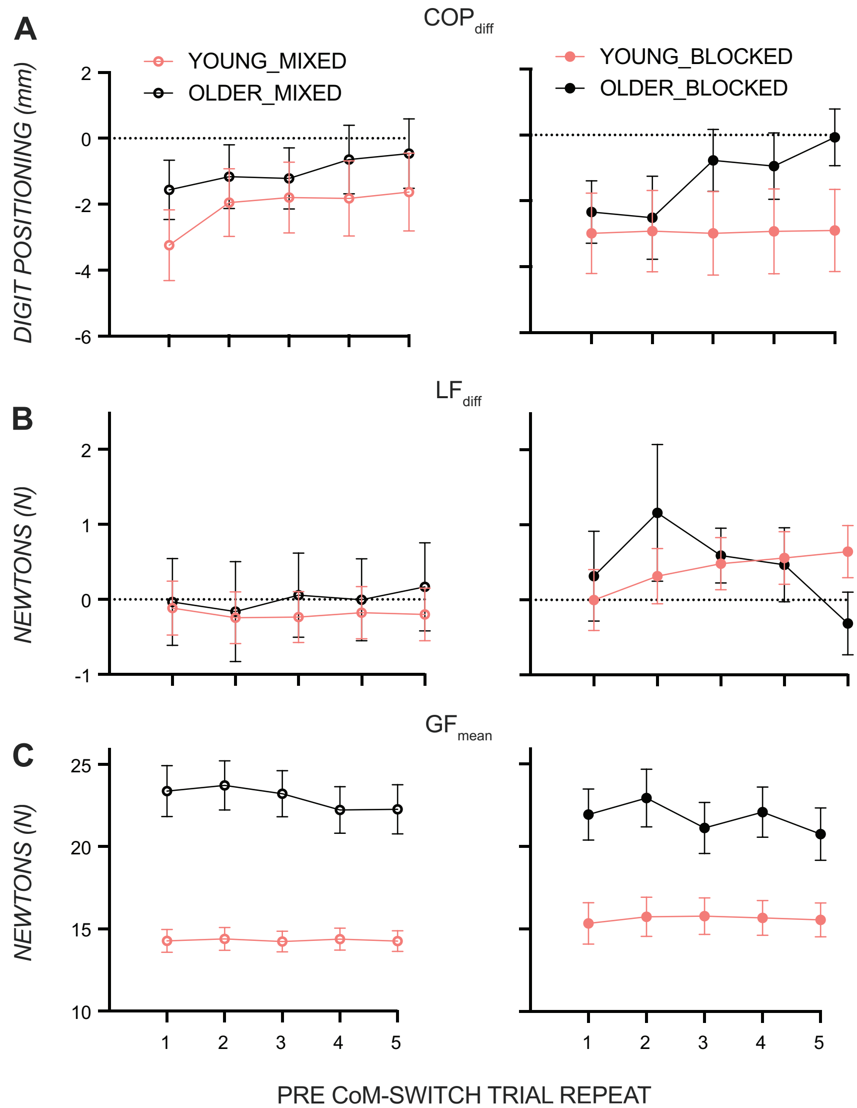

Figure 4. Effect of preswitch trial repeat on contributors of compensatory torque on postswitch trials. Digit positioning (*A*, COP_{diff}), digit lift force partitioning (*B*, LF_{diff}), and grip force (*C*, GF_{mean}) on trials following a center of mass (CoM) switch as a function of increasing the number of preswitch trials in younger (pink line) and older (black line) participants in mixed (*left*, open circles) and blocked (*right*, solid circles) task iterations. Error bars show ± 1 SE.

DISCUSSION

In this study, we investigated whether repeated motor behavior interferes with the feedforward adjustment of motor commands in younger and older adults. We manipulated the number of trial repeats in lifting and minimizing the tilt of an object with a given mass distribution before we switched the mass to the other side. Consistent with our hypothesis, increasing the number of preceding trials with a given mass distribution increased errors following a mass distribution switch in both young and older groups. We show these effects on an internal model-driven motor planning task that relies predominantly on sensorimotor memory, with no differences in sensory processing inputs from the repetition manipulation, therein minimizing the possibility of these effects being driven by age-related sensory processing decline. These results provide evidence that failure to anticipatorily respond to dynamic changes in the environment can arise from repetitive stereotyped motor behavior across younger and older populations.

The main results described here are in line with previous reports that repetition in one motor task has anterograde interference effects on another motor task (9, 12, 14). We show here for the first time repetition magnifying effects of anterograde interference on a motor planning task where current trial performance relies predominantly on sensorimotor memories (i.e., internal predictive models). Critically, any sensory inputs, even if only serving to inform the next trial performance, did not vary between repetition conditions. Previous studies have not isolated the effect of repetition on the ability to switch between sensorimotor memory-driven memory plans independent of sensory processing. Although repetition is essential for acquiring sensorimotor memories that are context-specific at least during early sensorimotor learning, here, we show the deleterious effects of repetition on motor flexibility in learning to generalize anticipatory force control policies that are context-independent. This indicates that repetition might reinforce an overgeneralized default memory representation that is stubborn to change.

Unlike that seen in force field adaptation (13), amplified interference effects as a function of repetition were demonstrated rapidly, in as little as five trials, in an object manipulation requiring anticipatory force control. With matched

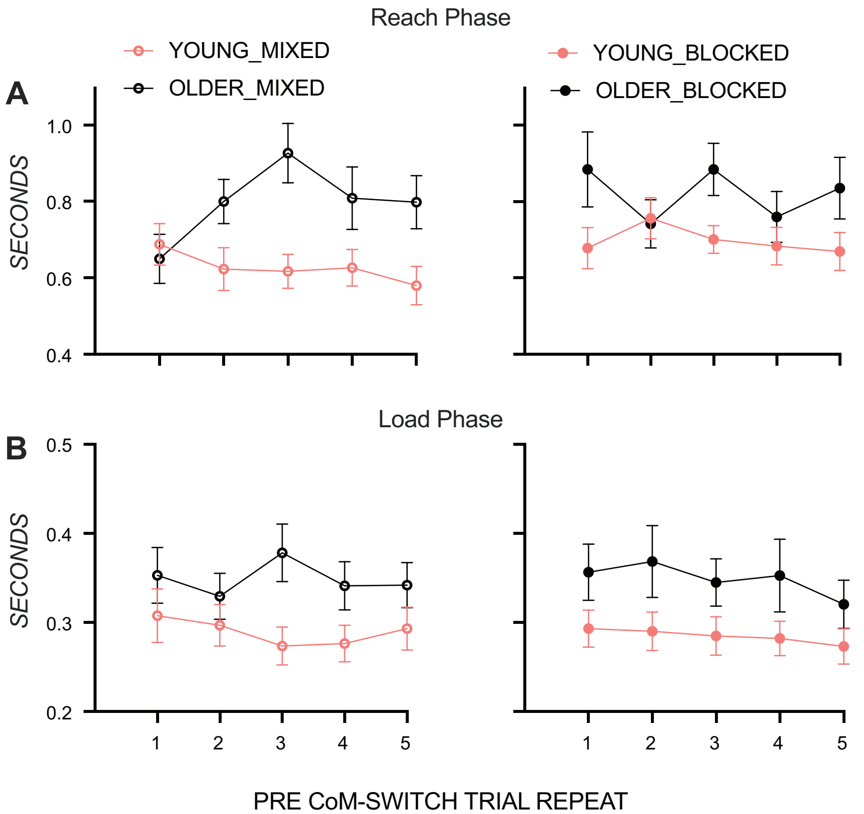

Figure 5. Reach and load phase. Reach phase (*A*) and load phase (*B*) on the postswitch trial as a function of preswitch trial repeats in younger (pink line) and older (black line) subjects with error bars at ± 1 SE in mixed (*left*, open circles) and blocked (*right*, closed circles) task iterations.

effects in blocked and mixed iterations of the task, interference effects were contingent only on one set of preceding trial numbers. In other words, five preswitch object lifts before the CoM switch consistently resulted in an interference effect, irrespective of the number of trials preceding those preswitch trials. Similar to the repetition condition here with one preswitch trial, previous studies showed anterograde inference effects using an even number of trials in pre- and postswitch conditions (9, 26). Here, anterograde effects persist with matched (9) or unmatched lifts before the switch. Given the evidence for improved performance with repetition shown here and previously (17–20), amplified anterograde interference effects might in part be explained by unmatched pre- and postswitch trials. That said, the preceding postswitch trial likely interfered with the subsequent first preswitch trial, which conceivably in part explains preswitch trial performance differences (with better performance after 5 preswitch trials than 1 preswitch trial).

In line with our hypothesis, the hampering effect of repetition on flexibility was similarly present in older and younger participants, with no significant effects of age. That older adults were slower to reach and generate force, it is unknown whether an age-related performance effect would have emerged with greater errors due to repetition with an imposed match in the reach and load phase between groups. In addition to minimizing processing speed demands by allowing participants to perform tasks at their natural pace, we only included cognitively intact older adults in our sample. Future studies might induce experimental manipulations on cognitive demand to causally examine its potentially magnifying effect of repetition and its potential interaction with age.

To our knowledge, we are the first to explore the interference effects of repetition in older adults. Motor flexibility to adjust planned action in response to change degrades with advanced age (4–6). This decline in motor flexibility can be attributed to various factors, including issues with processing sensory information (5, 6) and added cognitive effort (2, 7, 8). Our study highlights that repetition may be another significant contributor to motor flexibility decline in advanced age. We did not expect an age effect in our study as both young and older groups were similarly exposed to manipulations of repetition in a novel object manipulation task. That said, our results suggest that stereotyped motor patterns, if present in the more senior years of life, can independently deleteriously affect the preservation of optimal motor adaptability.

As people age, they engage in stereotyped motor behavior between tasks more so than younger adults (27–29), despite more within-task variability in older adults (see Ref. 30, for a review). Between-task similarity is reflected in the cocontraction of agonist and antagonist muscles (31–33) (i.e., agonist individuation loss), dedifferentiation in representational activity patterns (34–36), and digit force scaling (37–39). Although older individuals show some evidence of anticipatory force control in object manipulation (e.g., see Ref. 30, for a review), force scaling profiles in manipulating objects with different textures are more similar (i.e., stereotyped) in older than younger adults (37, 38). Similarly, age-related motor adaptation difficulties likely stem from rigid stereotyped motor patterns that hinder flexible adjustments to changing task demands (29, 40). In our study, an increase in trial repetition resulted in older adults reverting to default collinear stereotyped strategies in both digit position and lift force partitioning. Higher grip force strategies in older than younger participants might limit the need for variation in partitioning digit position and force. The manipulation of lift repetition had a byproduct of reinforcing stereotyped motor digit position and lift force strategies that were particularly evident in the older group.

In conclusion, we manipulated repetition to investigate its effects on motor flexibility in both young and older adults using an object manipulation task that emphasized sensorimotor memory over sensory feedback. We found deleterious effects of repetition on motor flexibility in learning to generalize anticipatory force control policies that are CoM-independent. These results suggest that motor control errors due to motor inflexibility can arise from repetitive stereotyped planning and execution of motor behavior. Stereotyped behavior might overgeneralize internal models that are resistant to change, hindering adaptability and contributing to deficits in responding to dynamic changes in the environment.

DATA AVAILABILITY

Data will be made available upon reasonable request.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

M.R.H-V. and M.M. conceived and designed research; C.A.S., E.D., and M.R.H-V. performed experiments; C.A.S. and M.M. analyzed data; C.A.S. and M.M. interpreted results of experiments; C.A.S. and M.M. prepared figures; C.A.S. and M.M. drafted manuscript; C.A.S., M.R.H-V. and M.M. edited and revised manuscript; C.A.S., E.D., M.R.H-V. and M.M. approved final version of manuscript.

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