EFFECTS OF PAST AND FUTURE MOTOR EVENTS ON PRESENT MOTOR STABILITY, AND RELATIONSHIPS WITH MOTOR AND COGNITIVE FLEXIBILITY

by

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ABSTRACT

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Stability of motor performance is important for voluntary movement control, but it should not be maximized to the exclusion of all else. To transition to a new task, the current task must be destabilized. When expecting to switch tasks, people are known to reduce their stability prior to initiating the change. Here, we determine if the observed stability modulation is influenced by the expectation of future movement, is a relic of the movements performed in the recent past or is a consequence of both those processes. Furthermore, this work explores the relation between stability modulation observed in isometric finger force production tasks to cognitive flexibility and clinical measures of manual dexterity. Stability modulation can be viewed as a motor response to the recognition of altered environmental demands or internally generated desires to change body movements or postures. Therefore, it is hypothesized that cognitive flexibility – the efficacy of cognitive processing – will relate to stability modulation. Finally, it is hypothesized that the motor adjustments in response to changing task/environment demands will correlate with clinical tests of manual dexterity that involve placing pegs into holes.

Twenty-two young-adult participants (age 21.05 ± 0.44 years) completed tasks in the three domains. The Grooved Pegboard and NIH 9-Hole tests of manual dexterity measured their manual function by time to complete the tests. Cognitive flexibility was measured by a task-switching task which required adjusting to a changing set of rules, and the reaction time and accuracy costs of

task-switching were recorded. Lastly, participants' stability of performance in an isometric finger-pressing task was assessed using the uncontrolled manifold analysis and root-mean-square error (RMSE) in the performance. Participants produced pressing forces with four fingers to match a single total force targets presented as feedback on a computer screen. In the 'Steady' task, target remained motionless. In the 'Future Effects' task, the target remained motionless for several seconds and then began moving. The 'Past Effects' task comprised of a dynamic initial portion followed by a stationary target. Lastly, the 'Combined' task had a constant force section flanked on either side by epochs of target movement.

The RMSE results confirmed the existence of stability modulation and established that this is driven by the expectation of future movement, and not by the history of previous movements. The Steady and Past Effects tasks exhibited higher stability than the Future Effects and Combined tasks. The stability estimates obtained from the uncontrolled manifold analysis showed similar trends. Cognitive flexibility (quantified as global accuracy cost) correlated with stability modulation indicating that individuals who show greater cognitive flexibility tend to demonstrate greater stability modulation. However, an association between stability modulation and clinical pegboard tests of manual function were not observed. This may possibly be due to the homogeneity of the test sample, or because the finger-force-production task and pegboard task measure disparate aspects of manual function.

INTRODUCTION

Stability of motor action, defined as the skill to resist external disturbances to the motor state (Hasan, 2005), has been widely studied (Bernstein, 1996). A stable system effectively resists gravitational perturbations to achieve a particular posture or movement pattern (Klous, Mikulic, & Latash, 2011; Krishnan, Aruin, & Latash, 2011) as well as the effects of external disturbances such as a contact force moving the body from its intended configuration (Gorniak, Feldman, & Latash, 2009; D. J. S. Mattos, Latash, Park, Kuhl, & Scholz, 2011). In healthy individuals, stability has been studied in movements such as hammering (Bernstein, 1996), reaching (Freitas & Scholz, 2009; D. Mattos, Kuhl, Scholz, & Latash, 2013), gait (Dingwell, John, & Cusumano, 2010; Menz, Lord, & Fitzpatrick, 2003), and multifinger pressing tasks (Ambike, Mattos, Zatsiorsky, & Latash, 2016; Cuadra, Bartsch, Tiemann, Reschechtko, & Latash, 2018; John P. Scholz, Kang, Patterson, & Latash, 2003; Shapkova, Shapkova, Goodman, Zatsiorsky, & Latash, 2008), etc.

Diminished skill to maintain stability can lead to falls across the lifespan (Hartholt et al., 2011; Iglesias, Manca, & Torgerson, 2009; Yozbatıran, Baskurt, Baskurt, Ozakbas, & Idiman, 2006), which can cause injury, and limit mobility. In manual function, impaired stability results in larger forces necessary to handle objects (Cole, 1991). Impaired stability leads to a loss in the quality of life, and recently, Latash & Huang (2015) proposed that impaired control of movement stability should be used as a clinical indicator of movement disorders.

In motor behavior research, perhaps due to the risks associated with stability loss, maximizing stability is commonly seen as the primary goal of the motor system (Hasan, 2005). However, in some cases, maximizing stability may hinder successful task performance (Hasan, 2005; Riley & Turvey, 2002; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). Stability requirements are task specific, and in the context of switching between motor tasks, a system must destabilize current performance to accomplish the transition (Shim, Olafsdottir, Zatsiorsky, & Latash, 2005). The process of modulating stability to accomplish a transition requires preparatory time for the central nervous system (CNS) to adjust its priorities (Herrmann, Pauen, Min, Busch, & Rieger, 2007). There are two motor components to this preparation. The first, Anticipatory Postural Adjustment (APA), is a change in the body's mean configuration in response to an imminent self-initiated movement. This allows the person to better accomplish the intentional upcoming movement, or better resist an expected external perturbation (Krishnan et al., 2011; Piscitelli, Falaki, Solnik, & Latash, 2017; Santos & Aruin, 2008). APA has been reported in arm flexion (Lee, Buchanan, & Rogers, 1987), vertical posture maintenance during perturbations (Klous et al., 2011; Piscitelli et al., 2017; Santos & Aruin, 2008), squat posture maintenance (Krishnan et al., 2011), and gait initiation (Colné, Frelut, Pérès, & Thoumie, 2008; Lepers & Brenière, 1995). The second type, called Anticipatory Synergy (or Stability) Adjustment (ASA), is the drop in the stability of the current behavior before transitioning to a new one. In this type of preparation, the variability in the posture changes without change in the mean configuration (Cuadra et al., 2018; Kim, Shim, Zatsiorsky, & Latash, 2006; Latash & Huang, 2015; Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2007; Shim et al., 2005; Wu, Matsubara, & Gordon, 2015; Zhou et al., 2013). ASA has been documented in vertical posture maintenance (Klous, Danna-dos-Santos, & Latash, 2010; Klous et al., 2011; Piscitelli et al., 2017) and isometric multifinger pressing tasks (Arpinar-Avsar, Park, Zatsiorsky, & Latash, 2013; Cuadra et al., 2018; Olafsdottir, Yoshida, Zatsiorsky, & Latash, 2005; Shim et al., 2005; Togo & Imamizu, 2016; Zhou et al., 2013). ASA typically begins up to 300ms before a self-initiated state transition (Latash & Huang, 2015; Togo & Imamizu, 2016), and they are observed before APA (Klous et al., 2011). ASA constitutes empirical evidence supporting the notion that maximizing stability of the current task is not always the goal of the motor control system.

In daily living, motor task changes may be performed under various conditions. One may initiate a task change with a-priori knowledge of the timing and the nature of the change (e.g., getting up from a chair). The stability of the previous behavior (sitting) would be diminished before the transition to the next behavior (getting up) begins, and this reduction would be an ASA. ASAs have been observed in self-initiated tasks (Getchell & Whitall, 2004; Kim et al., 2006; Olafsdottir, Kim, Zatsiorsky, & Latash, 2008; Shim, Park, Zatsiorsky, & Latash, 2006). Other contexts may require more dexterous transitions because of uncertainty in some aspect of the upcoming movements. For example, the performer may not know the nature of the upcoming task (task uncertainty) or when the next task will occur (temporal uncertainty) (Bernstein, 1996). ASA for uncertain tasks have been examined in the context of reaching (de Freitas, Scholz, & Stehman, 2007; Freitas & Scholz, 2009; Horak, Esselman, Anderson, & Lynch, 1984) whereas ASA in temporally uncertain tasks have been studied in isometric four finger pressing, (Kim et al., 2006; Olafsdottir et al., 2005) and vertical posture maintenance (Yamagata, Falaki, & Latash, 2018). In particular, prior to a dexterous transition in temporally uncertain conditions, such as in reaction time tasks, ASA is vanishingly small (Kim et al., 2006; Olafsdottir et al., 2005, 2007; Zhou et al., 2013).

A common feature of the previous work mentioned above is that participants always expected to perform a movement transition. ASAs are observed if certain type of information about the transition is available to the participant prior to the transition. However, previous work has not examined if the mere expectation of motor transition led to a reduction in the stability of the current behavior, independent of the uncertainty involved in that transition. My previous work made the novel comparison of the stability of performance with and without any expectation of an upcoming transition. Using isometric finger pressing as a model system, I documented a previously undescribed form of ASA (Tillman & Ambike, 2018a, 2018b) that occurs solely in response to anticipation of state change. This phenomenon was termed “Stage-1 ASA”, and is distinct from the “Stage-2 ASA” that had been described in the literature previously (Olafsdottir et al., 2008; Olafsdottir et al., 2005; Shim et al., 2005). The new observation was termed “Stage-1” because the expectation to transition must occur prior to the actual transition. In this study, the stability of finger pressing performance was assessed when the sum of the four finger forces was used to track a target on a computer screen in two conditions. In the ‘Steady’ condition, there was no expectation of movement (Fig. 1A). In the ‘Tracking’ condition, rapid movement was expected at an unknown time and in an unknown direction (Fig. 1B). Thus, across conditions, the participant produced the same constant total force (identical current motor state), but the expectation of upcoming motor tasks was different. We observed that participants reduced their stability from the Steady to the Tracking condition (Tillman & Ambike, 2018b), which indicated that the anticipation of upcoming action led to a controlled lowering of the stability of the current state.

However, there is a potential confounding factor that casts doubt on this interpretation of the result. The Tracking condition in this study contained a variable target tracking portion preceding the constant force portion that was used for the stability analysis, evident in Figure 1B. Therefore, the analyzed data was preceded by a history of variable behavior. In contrast, the behavior history preceding the analyzed part of the data in the Steady task was more consistent (Fig. 1A). These dissimilar histories may have influenced the stability reduction that we observed between the two tasks, since movement history is known to affect current movement performance (Kostyukov, 1998). Therefore, my goal is to parse the effects of movement history and expectation of future movement on the stability of finger force production. This will be accomplished with a finger pressing task with four conditions: two that replicate the previous tasks (Tillman & Ambike, 2018a), and two that isolate the effects of prior events and future events. In first new condition, the target will first stay stationary, and then start moving, thereby controlling the history, or the prior events leading up to the expectation of upcoming motion. In the other novel task, the target will first move, and then become stationary, thereby generating variable prior events before transitioning into a phase where no further motion is expected. I hypothesize that stability will be largest for the 'Steady' and smallest for the 'Tracking' tasks. In the two novel tasks, I predict that stability will be lower due to the effects of future events than of prior events.

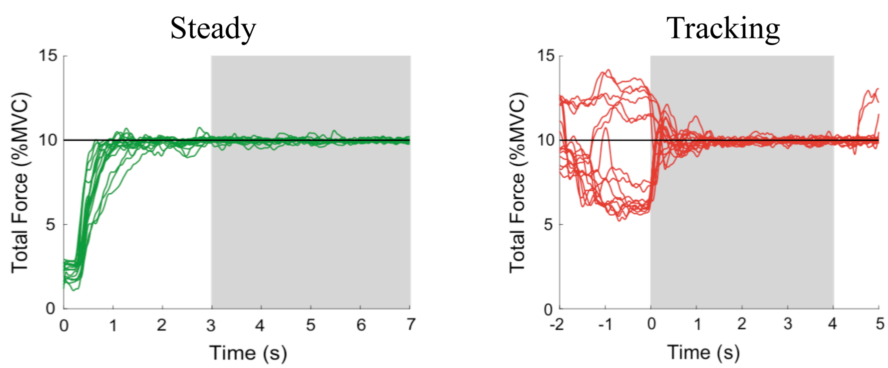


Figure 1. Representative total finger force time series of multiple force tracking trials by one subject in (A) the entire duration of the Steady task and (B) the time-aligned period around the analysis window in the Tracking condition.

Clinical assessment of manual function is commonly done with pegboard tests in which participants are timed on how quickly they can place pegs into similarly shaped holes. These tests provide a quick and reliable measurement (Gallus & Mathiowetz, 2003; Hardin, 2002; Mathiowetz, Weber, Kashman, & Volland, 1985; Wang, Bohannon, Kapellusch, Garg, & Gershon, 2015). However, they provide only time to completion scores that indicate any change in dexterity but offer no insight into the mechanisms for the observed change. There have been several previous efforts to identify physiological factors within the manual domain that influence pegboard scores (Almuklass, Price, Gould, & Enoka, 2016; Hamilton, Mazzo, Petrigna, Ahmed, & Enoka, 2019; Marmon, Gould, & Enoka, 2011; Marmon, Pascoe, Schwartz, & Enoka, 2011). They found that force steadiness with any of several effectors – index finger abduction, index and thumb finger precision pinch – significantly predicts pegboard times. However, not all of the variance in pegboard times is explained by these studies.

Therefore, the second goal of this study is to explore if *stability modulation* (i.e., change in the stability of behavior in response to context) in finger force production tasks can explain pegboard performance. (Note that ASA is stability modulation. However, stability modulation is a more general term that implies both increase and decrease in stability in response to the context of the behavior. The terms ASA and stability modulation will be used interchangeably in the remainder of this thesis.) If a relationship is found, it would indicate that control of stability is a significant predictor of clinical measures of manual dexterity, and this would be one step in explaining the mechanisms underlying manual dexterity.

Lastly, previous work has shown that cognitive skill or concurrent demands alters performance of motor tasks. For example, changing working memory load modifies finger forces exerted on an object during a grasp-and-lift movement, likely to reduce attentional resources necessary to maintain performance (Guillery, Mouraux, Thonnard, & Legrain, 2017). Also, higher cognitive flexibility is associated with slower hand speed while approaching the pins in a pegboard tasks, which suggests recognition of the dexterity requirement of the task as well as appropriate motor planning and execution to meet the challenge (Rodríguez-Aranda, Mittner, & Vasylenko, 2016). This suggests that the performance in manual tasks will correlate with cognitive function. Cognitive function is described with a set of executive functions which are higher-order mental abilities not regulated by automatic or instinctual processes. This set is comprised of three core categories: working memory, cognitive flexibility, and self-control (Diamond, 2013). All components of executive function likely impact manual function. However, I aim to associate one aspect of executive function – cognitive flexibility – with stability modulation in finger force tasks. Cognitive flexibility is operationalized as the efficacy with which an individual can recognize changes in response-selection rules in typical reaction time tasks, where the responses are button presses on a computer keyboard. Stability modulation can be conceived as the degree to which an individual changes their motor plan in response to a change in the demands of a finger force production task. Therefore, I hypothesize that cognitive flexibility will correlate positively with stability modulation.

To summarize, in this work, participants perform pegboard tasks, cognitive task-switching tasks, and isometric finger force-production tasks. The pegboard task provides a measure of manual function that is considered relevant to daily living (i.e., it is functional). The cognitive task provides a measure of cognitive flexibility. The finger force-production task provides a measure of stability modulation. These measurements allow the comparison of stability modulation to cognitive function and manual function. This investigation is depicted in Figure 2. I hypothesize that cognitive flexibility will correlate with stability modulation, which, in turn, will correlate with functional manual behavior.

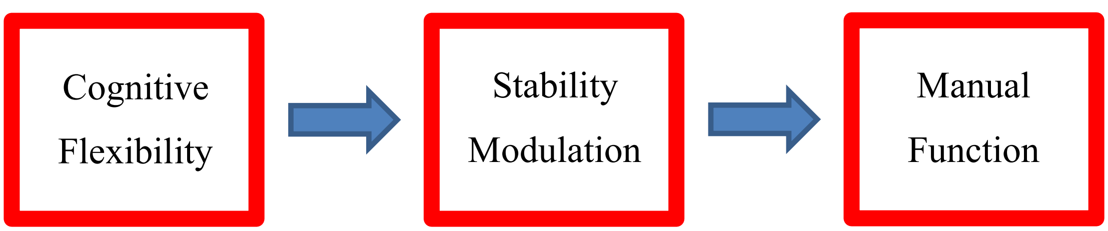


Figure 2. A person's level of cognitive flexibility will influence stability modulation capabilities, and stability modulation skill will influence manual function.

METHODS

Participants

Twenty-two young participants (age 21.05 ± 0.44 years; 12 female) were recruited from the student population on the Purdue University campus. I administered a pre-screen questionnaire via email to potential participants to determine their eligibility. I asked their age, handedness, history of musculoskeletal disorders, and recent injury and pain in the dominant hand and arm. A potential participant was deemed eligible if their age was between 18 to 30 years, had no history of musculoskeletal disorders, and had no recent pain in the dominant upper limb. Participants that met these inclusion criteria were then scheduled for a data collection session. All participants had normal or corrected to normal vision.

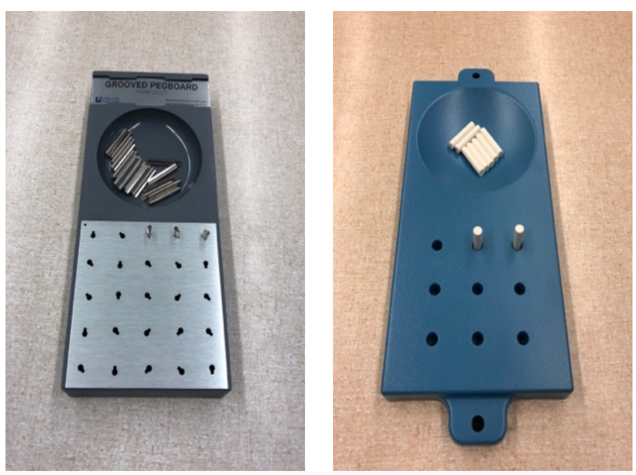
Procedure

The data collection began with obtaining Purdue University IRB-approved informed consent from the pre-screened participant. They were asked their age, gender, height, weight, handedness, history of musculoskeletal disorders, recent injury/pain in dominant limb or arm, and use of visual assistive devices (glasses or contacts), and their responses were recorded. Each person completed one data collection session that lasted approximately two hours. The session consisted of tests of manual function (pegboard tests), a cognitive screen, a cognitive flexibility assessment, and a finger pressing task. Some participants did not complete all components of the study; this is noted in the appropriate subsections in the Results.

Pegboard Tests

First, participants completed the Grooved Pegboard Test (Lafayette Instruments, Lafayette, IN, USA) and 9-Hole Peg Tests (Jamar Technologies, Hatfield, PA, USA) of manual dexterity with the dominant hand. These are validated, clinical assessments of manual dexterity (Bryden & Roy, 2005; Wang et al., 2015) that use time taken to place all pegs, one at a time, with one hand into the holes on the board as a measure of dexterous manual function. The 9-Hole Peg Test is NIH-recommended, while the Grooved Pegboard test is recommended as a supplemental measure (Wang et al., 2011). They differ from one another in that the Grooved Pegboard Test has grooves on the side of each of the 25 pegs that correspond to grooves in the peg slots in the board facing in varying directions, which forces adherence to directionality of peg placement (Fig. 3A). The 9-Hole Peg Test has nine smooth pegs and the pegs must be replaced one at a time in the starting container to end the test (Fig. 3B). Differences across participants in the time taken to complete each task are interpreted as evidence of varying degrees of manual dexterous skill.

A



B

Figure 3. (A) The Grooved Pegboard apparatus. (B) The 9-Hole Peg Test apparatus.

Cognitive Assessment

Next, participants completed a cognitive task-switching task using the E-Prime software (Psychology Software Tools, Sharpsburg, PA). This task was used to quantify the participants' cognitive flexibility. They used their left and right index fingers to complete tasks that require them to press a left key ('C') and right key ('M') on a standard computer keyboard (Dell Windows 10 Latitude 5490 Intel® Core™ iS-8250U) with index fingers of the left and right hands, respectively, in response to visual stimuli presented on a computer screen. Participants were shown either a solid-outlined or dashed-lined box with a number (1-4 or 6-9, but never 5) displayed inside. If the box outline was solid (Fig. 4A), then the correct button press was dictated by whether the number is smaller or larger than 5 (left for less than, right for greater than). If the box was dashed (Fig. 4B), then the correct response was the left button for odd numbers, and the right for even numbers.

A

B

Figure 4. The cognitive task-switching task. Visual feedback showing the entire display area. Boxes are either (A) solid or (B) dashed, with a number 1-9 (except 5) inside it. The box and number appear and disappear together.

The participant performed three different tasks, each consisting of multiple trials. The first two tasks are homogeneous with respect to box type (all trials of the task displayed either the solid or the dashed box type), although the numbers change randomly with every trial. The last task is heterogeneous, in that each successive trial can have a different box type. Thus, the participant has to first decide which rule to abide by for the current trial based on the box type, and then which key to press, based on the number shown. The reaction time (time between the presentation of the visual stimulus and the button press) and accuracy of responses are recorded.

Finger Force Tasks

For the finger-force production tasks, participants sat at a desk and tracked a square target on a computer screen. They produced a total force (FT) by pressing with the four fingers placed on four force sensors on the desk in front of them (FT=ΣFi, i=1 to 4). The total force was shown as an 'X' cursor on screen (Fig. 5B). The force sensors used are four 17-mm diameter, six-axis force transducers (Fig. 5A) (Nano 17; ATI Industrial Automation, Garner, NC), spaced medio-laterally at a fixed 30-mm center-to-center distance. The anterior-posterior configuration of the sensors was adjusted such that each fingertip was comfortably placed on the center of one force sensor, and then the sensor positions were fixed for the remainder of the study. The force signals were sampled at 1000 Hz. Each participant performed the following force production tasks.

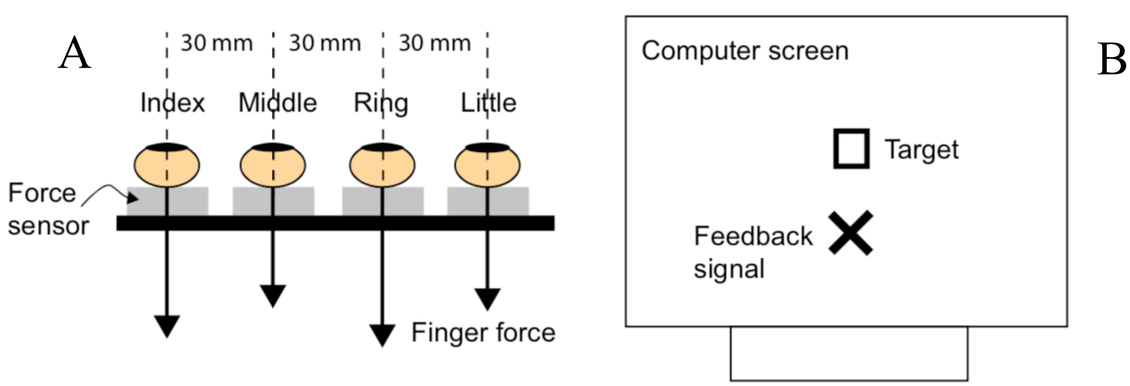


Figure 5. The finger force test apparatus. Subjects (A) use their fingers to press vertically on four force sensors to (B) control a target on a computer screen.

Maximal Voluntary Contraction Task

Participants produced one sustained maximal finger pressing effort for seven seconds, and the maximum total force produced during each trial was recorded. If improper form was observed during the trial or at least near-maximal effort was not given, the trial was repeated. Proper form means that the person maintained a static position throughout the trial. The average of three ‘good’ trials’ maximum force values – with one-minute rests provided between all trials – was recorded as the maximal voluntary contraction (MVC). This value is used to scale the rest of the trials such that all participants produce the same forces in %MVC units.

The tasks that follow were configured so that all target forces were between 5% and 15% of the participant’s MVC.

Steady Task

For this task, participants were required to track a stationary target at 10% MVC for eight seconds. They were informed that the target would not move throughout the trial, and that they were to keep the cursor in the target as best as they could. Twenty trials were administered, and only the last 15 were analyzed – the first five were considered practice. Data from one representative trial for this task is shown in Figure 6, in which the participant begins the trial not producing force, and then quickly converges to the target force value and maintains that force.

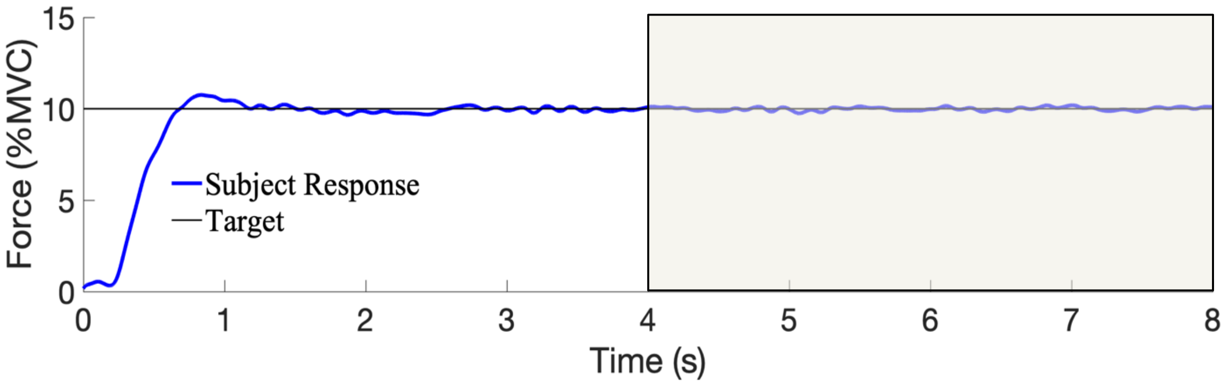


Figure 6. One representative trial of the Steady task. The box indicates the analysis window. The subject converges to the target force value and maintains this force until the end of the trial.

Future Effects Task

Twenty trials were administered in this task, with 15 second rest intervals between each trial. Participants were instructed to track the square target as it moved vertically in an unpredictable manner. They were informed that the target is color coded: a purple target does not move, and a yellow target can move vertically. Each trial was 15 seconds long and begins with the target in an extended stationary period. From the first four seconds of each trial the target was a purple color at 10% MVC, indicating that it would not move. From t=4 seconds until the end of the trial, the target was a yellow color indicating that movement was possible. The target began moving at some point between t=8 and 9 seconds into each analyzed trial – different for each target profile – and continued moving until the end of the trial. Four distinct profiles were composed for the analyzed trials. In the trials that were not analyzed – one profile repeated five times – the target began moving at t=5 seconds. This was done to prevent the participant from anticipating the occurrence of the transition from the stationary to the tracking component of the trials. The same

20 profiles – 15 analyzed and five not analyzed – were administered to all participants in a randomized order. The target trajectory and participant response from one representative analyzed trial and one representative trial that is not used for analysis are depicted in Figure 7A and 7B, respectively.

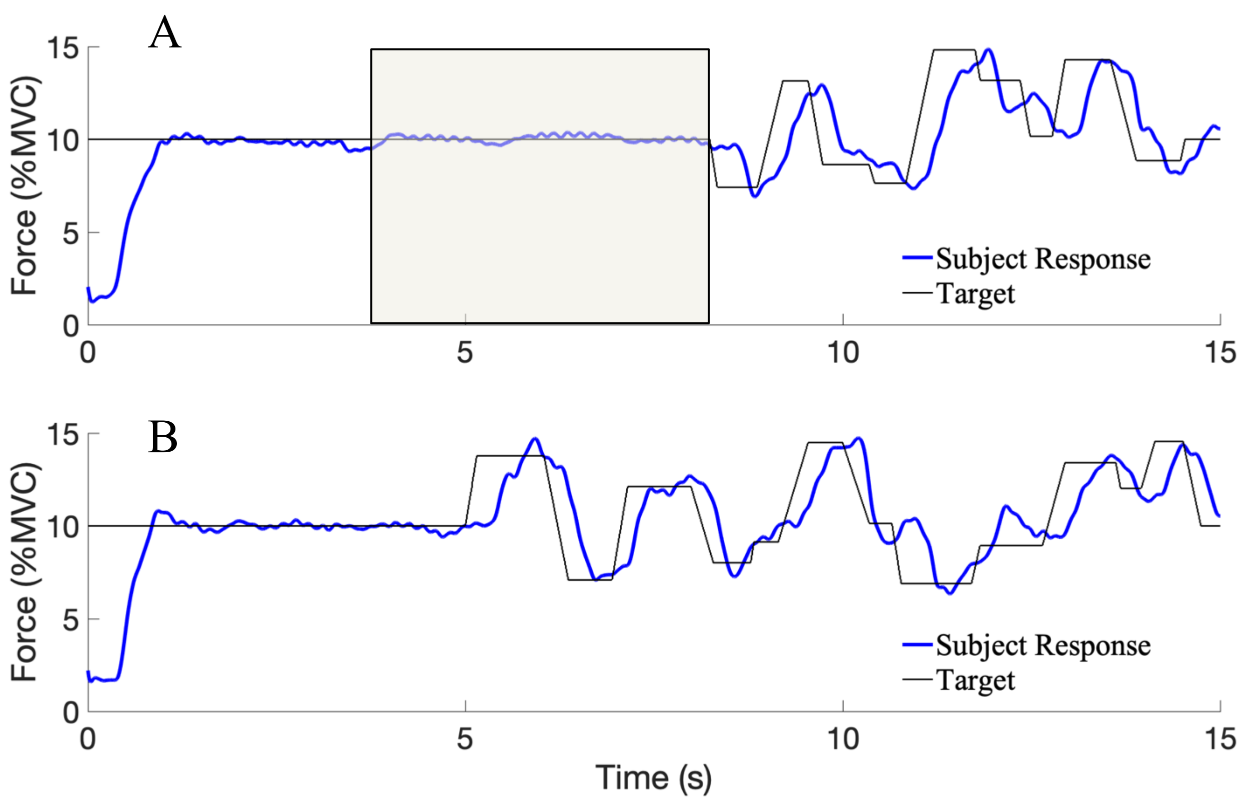


Figure 7. The Future Effects Task. (A) A representative trial used for analysis, with the analysis window shown as a box. (B) A representative trial which was not analyzed.

Past Effects Task

Twenty trials, each 15 seconds long, were administered in this task, with 15 second rest intervals between them. Similar to the 'Future Effects' task, there were 15 analyzed trials composed of four repeated profiles and one profile repeated five times that was not analyzed, to disguise the time of the occurrence of the transition between the moving-target and stationary target phases of the task. All participants performed the same 20 tasks in a random order. Each trial begins with the target as a yellow color, moving unpredictably in the vertical direction. Between t=8 and 9 seconds into each analyzed trial, the target stopped moving at the 10% MVC level and changed color to purple, indicating that it would not move for the remainder of the trial. For the trials that were not analyzed, the transition to purple and stationary occurred much later, at t=13 seconds. The participants were informed about the nature of the task. The target trajectory and participant response from one representative analyzed trial and one representative trial that is not used for analysis are depicted in Figures 8A and 8B, respectively.

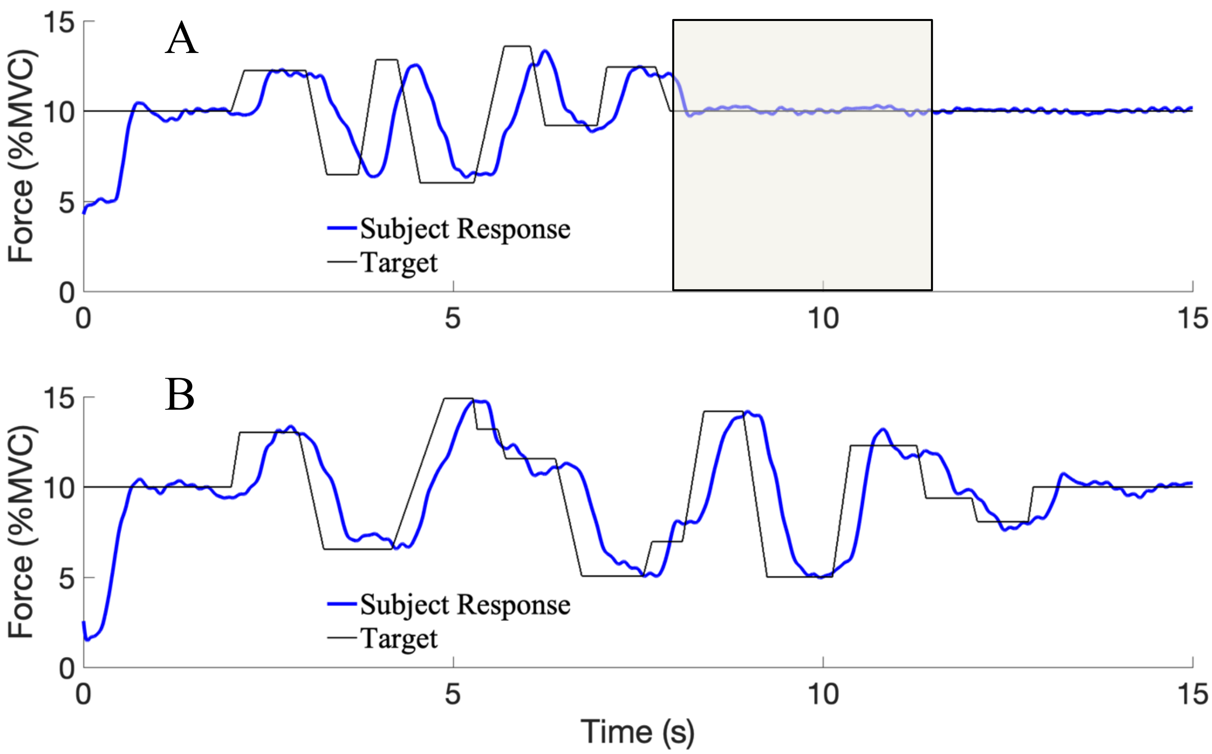


Figure 8. The Past Effects task. (A) A representative trial used in the analyses with the analysis window shown as a box. (B) A representative trial that was not analyzed.

Combined Task

Twenty trials, each 15 seconds long, were administered in this task, with 15 second rest intervals between them. Similar to the 'Past Effects' and 'Future Effects' tasks, there were 15 analyzed trials composed of four repeated profiles and one profile repeated five times that was not analyzed, to disguise the time of the occurrence of the transition to an extended flat period within each trial. Each participant performed the same 20 tasks in a random order. The target was yellow throughout the entire trial, indicating that it would move throughout the trial. The participant was instructed that the target would remain yellow and moving vertically throughout the entire trial, and that they were to track it with their total force. However, unknown to the participant, in the analyzed trials there was a period four to five seconds long, beginning between t=8 to 9 seconds, where the target remained stationary at 10% MVC (Fig. 9A). In the trials that were not analyzed, this extended stationary period did not occur (Fig. 9B). This was used to minimize anticipation of the extended stationary period. The same 20 profiles were administered, in a unique random order, for each participant. The target trajectory and participant response from one representative analyzed trial and one representative trial that is not used for analysis are depicted in Figures 9A and 9B, respectively.

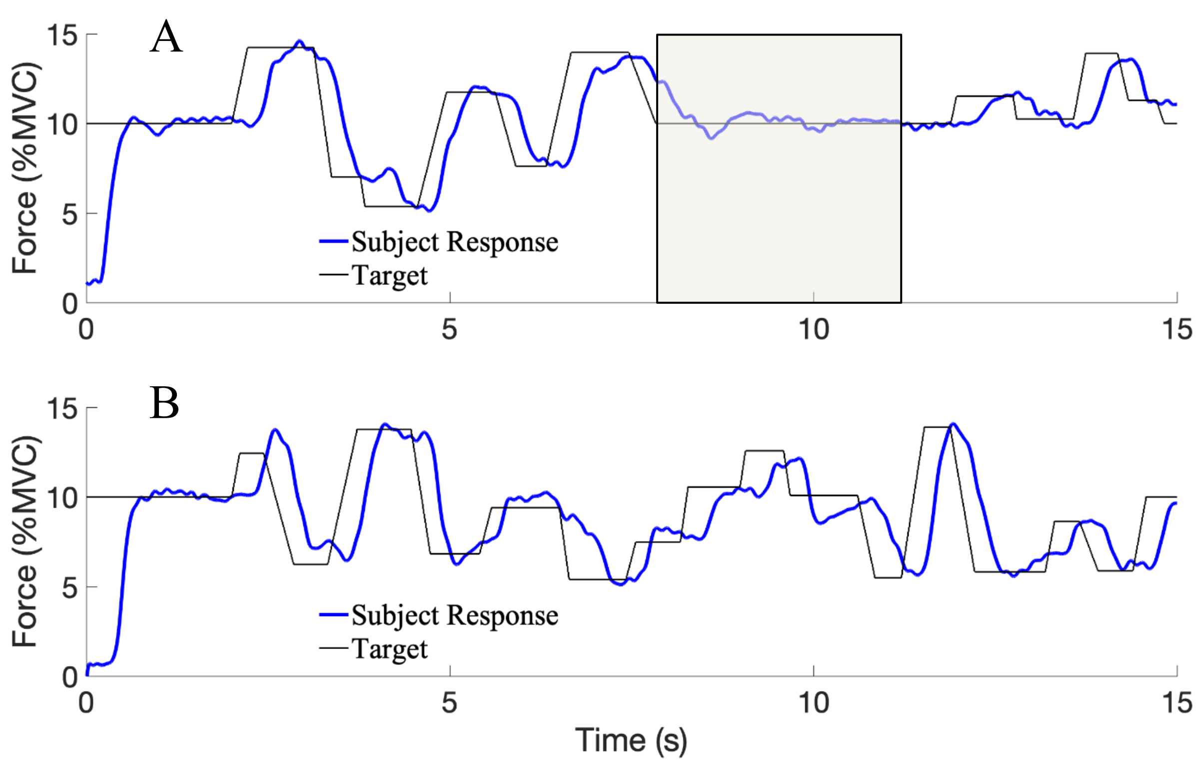


Figure 9. The Combined task. (A) A representative trial to be analyzed, with the analysis window shown as a box. (B) A representative trial that was not analyzed.

Finger Force Protocol

First, the sensors were calibrated to remove the weight of their fingers resting on the sensors. Next, the MVC task was administered to determine an MVC value for the participant. Next, the participant was given a block of eight practice trials that include all types of tracking tasks required in the study. Then the participant performed the Steady, Future Effects, Past Effects, and Combined tasks in a block randomized fashion, with the order of the 20 trials – 15 analyzed trials composed of four repeated profiles and one profile not analyzed repeated five times – randomized within each block.

Analyses

Pegboard Tests

Time taken to complete both pegboard tasks was recorded in seconds. Timing the Grooved Pegboard test begins when the experimenter speaks the word 'Begin' and ends when the participant successfully places the final peg. Timing the 9-Hole test begins when the participant first touches a peg and ends when the last peg is returned into the tray.

Cognitive Assessments

Cognitive flexibility was measured by the global and local cost in response time and accuracy. The global cost is the difference between the homogeneous and heterogeneous reaction time and accuracy values. The local cost is the difference between 'Switch' and 'Non-Switch' accuracy and reaction time within the heterogeneous task. 'Switch' trials are those in which the rule of the task changed compared to the preceding trial. For example, if trial number N displayed a solid box – indicating that the rule to follow is whether the number shown is larger or smaller than five – and the trial before it, trial number N-1, displayed a dashed box – such that the rule to observe is whether the number is odd or even – then trial N is a 'Switch' trial. The 'Non-Switch' trials are those in which trial N-1 follows the same rule as trial N. Because these are costs, the absolute value of the differences is taken. Greater cognitive flexibility would imply more efficient switching between the task types, and lower impact on performance accuracy and/or reaction time. Therefore, lower costs indicate greater cognitive flexibility.

Stability of Finger Force Production

We use two metrics to compute stability for the total force produced by the fingers. These metrics are described below.

Uncontrolled Manifold (UCM) Analysis

The first stability metric is based on the uncontrolled manifold (UCM) analysis (Scholz & Schöner, 1999). The UCM analysis is a method of partitioning the variance in the input variables – the four finger forces – into variance that affects (bad variance orthogonal to the UCM, Vort) and does not affect performance or output (good variance along the UCM, Vucm) – total force in this case. The relative amount of good variance normalized by the total variance in the inputs yields a metric (DV), which represents the stability of performance (see Appendix for computational details). This metric is Fisher-Z transformed for statistical analysis, and the transformed metric (DVz) is used as an index of stability. Higher DVz indicates higher stabilization of the total force.

To compute DVz, the trials within each task are first time-aligned such that t=0 always represents the first instant of the extended constant force period of interest (Fig. 6, 7A, 8A, 9A). The analysis is performed separately at each point in time, across all repetitions of one task. Because there are 15 trials and four input finger forces, the input for the analysis is a 15 × 4 matrix of finger forces, and the output is the z-transformed stability metric DVz. Because the time series are 4,000 points long (4-s of data sampled at 1000 Hz) this analysis yields a time series DVz(t) that is also four seconds long.

The differences between the Future Effects, Past Effects, and Combined task values and Steady task values of DVz was also computed [$d(DVz) = DVz_{Steady} - DVz_{Task}$]. A positive value of d(DVz) indicates a reduction in stability compared to the Steady task. This difference between the Steady and other task's stability values represents stability modulation.

RMSE

The second stability analysis method focuses only on performance. Root Mean Square Error (RMSE) is a within-trial computation that measures how closely the force target and total force time series match each other. Note that in contrast to DVz, lower RMSE indicates higher stability of the total force. Furthermore, DVz is computed from data across trials, whereas RMSE is computed using data within individual trials that is then averaged across trials.

Similar to the method for the UCM analysis, the trials are time aligned such that t=0.001 represents the first instant of the extended constant force period to analyze (Fig. 6, 7A, 8A, 9A). The RMSE between the target force and the total force generated by the participant is computed over a 4-second window for each trial in %MVC units. Because each task was repeated 15 times, this yields 15 RMSE values for each task. These values were averaged across trials to obtain the RMSE value for the given task.

The differences between the Future Effects, Past Effects, and Combined task values and Steady task values of RMSE was also computed ($d(RMSE) = RMSE_{Steady} - RMSE_{Task}$). Therefore, a positive value indicates a reduction in RMSE and an increase in the stability compared to the

Steady task. This difference between the Steady and other task's values represents stability modulation from a steady state value.

Note that opposite trends in d(DVz) and d(RMSE) are associated with a similar change in stability across task. For example, if a Task has higher stability compared to the Steady task, then d(DVz) will be positive but d(RMSE) will be negative.

Statistics

All values are reported as the mean ± standard error unless reported otherwise. The last one second of the DVz(t) time series for each task is averaged, yielding one DVz value per task per participant. Similarly, there is one RMSE value per task per participant. These two metrics were then subjected to separate one-way repeated measures ANOVA's with factor *Task* (4 levels). These ANOVA's test the null hypothesis that none of the four *Tasks* are significantly different from each other ($\alpha = 0.05$). If a main effect is found, then all pairwise comparisons will be examined with Tukey-Kramer adjustments.

To quantify the relationship between stability modulation skill and clinical tests of manual function, regression will be performed by pooling data across participants, with the completion time of the two pegboard tests as the dependent variables and d(DVz) and d(RMSE) for each of the three tasks as the independent variables. Thus, a total of 12 regressions will be performed to explore this relationship (times for two pegboard tasks by six finger force task variables).

To explore the effects of cognitive flexibility on stability modulation, d(DVz) and d(RMSE) for each of the three tasks will be regressed against the global and local costs of both reaction time and accuracy. A total of 24 regressions will be performed with these variables (four cognitive flexibility variables by six finger force stability modulation variables).

RESULTS

Pegboard Times

Out of the 22 participants, 20 participants completed the pegboard tests. Completing the Grooved Pegboard test with the dominant hand took 62.15 ± 2.78 seconds. The 9-Hole test was completed with the dominant hand in 21.4 ± 2.48 seconds.

Cognitive Tests

Twenty-two participants completed the cognitive task-switching task. Accuracy for the homogeneous tasks was 0.962 ± 0.004 and reaction time was 492.26 ± 14.22 ms. Accuracy for the heterogeneous tasks was 0.871 ± 0.011 and reaction time was 795.39 ± 27.02 ms. Global cost for accuracy was 0.091 ± 0.011. The global cost for reaction time was 303.13 ± 19.30 ms. The local cost for accuracy was 0.066 ± 0.009. The local cost for reaction time was 99.60 ± 11.06 ms.

Stability of Total Finger Force

Twenty-two participants completed the finger pressing tasks. The Steady and Future Effects tasks both exhibit roughly constant values of DVz over the four seconds, while in the Past Effects and Combined tasks – coming off of dynamic movement periods – the stability values increased over the time period and then remained relatively invariant thereafter (Fig. 10). Recall that for statistical comparison of DVz across tasks, the time series are averaged over the one second depicted by the shaded window in Figure 10.

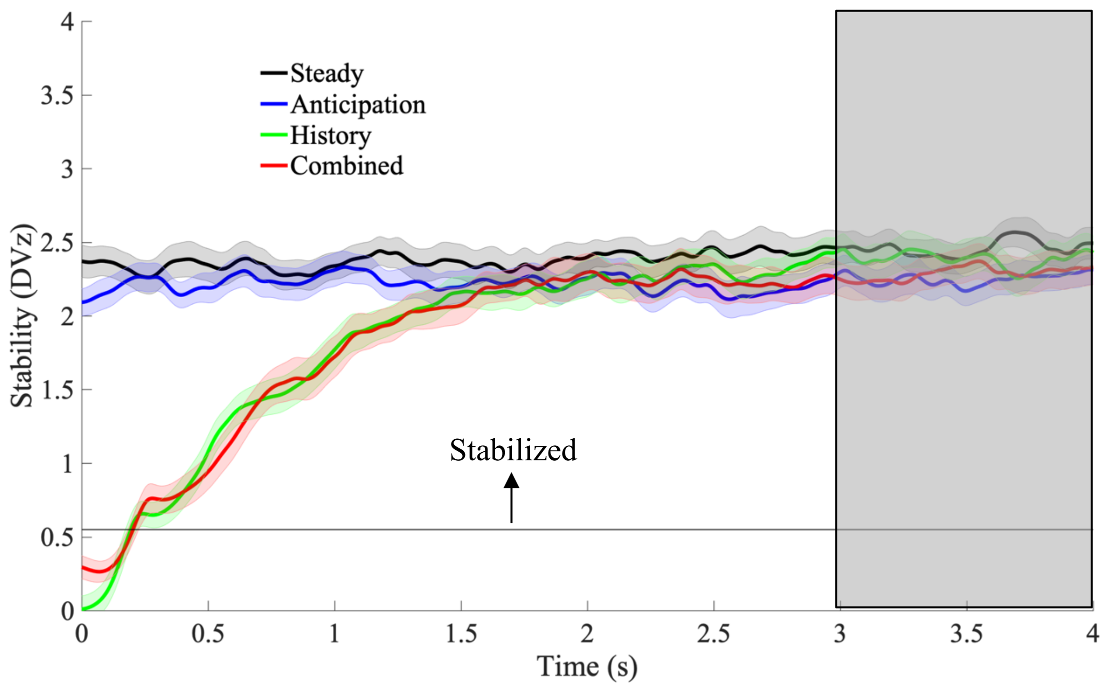


Figure 10. The across-subject mean ± SE time series of DVz for all four finger force task types. The black horizontal line represents the DVz value above which the behavior is said to be stabilized. The shaded region is the statistical analysis window. DVz greater than 0.5493 indicates that the finger forces covary to stabilize the total force.

Stability was lower in the Future Effects and Combined tasks compared to the Steady task due to the participants' expectation of upcoming state change. By contrast, no change in stability was observed in the Past Effects task compared to the Steady task. Thus, only the expectation of upcoming state transitions and not previous movement history affected the stability of the current behavior. This is supported by a main effect of *Task* for RMSE [$F(3,21)=14.02$; $p<0.0001$]. Pairwise comparisons revealed that the Steady and Past Effects RMSE were lower (higher stability) than the Future Effects and Combined tasks (Fig. 11). Changes in DVz also demonstrate a similar trend. However, the main effect of *Task* only approached statistical significance [F(3,21)= 2.26; p=0.112].

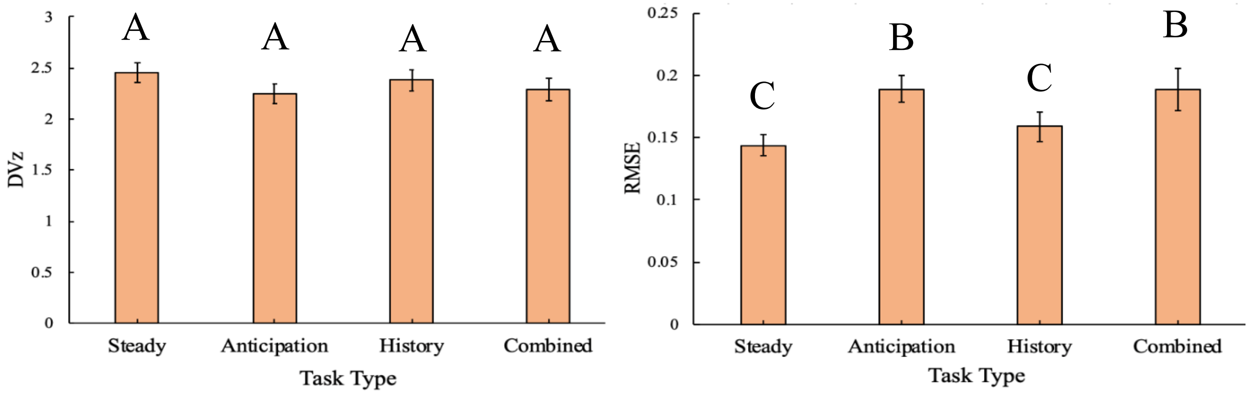


Figure 11. The across-subject mean ± SE values of DVz and RMSE for all finger pressing tasks. Letter labels represent the significantly different groups.

Relationship Between Stability Modulation and Manual Function

None of the six regressions between stability modulation measures and the pegboard completion times were significant (all $R^2 < 0.013$; $p > 0.3751$). Our sample was homogeneous in age. This may have resulted in a small range in the pegboard times. The six regressions were also conducted after standardizing these scores. However, this did not alter the regressions results.

Relationship Between Cognitive Flexibility and Stability Modulation

Of the 24 regressions between measures of cognitive flexibility and measures of stability modulation, only one showed a statistically significant relationship: d(DVz) for the Combined task correlated with the global accuracy cost ($R^2 = 0.253$; $p = 0.0171$) (Fig. 12). The relationship has a negative slope, meaning that as global accuracy cost increases, stability modulation skill – from the Steady to Combined task – decreases. Because higher switching costs represent poorer cognitive flexibility, this implies a positive relationship between stability modulation skill and cognitive flexibility. None of the other regressions yielded statistically significant relationships (all $R^2 < 0.083$; $p > 0.1932$).

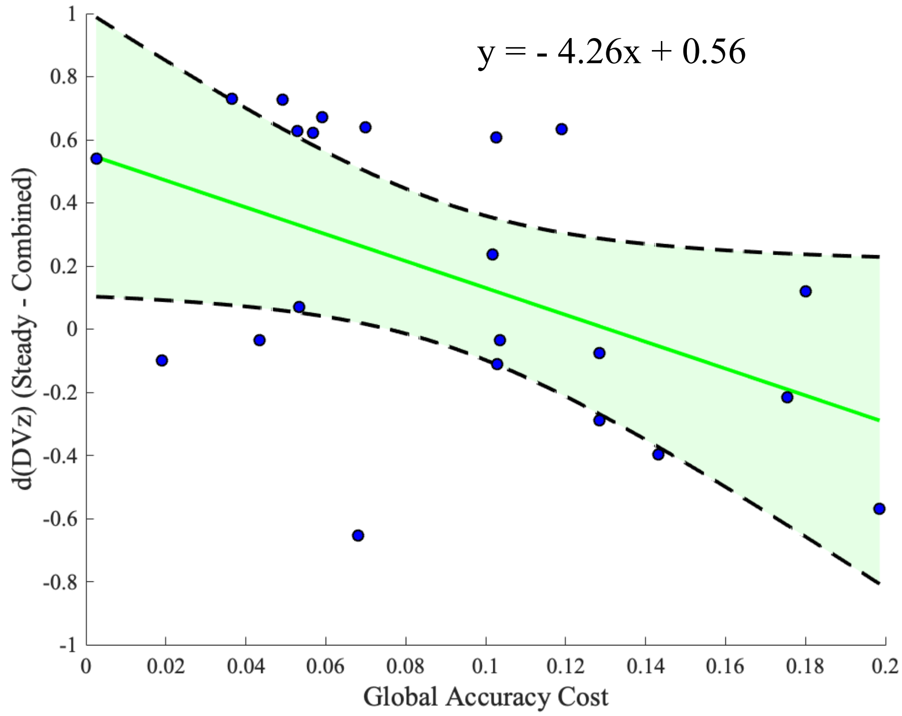


Figure 12. Scatter plot and regression line of global accuracy cost vs stability modulation. The green line is the line of best fit, and the green shaded region bordered by the black dashed lines is the 95% confidence interval.

DISCUSSION

The first hypothesis formulated in the introduction was that in the finger-force-production tasks, stability would systematically reduce due to the effects of anticipation and movement history. This hypothesis was partially supported; stability reduced in response to anticipation of future state change, but movement history did not induce a significant difference from Steady task stability values. Interestingly, the Combined task, containing movement anticipation and variable movement history, did not show greater stability modulation than that for the Future Effects and Past Effects tasks. Instead, the magnitude of stability modulation was similar for the Future Effects and the Combined tasks.

The second hypothesis was that stability modulation would correlate with pegboard tests of manual function. This hypothesis was not supported by the data. None of the regressions between stability modulation metrics and pegboard times were significant. Perhaps these tests measure independent areas of motor function.

The third hypothesis was that cognitive flexibility would predict stability modulation skill. This hypothesis was supported by one statistically significant regression. The stability modulation observed between the Steady and Combined tasks correlated with global accuracy cost. That is, individuals with lower global accuracy costs (i.e., greater cognitive flexibility) display greater stability modulation for the combined task.

Stability Modulation and Patterns in Variance Components of Input Finger Forces

The main result of this study is that stability of the current motor state in a finger force production task is influenced by the expectation of upcoming state changes, and not by the movement history. RMSE values across Tasks yielded statistically significant differences (p <

0.01) that support this interpretation. There is one caveat: although the changes in DVz across Tasks also matched this interpretation, this measure of stability did not reach significance ($p = 0.112$). My previous work employed a different experimental design but included similar 'Steady' and 'Combined' tasks. There, a significant reduction in DVz values was observed for the 'Combined' task relative to the 'Steady' task (Tillman & Ambike, 2018a, 2018b). This inconsistency in results of the two studies may be due to the difference in study protocols. Nevertheless, given the consistent trends in DVz in the present study, and significant differences in the RMSE metric, this work lends partial support to the findings of my previous work.

The uncontrolled manifold analysis uses a set of finger forces across multiple trials to compute the stability of performance. The stability metric DVz uses two orthogonal components of the variance in the input finger forces (see Appendix for details). The first component (Vucm) represents the covariation between the finger forces that does not affect the outcome, while the other component (Vort) is the variation between the fingers that does affect it. A reduction in the DVz value can occur due to (1) a decrease in Vucm, (2) an increase in Vort, or (3) disproportionate changes in both that decrease DVz. In my previous work, the reduction in DVz was driven by a 42% reduction in Vucm for young participants (Tillman & Ambike, 2018b). The present study recruited young participants of a similar age range, but Vucm did not show any changes across any task [$F(3,21)=1.05$; $p=0.3916$]. However, this inconsistency is consistent with previous inquiries into Vucm. For example, in my previous work, older participants performed the same study as the young adults, displayed a similar reduction in DVz for the 'Combined' task, but this change was driven by a 38% increase in Vucm (Tillman & Ambike, 2018b). Furthermore, in motor learning studies, stability of performance improves after training (higher DVz). However, this improvement is accompanied by unchanged or reduce amount of Vucm in different studies

(Latash, 2012). Similarly, individuals with Parkinson's disease consistently show reduced stability compared to control participants in a variety of behaviors, but the corresponding changes in Vucm are variable (Vaz, Pinto, Junior, Mattos, & Mitra, 2019).

The other variance component, Vort, is the across-trial variation in the input finger forces that changes the total force. Changes in Vort in my previous and current work are consistent. In particular, young individuals in my previous work tended to show an increase in Vort for the combined task, and older individuals showed a 267% increase in Vort for the combined task (Tillman & Ambike, 2018b). Here, a main effect of Task [$F(3,21)=11.29$; $p=0.0001$] was observed in Vort. Note that Vort is an across-trial analog of the variable RMSE, which is computed within each trial. Therefore, it is not surprising that across Tasks, Vort followed an identical pattern to that displayed by RMSE (Fig. 12). This correspondence between the two methods is further evidence that supports the stability modulation phenomenon as described earlier in this work.

Stability Modulation and Pegboard Tasks

Stability modulation and pegboard task performance did not relate to each other. This may be due to a ceiling effect in the pegboard times, as the age range of the cohort lies mostly in a narrow window (18 – 22 years). It is well known that in adult populations, pegboard times increase with age (Desrosiers, Hébert, Bravo, & Dutil, 1995; Marmon, Pascoe, et al., 2011; Wang et al., 2015) and that (Stage-2) ASA in isometric finger production tasks decreases with age (Olafsdottir et al., 2007). Although stability modulation during finger force production tasks is similar in the two age groups, the reduction is accomplished with greater finger force variability in the older adults and lower finger force variability in the younger adults (Tillman & Ambike, 2018b). Thus, it is clear that there are age-related changes in both types of tasks. It remains to be seen whether correlations between pegboard times and stability modulation will emerge when data is collected across the life span. However, it is also possible that stability modulation in isometric finger pressing and pegboard tasks measure independent dimensions of manual function. Therefore, it is also possible that no relation between these variables will emerge following a larger study.

Cognitive Flexibility and Stability Modulation

The degree of stability modulation for the ‘Combined’ task correlated with the global accuracy cost in the cognitive test. Recall that global accuracy cost arises from a greater number of incorrect responses during the heterogeneous trials compared to the homogeneous trials. The heterogeneous trials require the individual to select the appropriate rule set prior to selecting the appropriate response, and the increased rate of response errors is attributed to the additional cognitive operation required for the heterogeneous trials. This means that individuals who display lower global accuracy cost display greater cognitive flexibility. Therefore, individuals who display greater cognitive flexibility are likely to demonstrate greater stability modulation. This finding supports the relation between cognitive function and stability model as suggested in Figure 2.

However, other regressions were not significant. In particular, there was no association between stability modulation and global reaction time (RT) cost, or stability modulation and the local costs for accuracy or RT. The differential result for global accuracy and RT costs is interesting, and further analysis is required to understand why this is the case, and what interpretations follow.

One plausible explanation for why global costs correlated with stability modulation, and local costs did not, is the structure of the experimental protocols. Recall that, in contrast to the global costs, local costs are difference in RT and error rates between switch and non-switch trials that were administered within the same heterogeneous block. Therefore, the experimental structure utilized to compute stability modulation (across-block comparison of DVz) is consistent only with the experimental structure for the computation of global costs (across-block comparison of error rate), but not for that used for computing local costs. Furthermore, the nature of the behaviors in the corresponding blocks used to compute global costs and stability modulation is also similar. In one block (homogeneous for the cognitive task and 'Steady' for the finger forces), the rules of the game are fixed. The upcoming trial in the cognitive task has the same rules as the previous trial, and the finger force target will never move. In the other block (heterogeneous for the cognitive task and 'Combined' for the finger forces), the rule structure is altered. For the cognitive task, the rules for the upcoming task are uncertain, and for the force tasks, the target may start moving at any time. Thus, global cost and stability modulation correlate since they are obtained from similar experimental and computational protocols.

It is unclear why the global accuracy cost correlated with stability modulation in the 'Combined' task and not with the 'Future Effects' task. One explanation is the small sample size, or the amount of energy required to suitably perform the task. However, this is also a topic for future research.

Relations Between the Three Behavioral Domains

Recall from Figure 2 that we hypothesized that cognitive flexibility predicts stability modulation skill, and that stability modulation skill predicts pegboard task performance. The data did not support the second hypothesis: No relationship between stability modulation and pegboard performance was evident. There was some support for the first relationship, indicating that motor behavior is influenced by cognitive function. This finding is consistent with a body of work investigating multi-tasking behaviors, where a motor behavior is coupled with a simultaneous cognitive task. Typically, a decrement is observed in the performance of the cognitive task when engaging in motor behaviors (Ebersbach, Dimitrijevic, & Poewe, 1995; Kemper, Herman, &

Nartowicz, 2005; Kerr, Condon, & McDonald, 1985; Stegemöller et al., 2014; Teasdale, Bard, Larue, & Fleury, 1993). However, motor performance also suffers in such studies. Raffegeau, Haddad, Huber, & Rietdyk (2018) demonstrated that performance in both motor and cognitive tasks changes based on the difficulty of the tasks involved. Similar dependence and interference between the domains is seen in older adults. Seidler et al. (2010) states that due to system-wide neurophysiological and muscular changes, older adults rely on cognitive processes for motor control. Therefore, the dependence between cognitive and motor domains becomes evident when either or both behaviors are challenged. Note that while earlier reports document changes in the performance of the motor tasks, our findings suggest a novel hypothesis that a concurrent cognitive tasks will influence stability modulation, i.e., the preparation of the accompanying motor task.

The neurophysiological mechanisms behind ASA are not known. However, based on studies with neurological populations, Latash & Huang (2015) speculate cortical and sub-cortical involvement. Furthermore, peripheral mechanisms (spinal-feedback loops) likely play a part in stability and its modulation. We have proposed that the readiness potential (Brunia, Boxtel, & Böcker, 2011) and lateralized readiness potential (Smulders & Miller, 2011) relate to Stage-1 ASA (Tillman & Ambike, 2018a). The readiness potential (RP) is a slow wave across multiple centers in the brain in response to an expectation of upcoming action, including the primary motor cortex, primary somatosensory cortex, premotor cortex, and four mesial motor areas: supplementary motor area (SMA), pre-SMA, and rostral and caudal cingulate motor areas (Brunia et al., 2011). In manual tasks, the lateralized readiness potential (LRP) then occurs in the primary motor cortex contralateral to the side of the upcoming action (Smulders & Miller, 2011). The RP precedes the LRP, which begins after laterality information about the upcoming movement is available (Smulders & Miller, 2011). It is likely that the RP and LRP both relate to Stage-1 ASA – however, RP may be more closely related to Stage-1 ASA due to the fact that no information about the nature of the upcoming movement is needed to observe the RP, and they are observed under similar conditions (de Jong, Coles, Logan, & Gratton, 1990; Tillman & Ambike, 2018a).

Executive function, on the other hand, is mostly associated with the pre-frontal cortex (PFC) (Koechlin, Ody, & Kouneiher, 2003). However, the premotor areas (the premotor cortex and the SMA), apart from playing a key role in planning and coordinating motor actions, also play a role in cognition (Picard & Strick, 2001). These areas are integral for rule switching (Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006).

The overall idea is that preparation for upcoming action can be broken down into a cognitive and a motor component. The first process updates the rules of motor engagement and expectation of future movement, and the second process prepares the body to execute a movement. Our result suggests that efficiencies of these two processes are related. Based on the discussion above, we speculate that the pre-motor areas may be the substrate where the interaction between the cognitive and motor planning processes occur.

Limitations

The sample size used in this study may not have been sufficient to obtain significance in the regressions. Although the sample size here matches with typical cohort sizes in UCM-style analyses (Cuadra et al., 2018; Jo, Mattos, Lucassen, Huang, & Latash, 2017; Togo & Imamizu, 2016) and pegboard tasks (Marmon, Gould, et al., 2011; Olafsdottir et al., 2008), it is unclear what a proper sample size should be for the comparison between cognitive flexibility and stability modulation, since this is the first study of this kind. Rather, the results from this study will inform a power analysis for determining sample size in subsequent investigations.

The homogeneity of the participants is another limitation of this study. Participants were all recruited from the student population at Purdue University, and were of similar ages. A larger study with recruitment of participants with ages spanning the life span is required to establish relations between the cognitive, functional manual and stability domains.

Another limitation is that although we compare stability modulation with cognitive flexibility, these two phenomena were measured in different tasks. This limits the ability to interpret significant results.

Future Directions

Two of the three goals outlined in the Introduction were motivated by health considerations associated with aging. Therefore, moving forward, we plan to explore age-related changes within and between these domains. Although young adults' stability modulation reflected only anticipation and showed minimal associations to the other domains of this study, aging may change that. For example, healthy aging reduces hand force steadiness and grooved pegboard performance (Marmon, Pascoe, et al., 2011) and alters the structure of variance in ASA (Tillman & Ambike, 2018b).

Another direction of enquiry is the generalization of the notion of stability modulation, and Stage-1 ASA in particular across motor behaviors. So far, I have documented Stage-1 ASA in isometric finger pressing studies. Future work will aim to identify this phenomenon in grasping, upright posture and locomotor behaviors.

It is possible that even continuing to utilize multifinger pressing tasks could generate more sensitive results altered task designs. For example, switching to a between-participants design where every participant performs one or two of the finger force tasks would drastically reduce the current experiment’s long administration time, which may heighten participants’ interest in each task and therefore allow the tests to better reflect performance capacity.

CONCLUSION

In this study I documented Stage-1 anticipatory stability adjustment between a steady task and an anticipatory task involving isometric finger force production. I report evidence supporting a similar observation from my previous study, and further established that this adjustment occurs solely in response to anticipation of future state change, and movement history does not contribute. I also explored the relationships between stability modulation skill and the domains of clinical manual dexterity tests and cognitive flexibility. A person's level of cognitive flexibility, quantified using button-pressing accuracy in reaction-time tasks, correlated positively with their stability modulation. On the other hand, clinical manual dexterity tests and stability modulation did not relate to each other, either due to the homogeneity of the tested sample, or because stability modulation during finger pressing tasks and pegboard performance capture independent aspects of manual function. Overall, the results obtained provide a rationale for expanding the work, and identify associations between cognitive function, stability modulation and manual dexterity across the life span.

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APPENDIX

Uncontrolled Manifold (UCM) Analysis

UCM analysis is an across-trial analysis that quantifies the stability of motor behavior using the structure of variability in the motor system inputs (Scholz and Schoner, 1999). There are three prerequisites for employing this analysis: (1) A functional relation between the input variables and salient task-specific output variables must be available; (2) there must be more number of input variables than output variables, i.e., the system must be redundant; (3) measurements of the input variables during multiple performances of the same task must be available. In the present study, four input finger forces are related to one salient task variable (total force) by the constraint function

$$F_{Total} = \sum_{i=1}^{4} F_i$$

Therefore, the system is redundant. Participants performed 15 repetitions of each task, and therefore a 15 × 4 data set of the inputs is available to implement the UCM analysis.

First, the Jacobian of the constraint function above is obtained as: J = [1 1 1 1], which relates small changes in the input variables to changes in the output. The null space of the Jacobian is computed next. This subspace exists in the space of changes in input variables. Any vector of finger force changes that lies within the null space produces no change in the output. Therefore, this null space is the UCM, by definition. Conversely, any vector of changes that lies orthogonal to the null space (this subspace is called ORT) will change the output. In this case, the UCM is a three-dimensional (3D) manifold and the ORT is a 1D manifold in the 4D space of changes in finger forces. Note that the number of input variables defines the dimension of the space for the UCM analysis, the number of constraints on the inputs defines the dimension of the ORT subspace, and the dimension of the UCM is the difference between the dimension of the space and the dimension of ORT.

Once these subspaces are identified, changes in the input finger forces from their mean values are computed. The variance of the absolute distances from the origin to each of the 15 de-meaned data points is the total variance (V_{TOT}). The de-meaned force values are then projected onto the UCM and ORT subspaces. The variance of the projections onto the UCM (V_{UCM} = Vucm) and ORT (V_{ORT} = Vort) are calculated from these projections. The index of stability (DV) is calculated from these three variance values, after normalizing for the dimension of each space:

$$DV = \frac{\frac{V_{UCM}}{3} - \frac{V_{ORT}}{1}}{\frac{V_{TOT}}{4}}$$

A DV value greater than zero ($\frac{V_{UCM}}{3}$ and $\frac{V_{ORT}}{1}$ are of equal magnitude) indicates that the examined performance variable (i.e., total force) is stabilized. A value below zero is interpreted as the four finger forces being coordinated to change the total force. Note that DV is bounded between -4 (when $V_{UCM} = 0$) and 4/3 (when $V_{ORT} = 0$). Therefore, DV is Fisher Z-transformed to DVz for statistical analysis:

$$DV_z = 0.5 \times log\left[\frac{4 + DV}{\frac{4}{3} - DV}\right]$$

The stabilization threshold of DVz for this system of four finger forces is 0.5493.