STABILITY MODULATION IN FINGER-FORCE PRODUCTION TASKS

by

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ABSTRACT

Stability is the ability of a system to reject noise and maintain or return to the desired movement pattern and is an important feature of a motor system. In contrast, maneuverability is the ability of a system to transition between different motor states. A system that prioritizes stability inhibits its ability to transition between different motor states in a dexterous fashion. Since stability and maneuverability are opposing characteristics of a system, stability could be traded off to increase maneuverability. This study focuses on isometric finger force production, and its goals were to identify whether (1) the amount of information available about an upcoming motor transition influences the reduction in stability of total isometric force produced by the fingers, (2) stability reduction was correlated with greater maneuverability, i.e., less time for initiating a change in the total force, (3) the amount of stability reduction is correlated across tasks with different amount of information regarding the upcoming force changes, and (4) the times required to change force correlated across tasks with different informational content.

Twenty-nine young adults (17 women; age, 23.3 ± 4.3 years) participated in this study and completed three different finger force tasks. For each task, the participants modulated the total pressing force produced by the four fingers of their right hand to track a target presented on a computer screen. In each task, participants began by producing a consistent (10% of their maximum voluntary contraction, MVC) background force with their fingers. In the Steady task, the target remained stationary and participants knew the target would not move. In the Reaction Time (RT) task, the target moved randomly in the vertical direction and participants knew that this could happen at any point in time. In the Self-paced task, participants started producing a background force and then produced a quick increase in total force using a predefined target that was displayed at the beginning of the trial, and visible throughout the trial.

The uncontrolled manifold analysis was used to assess the stability of the total force during each task. This assessment was performed when the participants produced the same force (10% MVC), but expected different upcoming force changes, and had different amount of information about these upcoming force changes. This analysis yielded a stability index, and measures of the variance structure in the finger forces, computed across multiple repetitions. The reaction time and the movement time in the RT and the Self-paced tasks, respectively, was computed to quantify maneuverability.

In contrast to previous findings and our expectations, the stability index was not statistically different for the Steady, RT, and Self-paced tasks, meaning that stability of the total force was not reduced in response to the mere expectation of an upcoming change in total force. However, the stability index reduced immediately before individuals changed their total force in the Self-paced tasks, which supports findings from previous studies. The stability modulation between the Steady and RT tasks did not correlate with the RT, and the stability modulation between the Steady and Self-paced tasks did not correlate with the movement time. Therefore, this study did not reveal a stability-maneuverability trade-off in isometric finger force production tasks. The movement time for the RT and Self-paced tasks were also not correlated. However, the novel finding of this study was that participants changed stability similarly for the RT and Self-paced tasks.

Finally, the variance components obtained from the uncontrolled manifold analysis were higher in the RT task compared to the Steady task, consistent with previous reports. In fact, the increase in the performance error (greater variability in total force) while expecting to change total force in uncertain conditions (RT tasks) is the most striking and consistent result across multiple similar studies. This result indicates that despite the inconsistent results regarding the

stability index, the performance of the current task (producing a constant total force) is hampered by the uncertainty and the expectation of upcoming changes in total force.

It is likely that the stability-maneuverability trade-off is not essential for young, healthy adults in manual force production tasks. Investigations that include participants across the lifespan will shed light on this relation and help identify whether it plays a salient role in understanding loss of manual dexterity with healthy aging.

INTRODUCTION

Stability plays a crucial role in human movement. Biological systems, including humans, have intrinsic noise, and they operate in noisy environments. Stability is the ability of individuals to reject noise, allowing them to achieve their desired movement goals (Hasan, 2005). Conversely, a reduced ability to sustain stability can lead to failed movements (Cole, 1991; Iglesias et al., 2009). Stability is studied in a wide range of human movements such as locomotion (Cui et al., 2020; Patla, 2003), upright stance (Aruin & Latash, 1995; Huang & Ahmed, 2011), and multi-finger pressing (Cuadra et al., 2018; Shim et al., 2004; Shinohara et al., 2004).

In contrast to stability, maneuverability, which is the ability to intentionally change movement patterns, is also a functionally important aspect of human movement. For example, maneuverability is essential for changing direction in an efficient and/or timely manner during locomotion (Jindrich & Qiao, 2009). Since stability and maneuverability are antagonistic features of a system – high stability will imply low maneuverability (Latash et al., 2010) – there exists a trade-off between stability and maneuverability. Indeed, this trade-off has been observed in a few studies in posture (Huang & Ahmed, 2011), locomotion (Acasio et al., 2017), and finger force production (Togo & Imamizu, 2016) in which a controlled reduction in the stability of the current motor state was shown to improve maneuverability. Nevertheless, in contrast to stability of human movements, which has been widely studied, maneuverability and the relation between stability and maneuverability have not received much attention.

Therefore, the overall goal of the current study is to quantify the relationship between stability and maneuverability using isometric finger pressing as a model system. This choice of

model system (1) allows a cleaner assessment of stability and maneuverability because inertial effects of moving limb segments are absent in isometric conditions, and (2) the findings of this study have potential applications in understanding manual dexterity loss that inevitably occurs with aging. Manual dexterity is essential for everyday tasks like cooking and writing, and it declines with healthy aging starting at age 60 years (Desrosiers et al., 1999; Wang et al., 2015). The decline leads to a loss of independence in activities of daily living and negatively impacts quality of life (Incel et al., 2009). Although this decline is well documented, the underlying reasons for the decline are poorly understood (Dayanidhi & Valero-Cuevas, 2014; Enoka et al., 2003; Marmon et al., 2011). Manual dexterity is usually thought to refer to the ability to handle small objects. However, dexterity is a multi-faceted notion. One main feature of dexterous behavior is the ability to rapidly transition between different motor states due to a change in task demands (Bernstein, 2016). Thus, manual maneuverability may be viewed as a component of dexterity, and understanding maneuverability is essential for understanding dexterity.

The five digits of the human hand work together to accomplish most manual tasks. Frequently, the hand can be viewed as redundant, where a multitude of inputs (e.g., digit forces) contribute to a smaller number of salient output variables that quantify the manual task. Redundant systems have many patterns of input variables that lead to the same output. This means that the input variables must be organized in such a way that they are united by a desired goal (Latash et al., 2002).

In human behavior, repetitions of the same movement will lead to slightly different outcomes. The stability of behaviors executed by redundant motor systems can be quantified by the uncontrolled manifold (UCM) method. The UCM method assumes that redundant sets of input variables are organized to achieve a specific output variable (Scholz & Schöner, 1999). The

method quantifies two components of variance in the input variables obtained from the repeated performance of the same task. 'Good variance' (V_{UCM}) does not change the value of the specified output variable. The other component – 'bad variance' (V_{ORT}) does change the value of the output variable. Higher V_{UCM} is associated with adaptability. In contrast, higher V_{ORT} represents increased variability in the task performance and indicates less stable performance. A synergy index (ΔV) is computed by taking the difference of the V_{UCM} and V_{ORT} and comparing it with the total variance within the input variables. A higher synergy index indicates a stronger synergy, as well as higher stability of task performance.

In human movements, stability needs to be modulated based on the goals of the current task. Since stability and maneuverability are opposing characteristics of a system, stability could be traded off to increase maneuverability in manual tasks that require motor transitions. There is indeed some evidence that supports this idea: anticipatory synergy adjustment (ASA) is a phenomenon in which the stability of the current manual state, as quantified using the synergy index, is decreased in order to transition to a new state (Shim et al., 2005; Olafsdottir et al., 2005, 2007). Two distinct stages of ASA have been documented. In early work, stability reduction was observed in *Self-paced* manual actions (Olafsdottir et al., 2005). In the Self-paced actions, information about the nature and timing of the upcoming motor task is known to the participant ahead of time. Such Self-paced actions are experienced in everyday life, like when an individual is transitioning from quiet standing to locomotion. The current stability of the quiet standing must be decreased in order to transition to locomotion. However, recent work has shown that ASAs are seen when there is merely an expectation of an upcoming change, even if the timing and direction of the change is unknown, such as in Reaction Time (RT) tasks (Tillman & Ambike, 2018a, 2018b, 2020). The latter result was called 'stage 1 ASA', and the former result

was called ‘stage 2’ ASA, for the simple reason that expectation of movement must occur before the movement is performed (Tillman & Ambike, 2018a). A similar effect of expectation was observed while manipulating a hand-held object as well (Naik & Ambike, 2020).

There are key differences between stage 1 ASA and stage 2 ASA. Stage 1 ASA occurs during Reaction Time tasks. Stage 1 ASA (Figure 1) is quantified by comparing the stability in an RT task prior to initiation of the movement, with the stability in a separate Steady task where participants produce the same amount of constant force as the RT task, and do not expect to change that force [stage 1 ASA: $\Delta Vz_{\text{Reaction Time task}} - \Delta Vz_{\text{Steady task}}$] (Tillman & Ambike, 2018a). In contrast, stage 2 ASA occurs only during Self-paced tasks (Figure 2). Stage 2 ASA is quantified by comparing the stability when the state change is initiated (at time T_F) to the steady-state stability at the beginning of the same set of trials [stage 2 ASA: $\Delta Vz_{\text{Self-paced (TF-delta)}} - \Delta Vz_{\text{Self-paced (TF)}}$] (Olafsdottir et al., 2005). Furthermore, stage 2 ASA occurs later (150-400 ms before the change in the task variable) than stage 1 ASA and only if the timing of the upcoming motor transition is known an adequate amount of time beforehand. Finally, compared to stage 2 ASA, stage 1 ASA lasts for a longer period of time (Tillman & Ambike, 2018b).

The current study will add to the existing literature by exploring stage 1 ASA in Self-paced tasks [Stage 1 ASA: $\Delta Vz_{\text{Self-paced}} - \Delta Vz_{\text{Steady}}$]. We hypothesize that the Self-paced and RT tasks will both have lower synergy indexes than the Steady task, demonstrating stage 1 ASA (Figure 1). The comparison of synergy indexes in the Steady and Self-paced task has not been made; this would be the first-time stage 1 ASA is demonstrated in a Self-paced task. We also hypothesize that stage 2 ASA will be present in the Self-paced tasks, consistent with previous reports (Olafsdottir et al., 2005; Togo & Imamizu, 2016)

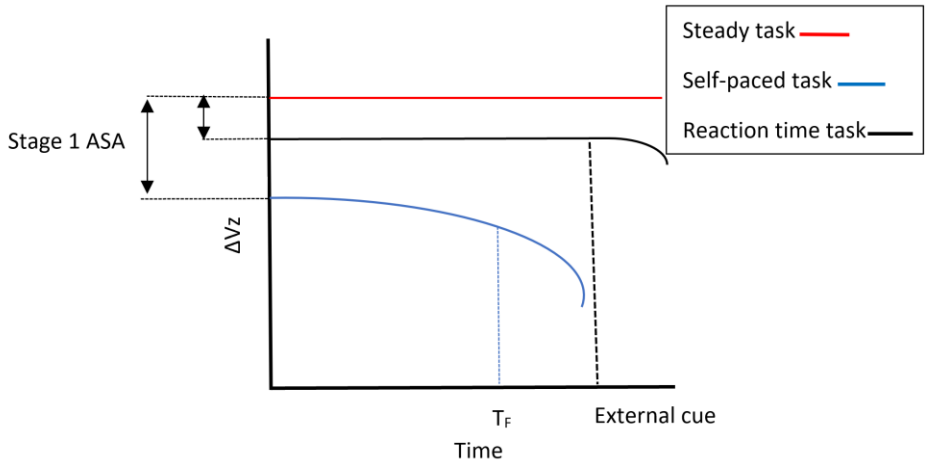

Figure 1. Representation of time profiles of the synergy index (ΔVz) for the three tasks. Stage 1 ASA is indicated by the two black arrows. T_F is the initiation of change in total force in the Self-paced task. The black dashed line represents the instant when the external cue is given to participants for the Reaction Time task.

The purpose of both stages of ASA is to prepare for upcoming action. Since this type of preparation consists of lowering the stability of the current state, it should enable the individual to become more maneuverable, i.e., more efficient in performing that action (Tillman & Ambike, 2020). However, this relation has not been well studied. Only one study has documented that individuals who prepare more, i.e., display larger *stage 2* ASA, are more accurate in achieving target force in a finger force pulse production task (Togo & Imamizu, 2016). It remains unclear if individuals who display greater stage 1 ASA are more maneuverable, i.e., respond faster in Reaction Time tasks. Therefore, we hypothesize that participants who exhibit greater stage 1 ASA will have shorter reaction times in the RT task. We also hypothesize that participants who exhibit greater stage 2 ASA will have a shorter movement transition time in the Self-paced task. These hypotheses reflect the argument that a system with lower stability will display greater dexterity and would support the stability-maneuverability trade-off. Since stage 1 ASA in RT and Self-paced tasks have not been measured in the same cohort, we will explore whether their

magnitudes are related. We will also explore whether reaction times found from RT tasks are correlated to the movement transition times of Self-paced tasks. Finally, we will quantify changes in the variance structure (V_{UCM} and V_{ORT}) in stage 1 ASA for RT and Self-paced tasks as well as stage 2 ASA in the Self-paced tasks.

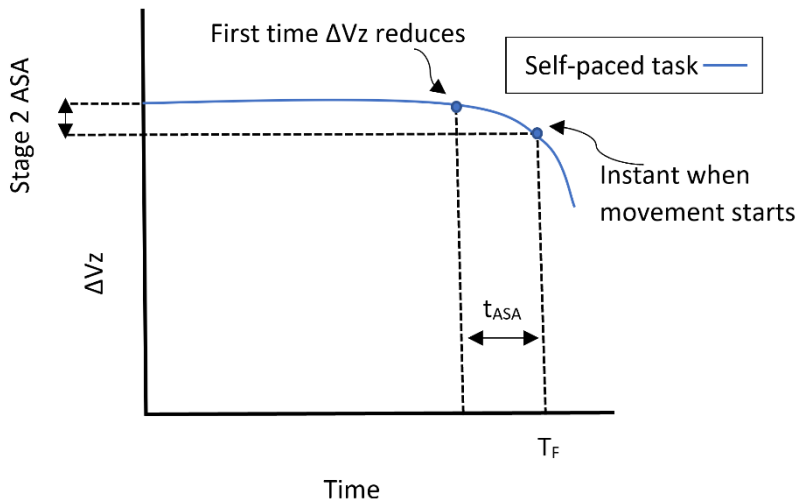

Figure 2. Representation of time profile of the synergy index (ΔVz) for a Self-paced task. Stage 2 ASA is shown by the black arrow. Time T_F is the initiation of change in total force. The t_{ASA} is the duration for which the synergy index declines prior to the initiation of the movement. It quantifies the duration of stage 2 ASA.

To summarize, the goal of this study was to (1) demonstrate stage 1 ASA in RT and Self-paced tasks within the same cohort, (2) determine if stage 1 ASA is related to reaction time in RT tasks and movement transition time in Self-paced tasks, (3) determine if individuals prepare to a similar extent for motor transitions in RT and Self-paced tasks, respectively, by comparing stage 1 ASAs in the same cohort, and (4) compare reaction times in RT tasks to movement transition times in Self-paced tasks. The current study focuses on young adults. This study will (1) develop the theory of stability and maneuverability in manual actions and (2) be part of a larger study that will identify changes in stage 1 and stage 2 ASA as well as the changes in

manual dexterity across the lifespan. Information from this study will help discover to what extent individuals are able to prepare for upcoming motor transitions. This information can be later applied to populations that have a decreased ability of stability modulation, such as individuals with Parkinson's disease (Park et al., 2012) and older adults (Olafsdottir et al., 2007).

METHODS

Participants

Twenty-nine participants [17 women; age, 23.3 ± 4.3 years; weight, 80.2± 17.6 kg; height, 1.7± 0.1 m (means ± standard deviation)] participated in the study. All participants reported normal or corrected-to-normal vision. Exclusion criteria were left-handedness and the presence of neuromuscular disease. All participants provided informed consent in accordance with the procedures approved by the institutional review board of Purdue University.

Experimental Procedure

Participants were seated comfortably in a chair in front of a table and performed isometric finger force production tasks with the right hand. The right forearm was placed on a wooden board, with the distal phalanx of each finger placed on a force transducer (Nano 17; ATI Automation) as shown in Figure 3A. The anterior-posterior position of the finger force sensors were adjusted to fit the participant's hand. The force signals from the transducers were collected by The MotionMonitor software at 1,000 Hz. Before the experiment began, the sensors were zeroed with the participant's fingers resting on the sensors, so the weight of the fingers would not be included in the sensor readings. The sum of the vertical forces on the sensors ($F_T=\sum F_i$, i=index, middle, ring, and the little finger) was presented on the computer screen as visual feedback as a cross for each trial as shown in Figure 3B. The cross moved upwards if the total finger force F_T increased and downward if F_T decreased.

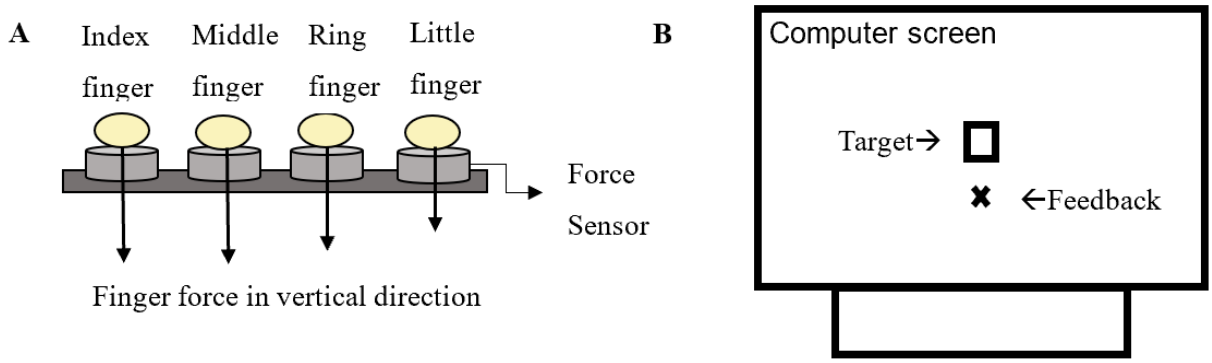

Figure 3. A) Experimental setup. B) Participants used their fingers to press in the vertical direction on four force sensors and track a target on the computer screen. The sum of the forces was represented as a cross. In most experimental trials, a target force was presented as a square.

The experiment consisted of four different tasks. This included maximal voluntary contraction (MVC) tasks, Steady tasks, Self-paced tasks, and Reaction Time tasks. There were three trials for the MVC task. There were fifteen experimental trials for each of the remaining tasks. The participants performed the MVC trials first, and the remaining tasks were block randomized across participants. Practice trials were given in order to make the participant comfortable with the procedure; the number of practice trials ranged from five to ten depending on the task, as described below. To make sure participants were not fatigued, rest breaks were given between all of the trials within the experiment. Participants were also told to ask for additional rest periods if they felt fatigued at any point in time during the experiment. Before each task participants were given a set of instructions. The participants completed the tasks with the right hand only. This study took about 90 minutes.

MVC task

For the MVC task, participants were instructed to press with all four fingers on the sensors as hard as possible for seven seconds in order to produce a maximal total force. After

their maximum force was reached, participants were told to relax and remove their fingers from the sensors. The MVC task was repeated three times and there was a mandatory 30-second break after each trial. The highest total force observed across the three trials was defined as the MVC, and it was used to determine the background force used for the remaining tasks so that all participants exerted the same effort in terms of MVC percentage.

Steady task

A square target the same size as the cross was displayed at 10% of the participant's MVC. Participants were instructed to press with all four fingers and match their F_T (the cross) with the target presented on the screen for eight seconds. Participants were told that this square target would remain in the same position for the entire duration of the trial. For the Steady task, five practice trials were performed followed by 15 experimental trials.

Self-Paced task

For this task, there was a horizontal line at 10% of the participant's MVC that stretched from the left side of the screen until the midline of the screen. At the midline of the screen, a vertical line was displayed, followed by a horizontal line that extended from the midline to the end of the screen and was positioned at 20% of the participant's MVC, as shown in Figure 4. The vertical line indicated the time at which the participants were required to generate a rapid force pulse from the 10% MVC line to the 20% MVC line and then quickly relax but keep their fingers positioned on the sensors. The cross that represented the participant's F_T moved from left to right with time. Participants were told in advance that they would have to make a quick change in force when the cross reached the vertical line, and the targets were displayed at the beginning of the trial. Ten practice trials were performed to familiarize the participant with the task followed

by 15 experimental trials. The instant immediately before the total force increased was isolated. This instant (T_F) was defined as the time when the total force first reached 5% of its peak value during subsequent force pulse. All 15 trials will be time-aligned with respect to the corresponding T_F values.

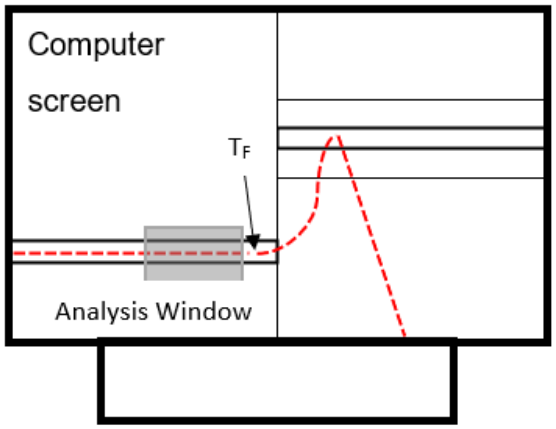

Figure 4. Self-paced task: Left half of the screen displays a force target at 10% MVC. The force target on the right half of the screen was displayed at 20% MVC. The red dashed line shows typical performance. T_F represents the beginning of the change in total force. The grey box represents the 1000 ms long window used for analysis.

Reaction Time (RT) task

Each trial of the RT task began with a square target presented on the screen at 10% MVC. The participants were instructed to modulate their F_T and match the cross to the square target as shown in Figure 5. The target was color-coded: participants were told that a purple target does not move, and a yellow target can move in the vertical direction at any time. Each trial began with a purple target. Two and a half seconds into the trial, the target switched color to yellow, indicating to the participant that it could start moving vertically at any time. The yellow target remained at 10% MVC between 3.8 and 4.2 seconds for various trials. After this stationary time period, the target began to move and continued to move unpredictably for the remainder of the

trial which was 15 seconds long. In the experimental trials, the first movement of the yellow target could occur either upward or downward (across trials). To familiarize the participants with the RT task, a set of 10 practice trials were performed. For these trials, the target started to move around six seconds into each trial, and the first movement was always upwards. The target trajectories for the practice trials were different from the ones used in the experimental trials, and the target moved slower in the practice trials compared to the experimental trials.

There were five different sets of target trajectories for the experimental trials of the RT task. For the first four sets, the target movement began at around 6.5 seconds. The first three target trajectories had four trials each, the fourth trajectory contained three trials. The fifth set of target trajectories were used as 10 catch trials where the target movement began at about four seconds. These were used as catch trials to induce uncertainty in the timing of the upcoming action. The data for the catch trials were not used for analysis. Trials within the RT task were randomized for each participant.

In total, 35 trials were performed for the RT task – 15 analyzed and 20 not analyzed. The portions of the trial where the target first turns yellow up to the point when the target first moves are used for stability analyses. Trials for the RT task will be aligned by the beginning of the change in total force (T_F).

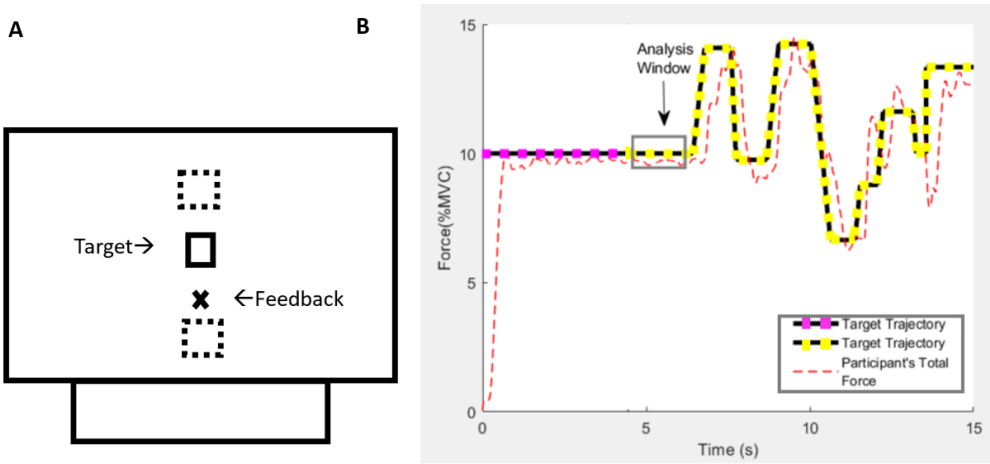

Figure 5. A) Reaction Time task: Solid box is the initial target. The target could jump up or down (dashed boxes) at any time. The cross is the participant's total force $F_{T.}$ B) Target trajectory and participant's performance from one trial, plotted as a function of time. Purple indicates the target will not move. Yellow indicates the target will move randomly in the vertical direction.

Analyses

Finger Force Tasks

MATLAB was used for data analysis. All of the data was filtered using a low-pass fourth-order, zero-lag Butterworth filter with a cutoff frequency of 10 Hz. Finger forces in the analysis windows for the Steady (Last 1 second of each trial), Self-paced (identified in Figure 4), and RT tasks (identified in Figure 5) was analyzed using the Uncontrolled Manifold (UCM) analysis (see appendix). This analysis yielded time series of the variables associated with the UCM analysis: V_{UCM}, V_{ORT}, and the z-transformed synergy index ΔVz.

Recall that for the Self-paced task and RT task, the finger force data will be time-aligned by T_F. For the Self-paced task, an analysis window 1,000 ms long prior to T_F will be used for UCM analysis. The period of time when the target is yellow and located at 10% MVC will be used for UCM analysis in the RT task. During these analysis windows, participants produce a

constant force of 10% MVC. However, they expect different actions in the future. For the Steady task, participants knew the target would remain in a constant position for the entire trial. For the Self-paced task, participants expect to produce a single change in force and knew nature and timing of the required force changes ahead of time. In the RT task, participants expect that they will have to modulate their total force and are unaware of the time and direction that the target will move.

To quantify stage-1 ASA, the differences between ΔVz for the Steady task and the ΔVz for the Self-paced, and RT tasks was computed [$(\Delta\Delta Vz)=\Delta Vz_{\text{Task Type}} - \Delta Vz_{\text{Steady}}$]. A negative value of $\Delta\Delta Vz$ will demonstrate a stability reduction compared to the Steady task. To quantify stage 2 ASA, ΔVz at T_F compared to the ΔVz in the steady-state portion in the beginning of the Self-paced task was compared [$(\Delta\Delta Vz)=\Delta Vz_{(t0)} - \Delta Vz_{(t0-dt)}$)].

Reaction time was calculated for the RT task by subtracting the time at which T_F occurred from the time at which the target began to move. Movement transition time was calculated in the Self-paced task by taking the time of when peak force occurred and subtracting the time when T_F occurred.

Statistics

Values reported are means ± standard error. A one-way repeated measures ANOVA with *Task Type* as an independent variable and dependent variable ΔVz was performed to show the differences in stability across task types. For this analysis, the ΔVz value over the first two seconds of the analysis window was averaged for the Steady and the RT tasks. The ΔVz value at T_F was used for the Self-paced task. To verify that stage 1 ASA is present in Self-paced and RT tasks, separate one-sample t-tests was performed on $\Delta\Delta Vz$ for each task, to compare the value to zero. Similarly, to verify whether stage 2 ASA is present in the Self-paced task, one-sample t-

tests was performed on ΔΔVz computed for that task. A one-way repeated measures ANOVA with factor *Task Type* (3 levels) was used to compare V_{UCM} and V_{ORT}. Similar to ΔVz, the values of these variables were averaged over the first two seconds within the analysis window. This ANOVA assessed the null hypothesis that none of the variance components in the different task types were significantly different from each other. A significant difference in V_{UCM} and V_{ORT} will show the specific changes in the variance structure. Significant main effect in any of the ANOVAs was investigated using Dunnett's post-hoc tests to identify pair-wise differences relative to the Steady task. The sequence of tasks was randomized for each participant; for this reason, *Task Sequence* was added to the ANOVAs as a blocking factor to account for learning effects or fatigue.

The reaction time for each participant for the RT task will be the mean of the RTs for the 15 trials, yielding one RT and one movement time value per participant. Correlation coefficient was computed to test if greater stage 1 ASA is associated with shorter RTs. The movement transition time for each participant for the Self-paced task will be the mean of the movement transition time values for the 15 trials, yielding one movement transition time for each participant. Correlation coefficient was used to test if greater stage 2 ASA is associated with shorter movement transition times. A correlation analysis was used to test if RTs and movement transition times were related. Finally, to determine if stage 1 ASA in RT tasks and Self-paced tasks are related, a correlation analysis was performed on the ΔΔVz for the RT and Self-paced tasks. All the statistics were performed using the SAS statistical software (Version 9.4) and an alpha level equal to 0.05.

RESULTS

Total Finger Force Stability

Main effect of *Task Type* was not observed for ΔVz [$F_{(2,54)}$ =0.69; p=0.50]. The synergy index for the Steady task, Self-paced task, and the RT task was 2.2 ± 0.07, 2.1 ± 0.04, and 2.2 ± 0.08, respectively (Figure 6). Furthermore, *Task Sequence* was also not statistically significant [$F_{(2,54)}$ =0.22; p=0.80].

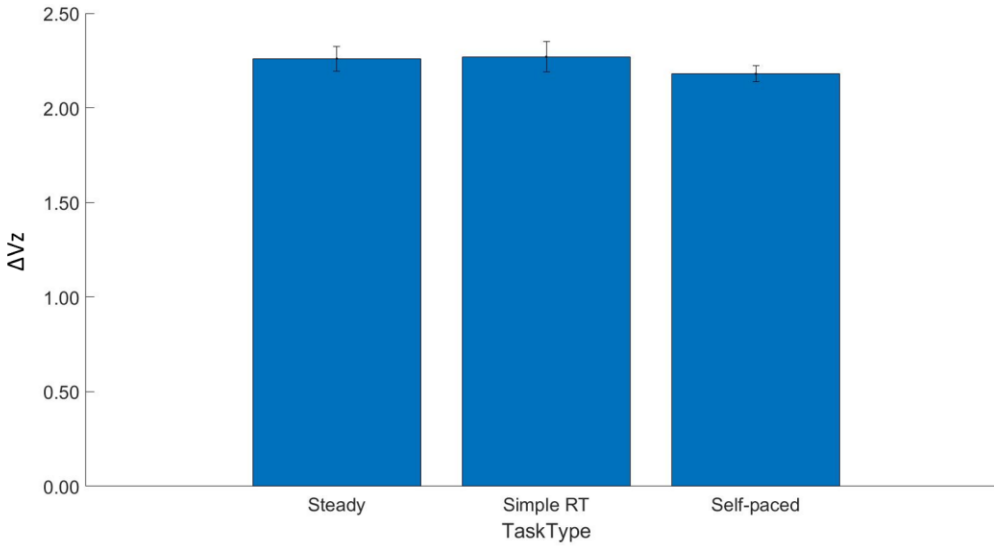

Figure 6. Mean ± SE of the z-transformed synergy index for each task.

Stage 1 ASA was not observed in our data for either the RT [ΔΔVz =0.007 ± 0.082; $t_{(28)}$=0.09; p=0.92] or Self-paced tasks [ΔΔVz =-0.073 ± 0.076; $t_{(28)}$ =-0.97; p=0.34]. In contrast, stage 2 ASA was observed in Self-paced tasks [ΔΔVz =-0.36 ± 0.061; $t_{(28)}$ =-6.0; p<0.0001; Figure 7].

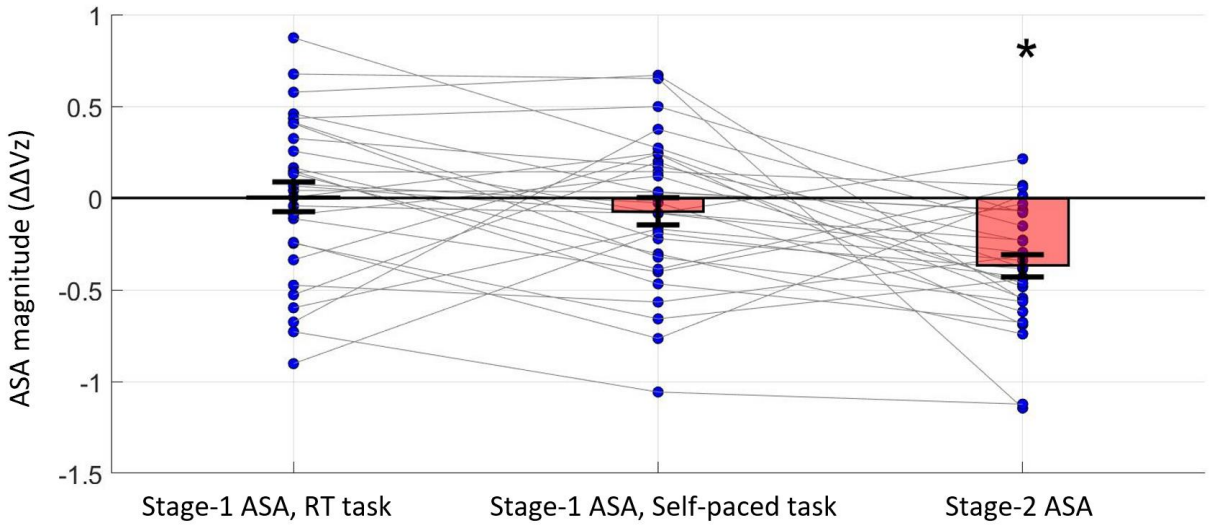

Figure 7. Mean ± SE of the ΔΔVz values for the three tasks. Blue dots represent the ΔΔVz value for each participant. Blue dots are connected by a line to show how ΔΔVz values differ across tasks for each individual. The asterisk indicates the group mean is significantly lower than zero.

Performance Measures and Types of Stability Modulation

The stage 1 ASA for the RT task (i.e., ΔΔVz for RT task) and the reaction time for the RT task were not correlated (r=-0.05; p=0.80). Similarly, stage 2 ASA in the Self-paced task and movement transition time were not correlated (r=0.09; p=0.64). Reaction time for the RT task and movement transition time for the Self-paced task were also not correlated (r=-0.04; p=0.84). However, the stage 1 ASA for the RT task (ΔΔVz for the RT task) and stage 1 ASA for the Self-paced task (ΔΔVz for Self-paced task) displayed significant positive correlation (r=0.43; p=0.017; Figure 8).

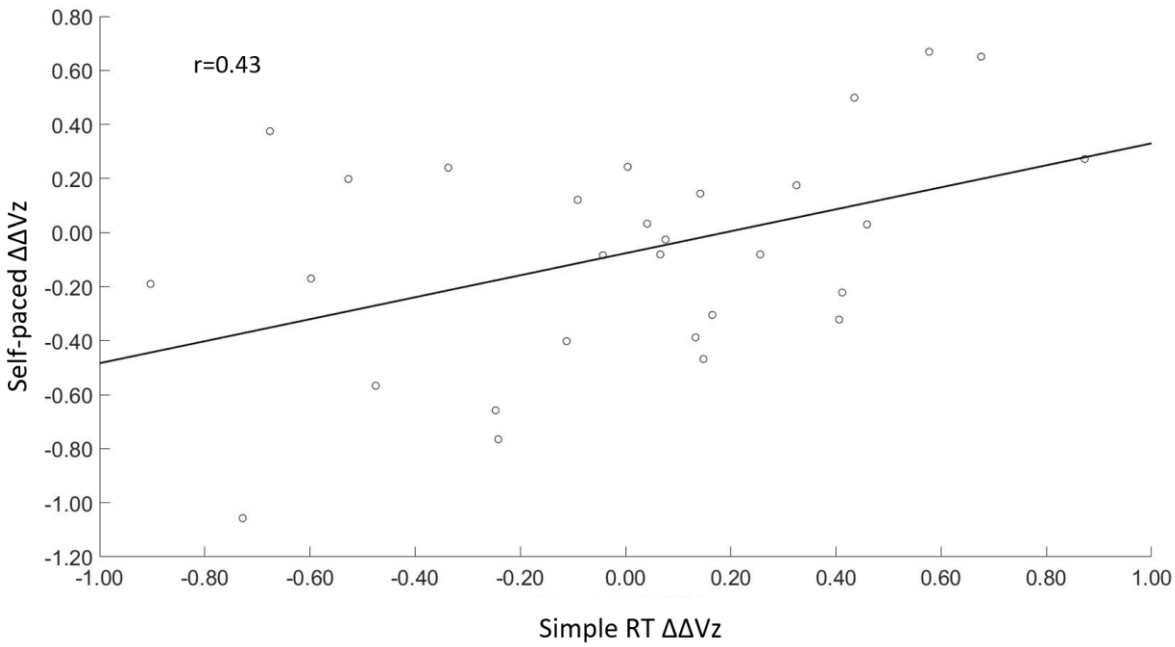

Figure 8. Scatter plot and regression line for ΔΔVz in RT task and ΔΔVz in Self-paced task.

Task Type and Variance Structure

A main effect of *Task Type* was observed for V_{UCM} [$F_{(2,54)}$ =5.6; p<0.01], and V_{ORT} [$F_{(2,54)}$ =6.3; p<0.01]. Recall that we performed pair-wise comparisons using Dunnett's method, with the values for the Steady task as reference values. V_{UCM} (0.49 ± 0.063 %MVC^2) and V_{ORT} (0.006 ± 0.0007%MVC^2) of the Self-paced task were not significantly different from V_{UCM} (0.60 ± 0.08%MVC^2) and V_{ORT} (0.007 ± 0.0009%MVC^2) for the Steady task. In contrast, V_{UCM} (0.93 ± 0.17%MVC^2) and V_{ORT} (0.009 ± 0.001%MVC^2) in the RT task were greater than the corresponding V_{UCM} and V_{ORT} values for the Steady task (Figure 9). Finally, the effect of *Task Sequence* was not significant for either V_{UCM} [$F_{(2,54)}$ =0.17; p=0.84] or V_{ORT} [$F_{(2,54)}$ =0.37; p=0.69].

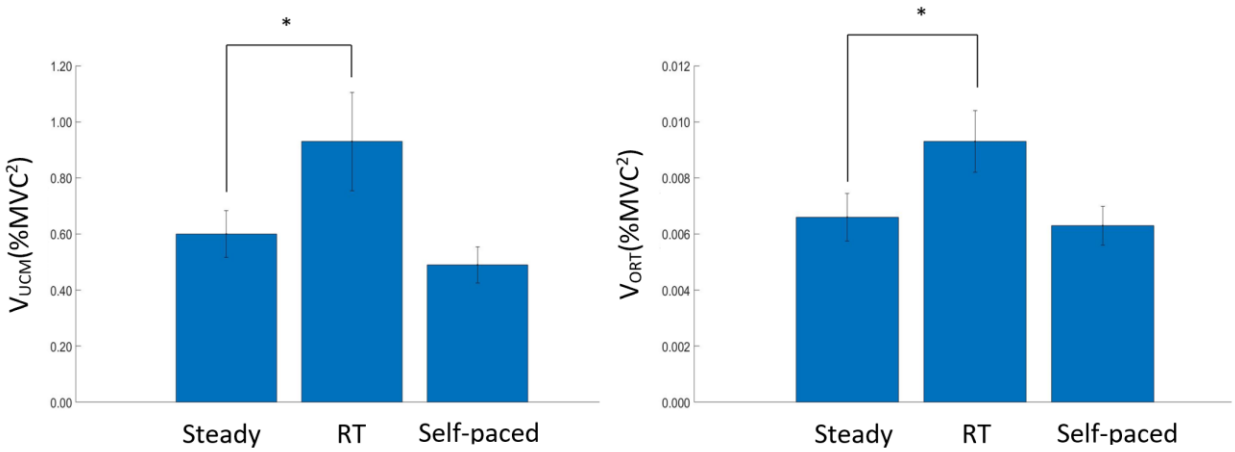

Figure 9. Mean ± SE of the V_{UCM} (A) and V_{ORT} (B) for each of the three different finger pressing tasks. The asterisk marks the significantly different groups.

DISCUSSION

Our first hypothesis was that the Self-paced and RT tasks will both have lower synergy indexes than the Steady task, demonstrating stage 1 ASA. However, the synergy index was not reduced in preparation for movement and was similar across the three different finger-force production tasks. Thus, our first hypothesis was not supported by the data.

We also hypothesized that stage 2 ASA would be present in the Self-paced task. This hypothesis was supported by the data, demonstrating that stability is reduced in preparation for an upcoming motor transition in Self-paced tasks, consistent with previous reports (Olafsdottir et al., 2005; Togo & Imamizu, 2016).

We hypothesized that participants who exhibited greater stage 1 ASA would have shorter reaction times in the RT task. We also hypothesized that participants who exhibit greater stage 2 ASA would have shorter movement transition times in the Self-Paced task. Support for these hypotheses would identify the stability-maneuverability trade-off in manual actions and argue that an individual who prepares more is able to change force more efficiently. Stage 1 ASA was not correlated with reaction times, and stage 2 ASA was not related to movement transition times. Therefore, our data do not support these hypotheses.

Anticipatory Synergy Adjustments and Performance

We were unable to replicate results from a previous study where stage 1 ASA was observed in RT tasks (Tillman & Ambike, 2018b, 2018a, 2020). Furthermore, we did not observe stage 1 ASA in Self-paced tasks, which has not been studied in previous research. The lack of main effect of *Task Type* could have been influenced by the order in which the tasks were performed, through learning and/or fatigue. To test for this possibility, we included *Task*

Sequence as a blocking factor in our statistical analyses. Since we did not find a significant effect for this factor, we conclude that both learning effects and fatigue did not impact ASA.

It is unclear why we were unable to replicate stage 1 ASA in RT tasks. In past research involving the study of stability modulation, not all young adults demonstrated stage 2 ASAs, and some adults displayed small changes in ΔVz in Self-paced (Kim et al., 2006; Olafsdottir et al., 2007). Similarly, although we did not observe stage 1 ASA in either the Self-paced or the RT tasks, we observed large inter-individual differences. Indeed, 12 out of 29 participants did display stage 1 ASA in the RT task, and 16 out of the 29 participants displayed stage 1 ASA in the Self-paced tasks (Figure 7). These results indicate that individual differences in the ΔVz in the RT task need to be studied. A discussion of how changes in the variance components led to these results in synergy indices is provided below.

We did not find stage 1 ASA or stage 2 ASA to be related to reaction time or movement transition times, respectively. Only one previous study has documented that individuals who display greater stage 2 ASA are more accurate in achieving a target force in finger force pulse production tasks (Togo & Imamizu, 2016). In other work, stage 2 ASAs were found to lead to quicker recovery of stability following a self-triggered perturbation (Kim et al., 2006; Olafsdottir et al., 2007). We were unable to check for this potential utility of ASA in our data since participants were told to relax after completing the force pulse in the Self-paced task. Thus, the functional role of ASA remains an important topic for future studies.

Stage 1 ASA and Performance Measures

Since stage 1 ASA in RT and Self-paced tasks had not been measured in the same cohort, we explored whether their magnitudes are related. We found that the ΔΔVz in RT task and ΔΔVz in Self-paced task have a moderate positive correlation. This shows that if a participant demonstrates stage 1 ASA in the RT task, they are likely to demonstrate stage 1 ASA of similar magnitude in the Self-paced task. Furthermore, this shows that individuals prepare in a general manner by either increasing or decreasing stability in order to prepare for any possible outcome.

We also explored whether reaction times found in the RT tasks were correlated to the movement transition times of Self-paced tasks. We found that reaction time and movement transition time were not related to each other. It is possible that ASAs do not facilitate quicker reactions but may help stabilize performance variables after an action occurs (Kim et al., 2006; Olafsdottir et al., 2007). It is likely that reaction time and movement transition time for the young individuals are already quite low, and that any improvements due to stability modulation are negligible. Alternatively, since the RT task required the participants to track the target as accurately as possible, some participants may have prioritized accuracy over speed (MacKenzie, 1992) which may have confounded the relation between stability modulation and reaction time.

Changes in the Variance Structure

The UCM method quantifies two components of variance in the input variables obtained from the repeated performance of the same task (Latash et al., 2002; Scholz & Schöner, 1999). Recall that V_{UCM} reflects the variance in the inputs that does not change the output variables, while V_{ORT} reflects the variance in the inputs that does change the output variables. A reduction in ΔVz can be a result of a reduction in $V_{UCM,}$ an increase in $V_{ORT,}$ or both. In this study, the RT task was associated with higher V_{UCM} and V_{ORT} values compared to the Steady task. Higher V_{ORT}

in the RT task tends to decrease the synergy index; however, this effect was nullified by a corresponding increase in V_{UCM} (Figure 9). Note that changes in V_{UCM} are commonly inconsistent across participants. Since the task does not constrain the movement or variance along the UCM, different individuals utilize this freedom in different ways. Values of V_{UCM} in young adults have been shown to increase or decrease, as well as remain unchanged in previous studies (Tillman & Ambike, 2020; Togo & Imamizu, 2016).

In the present study, V_{UCM} and V_{ORT} for the RT task was higher compared to the Steady task for 21 out of the 29 (72%), and 25 out of 29 (86%) participants, respectively. Similarly, V_{UCM} and V_{ORT} for the Self-paced task was higher compared to the Steady task for 12 out of the 29 (41%), and 15 out of 29 (51%) participants, respectively (Figure 10). Thus, the directional changes in the variance components are more consistent across participants in the RT task compared to the Self-paced task.

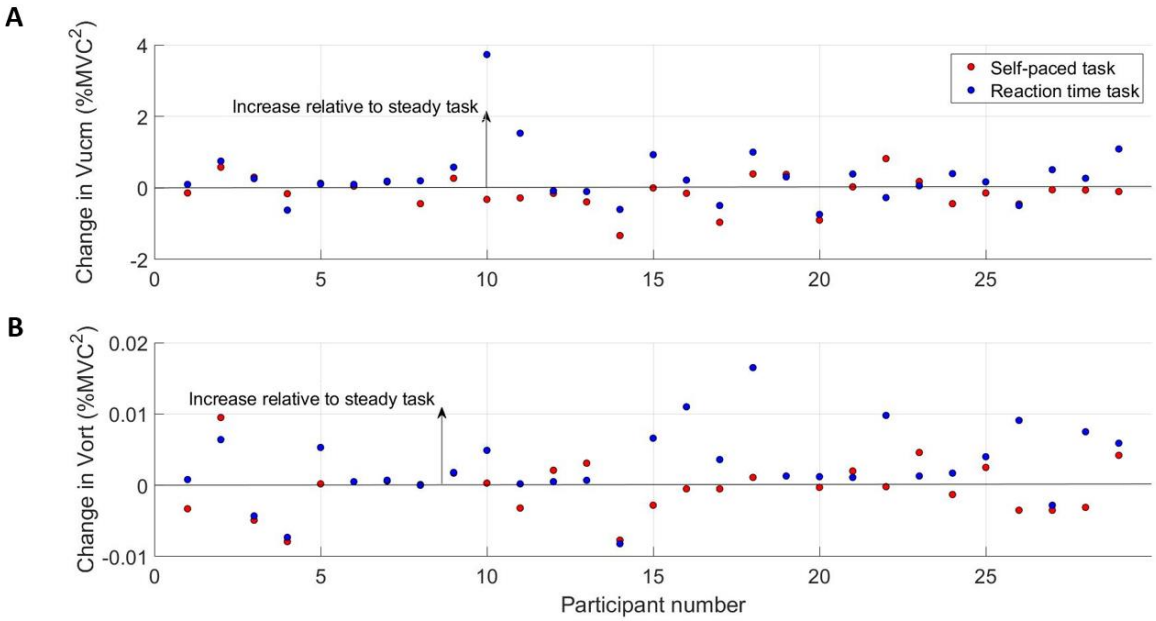

Figure 10. Changes in the variance components V_{UCM} (A) and V_{ORT} (B) for each participant for the RT and Self-paced task.

Furthermore, we observed greater consistency in V_{UCM} changes for the RT task (72% participants show an increase) compared to previous work by Tillman and Ambike (2020), where participants were more evenly split (only 58% participants show increase in V_{UCM}). In contrast to V_{UCM}, the consistent across-participant changes in V_{ORT} for the RT task in this study (86% participants increase V_{ORT} for the RT task) mirrors a similar finding by Tillman and Ambike (2020) (92% participants increase V_{ORT} for the RT task). Overall, the increase in V_{ORT} while anticipating voluntary changes in the finger forces is the most consistent finding across the present and previous studies (Tillman & Ambike, 2018b, 2018a, 2020).

Limitations

One limitation to this study is that all participants were young adults. Completing this experiment across the lifespan would give us a better understanding of stability modulation in finger-force production tasks. It is likely that age-induced changes in muscle function, e.g., lower rate of force production (Cole, 1991; Enoka et al., 2003) may influence both the performance (i.e., reaction and movement transition times) as well as the strategies employed to improve maneuverability (i.e., stability modulation).

Another limitation to this study is that there is no real consequence when participants do not track the force targets in the Self-paced or RT tasks as accurately as possible. An incentive such as increased payment for participants that complete tasks more accurately may better motivate participants to complete each task to the best of their ability. A score that is provided to the participants upon task completion may also be able to better motivate participants to complete all tasks as accurately as possible.

Future Directions

Manual dexterity has been shown to decline with age starting at the age of 60 years old (Desrosiers et al., 1999). To get a better picture of the mechanisms that lead to manual dexterity reduction with age, a study that includes participants across the lifespan is needed.

While stage 1 ASA was not found to be of significance in the RT or Self-paced task, several individuals still displayed stage 1 ASA. However, there is yet to be a study where stage 1 ASA and stage 2 ASA are observed within the same set of trials. Such a result will provide evidence for the claim that stage 1 ASA occurs before stage 2 ASA (Tillman & Ambike, 2018b).

Stability modulations have been studied in various motor behaviors such as posture and locomotion (Acasio et al., 2017). This study has looked at stage 1 and stage 2 ASA within finger force production tasks. However, future work should examine ASA stages in different motor tasks (such as locomotion) to evaluate if individuals prepare similarly for various human movements.

CONCLUSION

In the current study, we document further evidence that supports stability reduction in preparation for upcoming motor transitions in Self-paced tasks. One novel finding of this study was that participants prepare similarly for Reaction Time and Self-paced tasks by finding a positive correlation between the ΔΔVz values for both tasks. In contrast, we were unable to document a significant stage 1 ASA in Reaction Time tasks, contradicting previous findings. Furthermore, we did not observe Stage 1 ASA in Self-paced tasks, which is another novel finding in this work. This study provides insight on stability modulation in manual tasks in healthy young adults. Finally, we did not find evidence for a stability-maneuverability tradeoff in manual behavior in our cohort of healthy, young individuals. The information from this work will serve as a baseline for comparison for participants that struggle with manual dexterity, such as older adults or individuals with Parkinson's disease (Desrosiers et al., 1999; Park et al., 2012).

APPENDIX A. UNCONTROLLED MANIFOLD ANALYSIS

To use the UCM analysis, at least 15 trials of the same task are required. The 15 trials are organized by averaging the input values in a time window so that one value is associated with each input variable for each of the 15 trials. Organizing the input variables this way will give a 15 x 4 matrix of the average finger forces, which is used for the analysis.

There are two manifolds associated with the UCM analysis, the first manifold (UCM) contains changes that do not change the value of the specified output variable. In contrast, the manifold orthogonal to the UCM contains changes that do change the value of the output variable, which is known as ORT. For the UCM analysis, the number of input variables (four finger forces) determines the dimension of the space. The constraint (target total finger force for each task) put on the input variables determines the dimension for ORT. In this study, the UCM is three-dimensional, and the ORT is a one-dimensional manifold. The UCM method assesses two components of variance in the input variables obtained from the repeated performance of the same task. The variance that is projected onto the UCM is 'good variance' (V_{UCM}) and does not change the value of the specified output variable. Variance projected onto ORT is 'bad variance' (V_{ORT}), which does change the value of the output variable. A higher V_{UCM} is associated with more adaptable movement patterns. In comparison, a higher V_{ORT} is representative of increased variability in the task performance, which indicates less stable performance. A synergy index (ΔV) is computed by $\Delta V = \frac{\frac{VUCM}{3} - \frac{VORT}{1}}{\frac{VTOT}{4}}$. A higher ΔV means a stronger synergy, as well as higher stability. A comparison of ΔVz of the Self-paced and RT task compared to the ΔVz in the Steady task ($\Delta\Delta Vz$) was computed. If the $\Delta\Delta Vz$ is found to be greater than zero, it will indicate the

presence of ASA. Changes in the V_{UCM} and V_{ORT} will give an insight into the variance structures, specifically the mechanisms that lead to $\Delta\Delta Vz$.

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