Age-related differences in kinematic signatures of executive control of pre-potent motor responses

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Abstract

Age-related differences in kinematic signatures of executive control of pre-potent motor responses

Kevin Trewartha

The present study assessed traditional reaction time and accuracy as well as novel kinematic measures of younger (YA) and older (OA) adults performance on a fine motor/cognitive task using a midi keyboard and 3-D motion capture. The goal of the study was to assess the role of executive control in the production of sequential key presses that required spatial information learning. To this end, certain finger transitions were made pre-potent by manipulating their repetition frequency (presented 1, 3, or 5 times) within each trial during 3 learning blocks. These critical transitions (CT) were then used to create violation transitions (VT) presented during 3 testing blocks, that violated the pre-potent responses and required greater executive control. When learning was equated, OA were more affected in terms of reaction time by the VT than YA, suggesting that OA had more difficulty with the task when greater executive control was necessary. When key press responses were parsed into kinematic components, the results showed that OA spent more time planning their movements than YA. Crucially, when YA performed predictable CT they were found to slow down their key press execution, making smooth responses, whereas OA made rapid responses regardless of response predictability. This may be interpreted as a compensatory strategy of OA to overcome slowed movement planning. The results are discussed in terms of system-based theories of cognitive aging with an emphasis on the role of motor control processes in cognitive performance.

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Age-related differences in kinematic signatures of executive control of pre-potent motor responses

In order to perform complex tasks in everyday life (such as driving a car) one exercises a number cognitive processes such as working memory, selective attention, associative learning, etc., and also numerous motor processes such as fine motor control, balance, and reaching and grasping. Furthermore, such tasks become almost automatic or habitual because of the high frequency with which they are performed. Successful completion of these types of tasks requires that the cognitive mechanisms operate in harmony with one another and with the motor processes in a highly coordinated manner. There has been an increasing interest in the mechanisms by which the coordination of cognitive processes is achieved. These so called executive control mechanisms have been studied with a wide variety of cognitive and motor tasks with various populations from healthy younger (YA) and older adults (OA) to neurological populations. Many definitions of executive control have been debated in the literature (e.g., Salthouse, Atkinson, & Bersh, 2003; West, 1996; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Logan, 2004; Verhaeghen & Cerella, 2002; and Verhaeghen, Cerella, & Bopp, 2005), but most revolve around the concepts of coordinating, planning, monitoring and sequencing of cognitive processes. Recent research has provided evidence that tasks that rely more heavily on executive control mechanisms are more difficult for OA, and specific laboratory paradigms have been developed to test this hypothesis. For example, task switching (e.g., Mayr, 2001; and Kramer, Hahn, & Gopher, 1999), and dual task paradigms (e.g., Salthouse & Miles, 2002) have provided an effective way to explore age-related declines in executive processes. In addition, executive control functioning has been tested by employing tasks that consist of, or induce pre-potent (i.e., well-learned) responses. In order to successfully accomplish these tasks one must overcome the pre-potent responses in order to produce novel responses. One particularly common theory, developed by Hasher, Zacks, & May (1999), of the ability to overcome pre-potent responses is that one must inhibit the well-learned response (e.g., driving a car with an automatic transmission) in order to perform a new task (driving a car with a manual transmission). The most commonly used pre-potent response task for testing executive control in the laboratory is the Stroop task in which participants must suppress the pre-potent tendency to read the words in order to correctly indicate the colour of the ink in which they are printed. Other tasks such as the stop-signal paradigm (Logan & Cowan, 1984), also capitalize on the concept of pre-potent responses as way of examining the efficiency of executive control mechanisms in aging populations.

The ability to suppress pre-potent responses has become an important part of more general theories of cognitive control and its link to prefrontal cortex function in aging (see West, 1996 for review). Changes in the efficiency of executive control mechanisms supported by these frontal lobe networks, in later adulthood have been well documented (e.g., Verhaeghen, Cerella, Bopp, & Basak, 2005; and Ettenhofer, Hambrick, & Abeles, 2006). Furthermore, recent research has suggested that frontal lobe networks are important for sequence learning tasks (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Müller, Kleinhans, Pierce, Kemmotsu, & Courchesne, 2002; Sakai, Ramnani, & Passingham, 2002; and Kansaku, Muraki, Umeyama, Nishimori, Kochiyama, Yamane, & Kitazawa, 2005). Age differences in performance on sequencing tasks have been widely documented. Generally, the findings of these studies show that OA have diminished implicit (Harrington & Haaland, 1992; and Howard & Howard, 1997) and explicit learning of sequences (Harrington & Haaland, 1992; Howard & Howard, 1989; and Ghilardi, Eidleberg, Silvestri, & Ghez, 2003). In addition, age differences in sequence learning have been found for both spatial (e.g., Feeney, Howard, & Howard, 2002) and non-spatial sequences (e.g., Negash, Howard, Japikse, & Howard, 2003; and Krampe, Mayr, & Kliegl, 2005).

A more recent application of motor sequencing paradigms is to assess executive functioning of OA. In fact, researchers have proposed the idea that decreased executive functioning could explain some of the age-related differences in sequential performance (e.g., Krampe, 2002; and Krampe, et al., 2005). In their study, Krampe et al. (2005) presented a number of temporal sequences, i.e., rhythms, varying in complexity from simple, isochronous tapping, to more complex sequences with taps of varying target durations. Their results revealed that low level timing mechanisms are more crucial for isochronous tapping (only one target duration) and can be dissociated from executive control processes involved in more complex sequences (i.e., those that required a combination of multiple target durations). Furthermore, low-level timing mechanisms were found to be age invariant, whereas performance on complex sequences revealed age-related declines in executive control functioning. In their second experiment, they were able to demonstrate that executive control mechanisms are involved in the ability to switch between dominant and non-dominant rhythm patterns, and that this ability also declines with age.

Although it is quite evident that cognitive mechanisms involved in motor sequencing tasks do not operate in isolation from the motor processes involved, researchers have traditionally attempted to study motor and cognitive mechanisms in isolation. For some time, it has been argued that the many separately studied biological systems like the auditory, visual, and cognitive systems co-operate efficiently during normal, everyday tasks. However, only recently have researchers focused more on a systems approach to understanding human behaviour and performance. Research has shown that not all of the processes operating within the various biological systems deteriorate with advancing age. However, because of the intimate relationship between the various systems, decreases in efficiency of any one process can result in observable deficiencies in other systems. In order to understand any one human system we must consider the contributions of the other processes involved in the task. This point is especially crucial for aging researchers as it is not possible to understand the effects of normal aging on any one system without considering how other systems might contribute. For example, Schneider and Pichora-Fuller (2000) argue that the information processing system is a highly integrated system consisting of perceptual and cognitive processes that work together. Other authors have made similar arguments about the relationship between sensory and cognitive systems (Baltes & Lindenberger, 1997). Recognizing and exploring the complex interaction between different systems throughout the adult life-span is crucial to fully understanding the aging process.

As a result of the more system based approach to cognitive research the need to consider the link between cognitive and motor processes in the same manner as the perceptual/cognitive integration is becoming more salient (see Rosenbaum, 2005 for discussion). Evidence is emerging that suggests that there are indeed intricate relationships between sensory, sensorimotor, and cognitive performance in complex tasks (Li & Lindenberger, 2002; and Sosnoff & Newell, 2006). Most tasks that are used in the laboratory to study cognitive processing, as well as many everyday cognitive tasks, are embedded within a motor context. This confounded nature of traditional cognitive tests with motor control processes makes the study of the interplay between the two systems all the more poignant. In the past, the literature on physical and motor aging and the literature on cognitive aging have been widely separate disciplines. In fact, most cognitive aging research has given little thought to kinematic measures of performance, and likewise, motor aging research has often ignored the importance of cognitive factors.

There has been a growing literature interested in the physical and kinematic changes of movement with age. Age-related changes in the sensorimotor system such as general slowing, structural changes in the brain, muscles mass loss, decrease in voluntary contractile strength, slowing of afferent signals from the brain, etc., lead to changes in the efficiency of motor performance on a variety of tasks. Decreased performance of OA on motor tasks measured through reaction time, movement time, movement variability, force control, stability, gait and posture, etc. have been widely studied (for review see Ketcham & Stelmach, 2001). Furthermore, neuroimaging evidence has shown that OA recruit different neural networks than YA in order to perform simple motor tasks (Mattay, Fera, Tessitore, Hariri, Das, Callicot, & Weinberger, 2002), and that the neural correlates of motor performance change with age (Ward & Frackowiak, 2003). Kinematic measures provide a way of measuring dynamic aspects of movement separate from the effects of physical characteristics of different age groups. Those measurements allow researchers to go beyond simple accuracy and reaction time measures in order to parse movements into meaningful components like movement planning, movement execution, velocity, acceleration, and the time-course of those components. Research on the kinematic differences in performance of OA on a variety of motor tasks has revealed that aging affects the way in which movements are executed. This literature has provided numerous types of tasks that allow us to observe these age differences, including aiming tasks (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002; and Haaland, Harrington, & Grice, 1993), pointing movements (Romero, Van Gemmert, Adler, Bekkering, & Stelmach, 2002), circle drawing (Ketcham, Dounskaia, & Stelmach, 2004), and mirror drawing (Kennedy & Raz, 2005). Parsing movements into kinematic components has been common in the motor control literature and has revealed that OA are slowed in the planning of aiming movements (Haaland, et. al., 1993), in the time to completion of mirror drawing (Kennedy & Raz, 2005), and in the peak velocity and time-course of movement components in point-to-point reaching tasks (Ketcham, et al., 2002).

Although interest in studying sequential actions in a variety of motor tasks has been around for some time (for review see Rhodes, Bullock, Verwey, Averbeck, and Page, 2004), few studies have assessed the kinematic aspects of performance of older adults. The few studies that do examine kinematic measures of sequential action performance in older adults tend to focus on gross motor tasks such as arm reaching movements. For example, Ghilardi, et al., (2003) reported that without awareness, both younger and older adults slow down their arm movements when reaching responses are highly predictable, suggesting that they make more relaxed and smooth movements. In addition, more predictable movements tended to be associated with shorter movement planning times. Moreover, research has suggested that OA have more difficulty with the acquisition of motor skills than the transfer of motor learning to novel tasks (Seidler, 2006).

The current study focused on measuring both cognitive and motor performance in a sequential action task in order to determine if there are age differences in the functioning of both systems and to explore the relationship between them. Much of the literature on sequential behaviour has focused on reaction time (RT) as a way to quantify the age-related differences in performance. Moreover, RT is often used as evidence for age-related changes in executive functioning in these types of tasks. A strong assumption of this focus is that variations in the time between stimulus presentation and response mainly reflect differences in executive control functioning. However, it is clear that many other processes from perception and recognition of the stimuli, to recall processes, to motor processes involved in the response are all components of the reaction time. Finding a way of measuring performance such that some of these processes can be separated is an important step towards fully understanding the interplay between motor and cognitive processes in aging. One novel way of assessing age-related changes in a cognitive/motor task is to measure kinematic variables along with more traditional accuracy and RT measures in order to get a complete picture of the contribution of both systems to sequential performance. To the current author's knowledge, no studies have completed a kinematic analysis of fine motor sequence performance of YA and OA. The benefit of using kinematic measures to parse movements into different components is that it allows the detection of various age-related differences throughout the full movement trajectory that might be missed by RT measures. Furthermore, it provides a chance to explore the interaction between cognitive processes and kinematic signatures of the movements across different age groups, which has been missing from the literature. Using kinematic measures of performance to specifically assess executive functioning has not been studied previously. One way to induce executive control processes that can be measured kinematically is to create pre-potent motor responses. Recently, pre-potent gross motor responses have been induced in YA and OA in order to assess inhibitory functioning on an everyday motor task (i.e., wiping movements with a sponge). This research showed that OA had more difficulty inhibiting the pre-potent response than YA (Potter & Grealy, 2007). As discussed above, Krampe, et al., (2005) capitalized on pre-potency of motor responses by way of dominant and non-dominant rhythm patterns which require more fine motor control. If the executive control processes evoked by the switch between dominant and non-dominant rhythms is a general process for the control of sequential actions, then it should be possible to demonstrate similar findings with a non-temporal paradigm. Moreover, if OA have difficulty with rhythmic tapping when executive control demands are high, then similar age-related effects with a spatial movement task would strengthen the case for an executive control deficit hypothesis of sequential action in aging.

The goal of the current experiment was to examine the role of executive control processes by creating pre-potent responses in a fine motor task that required the control of information about spatial location of targets rather than temporal characteristics. In order to accomplish this we employed a multi-finger sequence task on a midi keyboard with unintentional learning of particular finger transitions embedded within larger, random sequences. The repetition of these critical finger transitions within each sequence was varied parametrically over learning blocks. Furthermore, test blocks were created in order to provide violations of the learned critical transitions in which successful performance relied on participants' ability to overcome the pre-potent response. The analysis of this ability included traditional accuracy and RT measures, but also included a kinematic parsing of different components of each motor response. Thus, individual components of participants' movements could be assessed as a way to measure the role of executive control in fine motor movements of younger and older adults.

A number of hypotheses were tested in the current experiment. In terms of the ability to learn subtle regularities embedded within random sequences it was expected that both YA and OA would be able to learn those regularities. In addition, it was expected that when the critical transition was repeated most frequently, OA would perform as well as YA in terms of accuracy and reaction time. With increasing repetition critical transitions would become pre-potent motor responses for both age groups. Theoretically, if executive control mechanisms must be exercised in order to overcome pre-potent responses, and OA have more difficulty performing tasks that require greater executive control, then age differences should be revealed in the ability to perform violations of pre-potent key press transitions. It was hypothesized that those age differences would be revealed in the key board measurements (accuracy and reaction time) as well as the movement kinematics (planning time, execution time, peak velocity and time to peak velocity). That is, it was predicted that OA would have longer reaction times to violations of pre-potent responses than YA, and would also spend more time planning those movements. It was also expected that the two age groups would have differing kinematic signatures of full key press responses if the executive mechanisms operating during movement planning were less efficient for older adults. Specifically, it was hypothesized that older and younger adults would differ in the amount of time that it took them to execute a full key press, in the time that it took them to get to peak velocity, and in the peak velocity of the key presses themselves.

Methods

Participants

Twenty five participants were recruited for this experiment including 12 younger adults (ranging from 19-30 years old) from the undergraduate population at Concordia and McGill Universities in Montreal, QC, and 13 older adults (ranging from 59-75 years old) from the Montreal community. Of the 25 participants there were 8 males (4 in each age group) and 17 females (8 in the younger adult group and 9 in the older adult group). All participants were screened to be right handed, have no history of neurological disorder, and no motor dysfunction (such as arthritis) that would inhibit fine motor movement (see Appendix 1 for telephone screening survey and Appendix 2 for medical questionnaire). In addition, participants were only included if they had less than 3 years of musical, or dance training, and if they had not been practicing in the past 10 years (see Appendix 1 for musical training questionnaire). Participants were also given the Weschler Adults Intelligence Scale (WAIS) Digit-Symbol test to assess speed of processing, and the Extended Range Vocabulary Test (ERVT) to test vocabulary. OA were found to be slower than YA, but had larger vocabularies (see table Table 1 for all neuropsychological test results). The study was reviewed and accepted by the Concordia University Human Research Ethics Committee. All participants gave informed consent and were compensated for their time.

Apparatus, Task and Stimuli

Table 1

Means and Standard Errors of the Neuropsychological Tests and the t-test Results of the Age Group Comparisons for Each Test.

Test	Age Group	Mean (SE)	t-Test Results
WAIS Digit Symbol	YA	95.08 (3.37)	*t*(23) = 4.189, *p* < .001
	OA	70.23 (4.77)	
ERVT	YA	10.32 (1.48)	*t*(23) = -2.883, *p* < .01
	OA	16.74 (1.64)	
Trails Difference Scores	YA	29.53 (5.57)	*t(23) = -1.26, ns*
	OA	41.57 (7.60)	
Stroop Interference Score	YA	0.387 (.038)	*t*(23) = -2.632, *p* < .05
	OA	0.607 (.072)	

The experimental task took place in a separate room in which a Yamaha PSR-290 Midi (musical instrument digital interface) keyboard was set up on a table with velcro strips placed on the four keys that were used in the experimental task. The velcro acted as a tactile cue to the participants in order for them to remain oriented on the correct keys without visual confirmation. The keyboard was used to record traditional measures of accuracy and reaction time. In addition, a 3-D motion capture system (Visualeyez by Phoenix Technologies) was set up in a half circle around the table. The nine cameras recorded the x,y,z coordinates of each L.E.D. marker relative to a reference point at a rate of 50hz. This system was used to capture all of the kinematic measures of performance during the task. Stimuli were presented on a 17" Samsung (SyncMaster 793DF) flat panel computer monitor that was situated on the table behind the keyboard. The experimental program was created using C Sharp.

Four dark grey boxes (3" x 3") were displayed horizontally on a light grey background on the computer screen in front of the participants. The boxes lit up one at a time by changing to a deep red colour in a 10 element series to make up one trial (Figure 1). L.E.D. markers were placed on each finger nail of the participant's right hand (excluding the thumb) and were secured into place with medical tape. Each of those fingers mapped in a one-to-one manner onto the four boxes on the screen from left (index finger) to right (baby finger). The task was to press down on the corresponding key as quickly and accurately as possible as each box lit up.

Practice blocks were presented to each participant before the actual testing phase of the experiment began. The first practice block consisted of a simple sequence of 1,2,3,4,1,2,3,4,1,2,3,4 presented once at a slow pace in which the stimuli remained on for 600ms, with a delay of 900ms between stimuli. This block was meant to orient participants with the keyboard, and to get them used to the mapping of fingers to keys to stimuli. The sequences for all other practice blocks were created in accordance with two rules: 1) that the same key press could not repeat in succession, and 2) that no transition was repeated in a single sequence. The second practice block contained 7 trials of these ten key press, quasi-randomly determined sequences (e.g., 2,3,1,4,3,4,1,2,4,2). The difference with this block over the first practice block was that the pace of presentation was sped up such that the stimulus remained on for 600ms, and the delay between stimuli was reduced to 600ms. This was the pace used for the rest of the experiment. The final practice block was implemented as an accuracy criterion block. Each participant completed 5 quasi-randomly determined trials, after which the computer scored their performance "on the fly". Once each participant reached a criterion of 85% correct key presses within two consecutive trials, the practice was stopped and the experimental trials began.

The actual experiment consisted of 3 learning blocks and 3 testing blocks. These blocks were created with the following rules. For each learning block a different pair of key presses was defined as the critical transition (CT). The repetition of the CT was manipulated parametrically over the three learning blocks such that it was either presented once (1-Rep block), three times (3-Rep block), or five times (5-Rep block) in every trial. The 5-Rep block constituted a saturation condition in which only the CT was presented. In the other two blocks each trial contained the defined number of CT repetitions, and all other transitions, referred to as non-critical transitions (NCT) were controlled such that no other transition was presented more than once, and no other transition started with the same key press as the critical transition. After each learning block was completed, participants were given a testing block which contained the CT once again in each trial, and a violation transition (VT) which was defined as a pair of key presses that started with the same key as the CT but ended with a different one. VTs were constrained such that the second press always went in the opposite direction on the hand from the second press in the CT (e.g., if the CT was 3,4, the VT would be 3,2). All other transitions within each trial followed the quasi-random rules discussed above such that each trial contained 10 key presses. Example trials from each of the learning blocks, and the corresponding testing blocks are shown in Figure 1. Participants were given no feedback about their progress during the task.

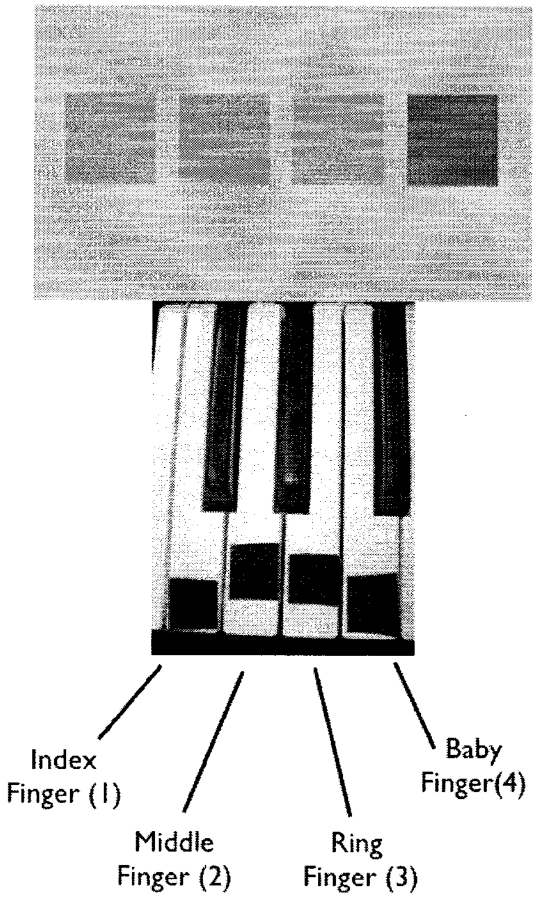
In order to examine general cognitive abilities and executive control functioning prior to participation in the experiment, participants were asked to complete a battery of tests including the WAIS Digit Symbol Coding (Wechsler, 1981), the Extended Range Vocabulary test (ERVT, Form V2; Educational Testing Service, 1976), the Halstead-Reitan Trail Making Test, parts A and B (Reitan, 2001) and the Stroop test (Adapted from Spreen and Strauss, 2001). All of these tests were administered in paper and pencil versions according to established procedures and all timing was recorded via a stopwatch. The final package given to the participants after the experimental task included a debriefing form that described the rationale and purpose of the experiment and provided participants with contact information should they have any questions.

Procedures

Prior to conducting the experimental task, the experimenter verified that the participant was comfortable and had free movement of their fingers. Participants were asked to place each finger on one of four consecutive keys on the keyboard, and were to take note of the feeling of the velcro beneath each finger. It was explained that this velcro would act as a tactile cue to orient themselves to the correct keys.

Participants were told that each of their four fingers were mapped onto four consecutive boxes on the computer screen in front of them in a simple left to right, one-to-one manner. They were instructed to press all the way down on each key as each box changed colour (one at a time) as quickly and accurately as possible. This experiment was interested in the implicit learning of critical pairs of key presses, so participants were merely told to follow along with the stimuli. There were no instructions to learn any pattern of key presses within each trial.

For the practice blocks participants were informed that these trials were presented in order to familiarize them with the keyboard and the task. They were also warned prior to the second practice block that the presentation speed would be increased. For the last practice block participants were told that the



Training Blocks:

1-Rep- CT is **2 1**
1 **2 1** 3 4 1 4 2 4 3

3-Rep- CT is **2 4**
2 4 1 3 **2 4** 3 4 **2 4**

5-Rep- CT is **3 4**
3 4 3 4 3 4 3 4 3 4

Testing Blocks:

1-Rep-VT is 2 3
1 2 3 4 **2 1** 3 2 4 1

3-Rep-VT is 2 1
3 1 **2 4** 3 2 1 4 1 3

5-Rep-VT is 3 2
1 2 1 **3 4** 1 4 3 2 4

Figure 1. Illustration of experimental set-up with stimulus presentation (top left), finger mapping shown (bottom left) and examples of sequences for training (top right) and testing (bottom right) blocks.

background on the screen would turn pink at some point and that they were to ignore this change. The colour change acted as a cue to the experimenter that the participant had reached the appropriate criterion level of accuracy and that the practice session could be stopped.

Prior to the experimental phase of the task, participants were told that the task would remain the same and they were reminded of need to be fast and accurate. No other instructions were given and the participants followed along until the experiment was finished. Immediately after the keyboard task was finished participants were asked to fill out the strategy questionnaire.

Data Analysis

For all of the analyses the transitions were assessed separately. The measurements for CTs and VTs were calculate using the second key press in the transition as this press would be primed by the learned first press of the transition. NCTs were calculated from all key presses that were unrelated to the CTs.

Keyboard data. A scoring program was developed in-house that measured the accuracy and reaction time of each key press. Key presses were deemed to be correct if the key press to the appropriate stimulus was recorded within the inter-stimulus interval. Reaction time was calculated only for correct key presses and was defined as the time from stimulus presentation to recorded response. If no key press was recorded within the time allowed, the response was recorded as an error of omission. If the incorrect key was pressed then it was recorded as an error of commission. For the purposes of this study both types of errors were removed from the reaction time analysis. Accuracy was scored for each individual as the percent of correct key presses out of the total key presses of that transition type in each block. The scores were aggregated as the average percent correct for each block across participants. Reaction time was calculated individually as an average of each transition type in each block. As with the accuracy measure, the average reaction for each block was calculated across participants.

Motion capture data: partial movement analysis. The first set of motion capture analyses focused on the incidence of partial key presses that were not recorded by the keyboard. The keyboard does not record a response until a key has been pressed down at least half way. Participants could press down on a key but not pass the half way point, and as such, the keyboard would not detect the response. Partial movements may be indicative of anticipatory responses to the upcoming stimulus, or as corrections of errors before the key is fully depressed. The goal was to see if partial movements occur more frequently for VT than CT, and to see if there are age differences in the incidence of partial movements. The data were first filtered using a 6th order Savitzky-Golay filter (frame size 25 samples). Secondly, a baseline had to be calculated in order to represent the rest position of the fingers on top of the keys. This position could change across participants because of the thickness of the fingers and angle of the wrist and fingers placed on the keys, and could also change during motion capture recording due to changes in the angle of the fingers. Thus, the baseline was calculated for each individual block using a robust least-squares curve fitting technique that would ignore the outliers (full movements) and model the rest position only. In order to locate the partial movements, it was first determined that a depression of 6 mm on a key was the threshold at which the keyboard would register a response. Therefore, we used this value as a threshold in the analysis such that any key press that was 6 mm or larger was recorded as a full key press. The second assumption of this analysis was that very small deflections downward in the signal could be due simply to jitter of the fingers, or noise. As such, a lower threshold was defined as one and a half standard deviations below the mean value in the y-axis for an entire block of trials. Any depression of the keys that was smaller than this value was considered to be noise. Therefore, any key press that was between the mean minus 1.5 *SD* and 6 mm below the baseline at any given time-point was considered a partial movement. The number of partial movements was calculated as a proportion of total number of movements required. These proportions were averaged for each age group, across each of the blocks.

Motion capture: full key press analysis. The second set of motion capture analyses concerned the kinematic signatures of full key press responses. The goal of this analysis was to determine what variables differed between CT and VT, and whether or not there were age differences in the kinematics of correct key press responses. Specifically, the motion capture data were used to calculate movement planning time, time to full depression of the key, time to peak velocity and peak acceleration in the key press (Figure 2). Analysis techniques were developed in-house using Matlab R2007a (The Mathworks, Inc.). The first step in this analysis was to center the data around zero, using a Matlab function for detrending digital signals. This process centered the data from all of the participants around the common baseline of zero, which is conceptually equally to the level of the keys at rest. As can be seen in Figure 2, full key presses show a characteristic asymmetrical trajectory. Therefore, we did not filter the signal before calculating the kinematic variables as the common filtering techniques tend to make the peaks more symmetrical, potentially eliminating valuable information about the key presses. The peaks, corresponding to full key presses were first detected using a simple upper threshold of anything greater than the mean plus 2 *SD* displacement below the baseline (zero in this case). In addition, a lower threshold was set at the lowest observed value of a meaningful peak in all participants' data (determined to be 15mm below the baseline) in order to ensure that large hand movements downward, and artefacts generated by the motion capture system were not selected as full key presses. Full key presses were pinpointed as local minima among the data points that fell within this threshold range. The beginning and end of the key presses were detected using a simple algorithm that searched for changes in the slope of the signal to a value less than a threshold of 0.5mm/s to the left and right of the peak. In order to ensure that these two positions were indeed at the surface of the keys the time-stamp was only accepted if the change in slope had occurred at a position equal to, or above the baseline of zero in the y-axis. This would eliminate the selection of any small slopes in the middle of a key press that were created as a result of a

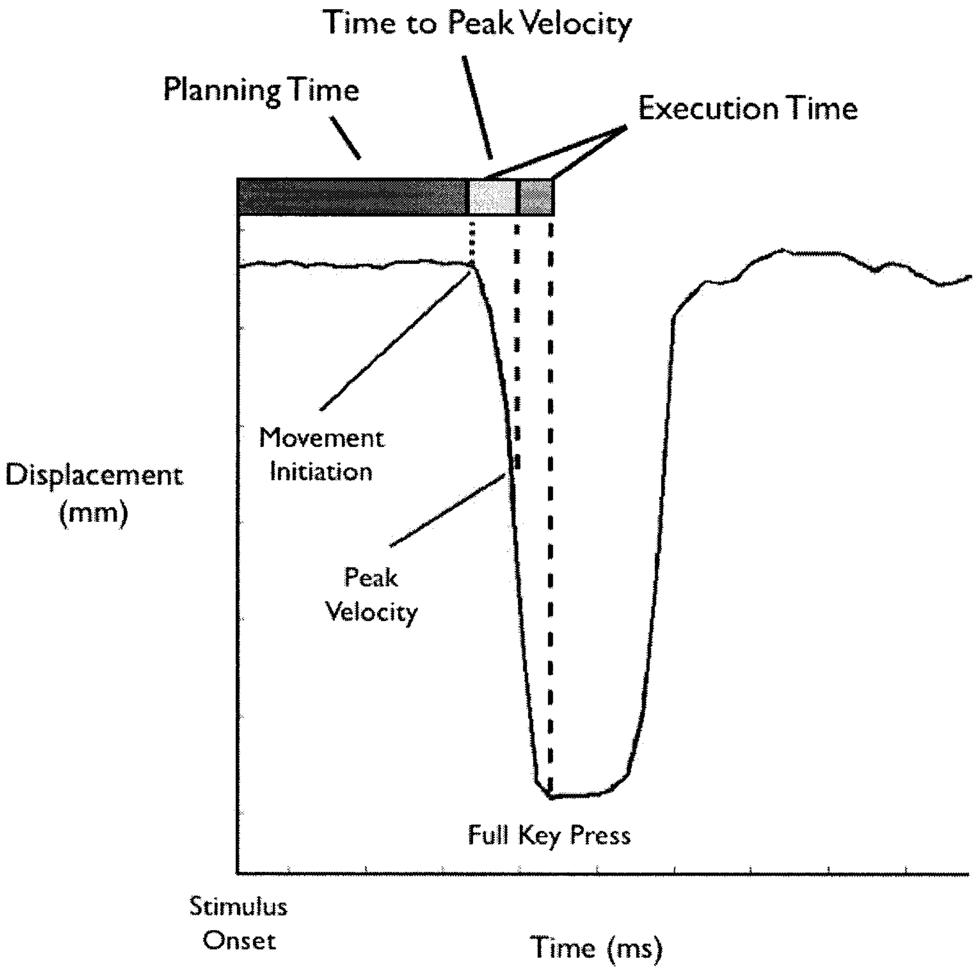


Figure 2. Example finger trajectory from stimulus presentation to key release. Important kinematic landmarks (movement initiation, peak velocity, and full key press) and parsed time components (planning time, time to peak velocity and execution time) are indicated.

participant resting briefly with a key depressed. The time-stamp of each stimulus onset was entered into the script in order to allow the calculation of planning time which was defined here as the time from stimulus onset to initiation of the key press. This variable measured the time that it takes participants to detect the stimulus and recognize its location before actually planning the movement. It was not possible in the current methodology to separate out movement planning itself from perceptual processes involved in stimulus recognition. The next variable that was calculated was the time from movement initiation to the peak in the trajectory. This gave us a measure of the time from the start of the movement to the end of the key press and will be referred to as execution time. The peak velocity and acceleration of each key press was also calculated, and velocity and acceleration profiles of the key presses were determined by calculating time measurements to index the amount of time that it took to go from movement initiation to peak velocity and acceleration of the key press. All of the kinematic variables of full key press responses were averaged across participants in each age group and block.

Results

Keyboard Analysis

Training blocks. Analysis for CTs were completed separately from NCTs as there are no NCTs in the 5-Rep block. Accuracy for CT were analyzed using a 2 x 3, age group x block mixed factorial ANOVA. There was a significant effect of block, $F(2,22)= 3.70$, $p < .05$, $\eta^2 = .25$, such that participants were more accurate in the 1-Rep block than the 3-Rep block ($p < .05$), but no other comparisons were significant ($p \geq .18$). There was no effect of age, but a marginally significant interaction ($p = .07$), however there may be a ceiling effect as the average accuracy was consistently high for both transition types and age groups across blocks (see Table 2).

Reaction time was again analyzed separately for CTs and NCTs. For CTs there was a significant main effect of age such that OA were slower to respond on average than YA, $F(1,23) = 11.94$, $p < .01$, $\eta^2 = .34$. There was also a significant main effect for block, $F(2,22)= 37.28$, $p < .001$, $\eta^2 = .77$. Post-hoc comparisons using a Bonferroni correction revealed that with increasing number of repetitions the speed of responding was faster (all comparisons significant at $p < .01$). Importantly, there was a trend towards an interaction between age group and block, $F(2,22) = 2.66$, $p = .09$, $\eta^2 = .20$. Post-hoc analysis revealed that OA were significantly slower to respond than YA in the 1-Rep ($p < .01$) and 3-Rep ($p < .01$) blocks, but OA were equally as fast as YA in the 5-Rep block ($p = .29$).

Table 2

Mean Accuracy of Younger (YA) and Older Adults (OA) Key Presses for Critical Transitions (CT) and Violation Transitions (VT)

Transition Type	Age Group	Block	Average Percent Accuracy	Standard Error
CT	YA	1-Rep	98.3	1.2
		3-Rep	98.1	0.8
		5-Rep	98.5	0.7
	OA	1-Rep	100	0
		3-Rep	96.4	1.1
		5-Rep	94.5	2.3
VT	YA	1-Rep	95.8	1.5
		3-Rep	100	0
		5-Rep	97.5	1.9
	OA	1-Rep	98.5	1.1
		3-Rep	98.5	1.1
		5-Rep	94.6	1.9

Note. The blocks refer to the repetition of the critical transition during learning either 1 repetition (1-Rep), 3 repetitions (3-Rep), or 5 repetitions (5-Rep).

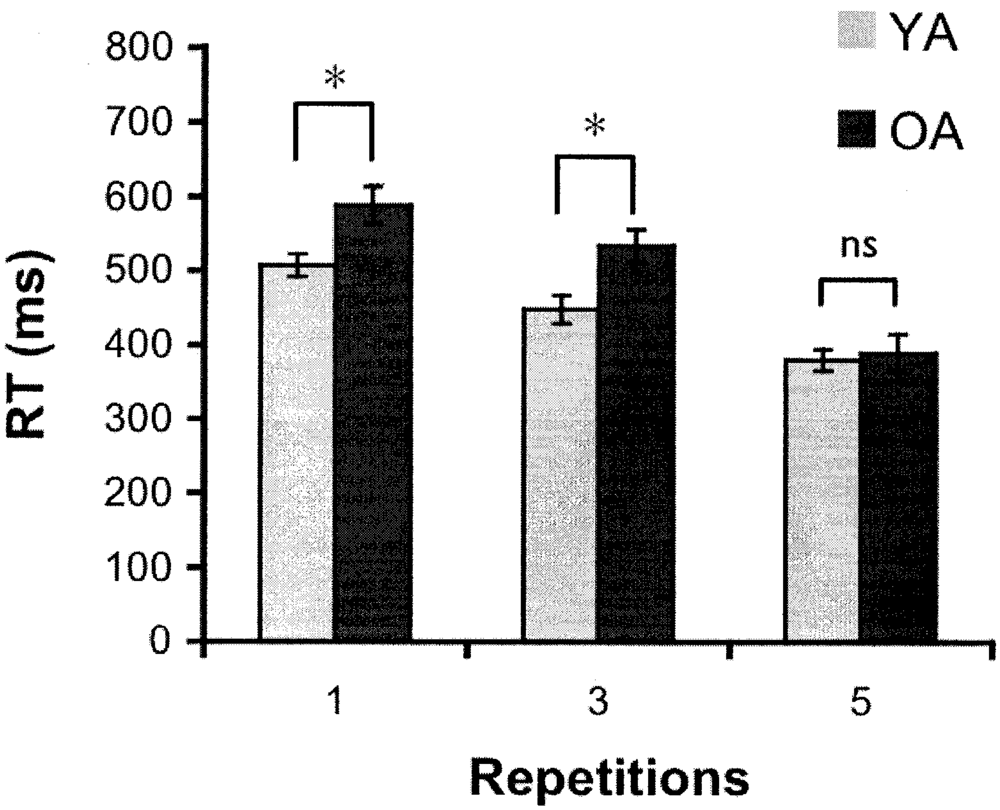


Figure 3. Reaction time (RT) for critical transitions (CT) of younger (YA) and older (OA) adults during learning blocks. OA are slower to respond when the CTs are presented once and three times per trial, but are equally as YA when the CT was presented five times per trial.

In order to ensure that the NCTs really were unpredictable random transitions, the accuracy and reaction time for NCTs were compared across the 1-Rep and 3-Rep blocks for OA and YA. The resulting 2 x 2 mixed factorial ANOVA for accuracy confirmed that there were no significant differences in accuracy for NCTs between blocks or age groups, and no significant interaction between age and block ($p \geq .21$). Again accuracy was high for both YA and OA at all blocks (see Table 3). For reaction time of NCTs there was a significant main effect for age such that OA were slower overall than YA ($F(1,23) = 10.74$, $p < .01$, $\eta^2 = .35$). There was no effect of block and no interaction between age and block ($p \geq .73$).

Testing blocks. Accuracy of key presses during the testing blocks was analyzed with a mixed factorial ANOVA where the within-groups variables were block and transition type, either CT or VT, and age group was the between-groups variable. For these analyses CTs during the learning phase were compared to VTs during test as this was the phase of the experiment in which the CT would be maximally predictable, and hence, most well learned. The results revealed that there were no significant main effects for accuracy across age, or block ($p \geq .22$). However, there was a significant main effect of transition type, $F(2,22) = 8.05$, $p < .01$, $\eta^2 = .26$, such that participants were more accurate on CTs than VTs, and there was a significant interaction between block and age, $F(2,22) = 3.61$, $p < .05$, $\eta^2 = .25$, such that YA did not differ on any block but OA were more accurate in the 1-Rep block than the 3-Rep block ($p < .05$). No other comparisons reached significance ($p \geq .08$). Participants were again performing at a high level of accuracy throughout the experiment (Table 2).

Table 3

Means and Standard Errors of all performance measures for Non-critical Transitions (NCT) during Learning and Testing Blocks

		Learning Blocks		Testing Blocks		
Performance Measure	Age Group	Mean (SE) 1-Rep	Mean (SE) 3-Rep	Mean (SE) 1-Rep	Mean (SE) 3-Rep	Mean (SE) 5-Rep
Accuracy	YA	98.0 (0.5)	97.0 (0.9)	96.9 (0.7)	96.9 (0.6)	96.0 (1.0)
	OA	95.3 (0.7)	93.6 (2.0)	97.2 (0.6)	94.3 (1.0)	92.4 (1.7)
RT	YA	509.61 (17.34)	503.98 (15.53)	502.53 (10.13)	518.07 (16.38)	511.54 (18.09)
	OA	613.31 (27.59)	599.38 (25.53)	614.44 (27.73)	608.98 (28.32)	620.44 (27.10)
Planning Time	YA	362.45 (20.35)	367.60 (19.42)	----	----	384.07 (20.69)
	OA	413.74 (24.93)	476.30 (33.51)	----	----	491.54 (22.33)
Execution Time	YA	195.82 (14.50)	187.00 (7.73)	----	----	205.01 (17.58)
	OA	191.67 (10.29)	184.42 (9.20)	----	----	191.17 (10.39)
Time to Peak Velocity	YA	126.55 (3.63)	122.76 (5.24)	----	----	131.17 (6.17)
	OA	119.78 (10.14)	117.44 (9.05)	----	----	116.95 (9.85)
Peak Velocity	YA	3.44 (0.14)	3.38 (0.17)	----	----	3.22 (0.17)
	OA	3.68 (0.14)	3.60 (0.17)	----	----	3.56 (0.15)

The critical analysis comparing reaction time on CTs to VTs across blocks and age during the testing blocks revealed that although OA were slower overall compared to YA there was a significant three-way interaction, $F(2,22) = 4.26$, $p < .05$, $\eta^2 = .28$, showing that for both YA and OA responses were slower for VT than CT but only in the 3-Rep and 5-Rep blocks (Figure 4). Furthermore, the difference between CT and VT in the five repetition block was larger for OA ($p < .001$) than YA ($p < .01$).

Like the learning blocks, NCTs during the testing blocks were compared between levels of repetition and age groups to ensure that there were no differences in accuracy (see Table 3). The resulting 2 x 3 mixed factorial ANOVA again confirmed that there were no block or age differences in accuracy ($p \geq .16$). Furthermore, analysis of the reaction time of NCTs during test revealed a significant effect of age such that OA were slower overall than YA, $F(1,23) = 11.48$, $p < .01$, $\eta^2 = .33$, but no other effects were significant ($p \geq .27$).

Motion Capture Analysis

Partial movements. For all of the kinematic measures one OA's data were removed from the analyses because of malfunction of the motion capture equipment. The kinematic data was assessed for differences in the frequency of partial movements that would be indicative of anticipatory or error correcting movements that were not picked up by the keyboard. Partial movements were compared between blocks and age groups on non-critical transitions during the learning and testing blocks separately. For learning, the only significant effect was a main effect of repetition, $F(2,20) = 4.64$, $p < .05$, $\eta^2 = .31$. Post-hoc

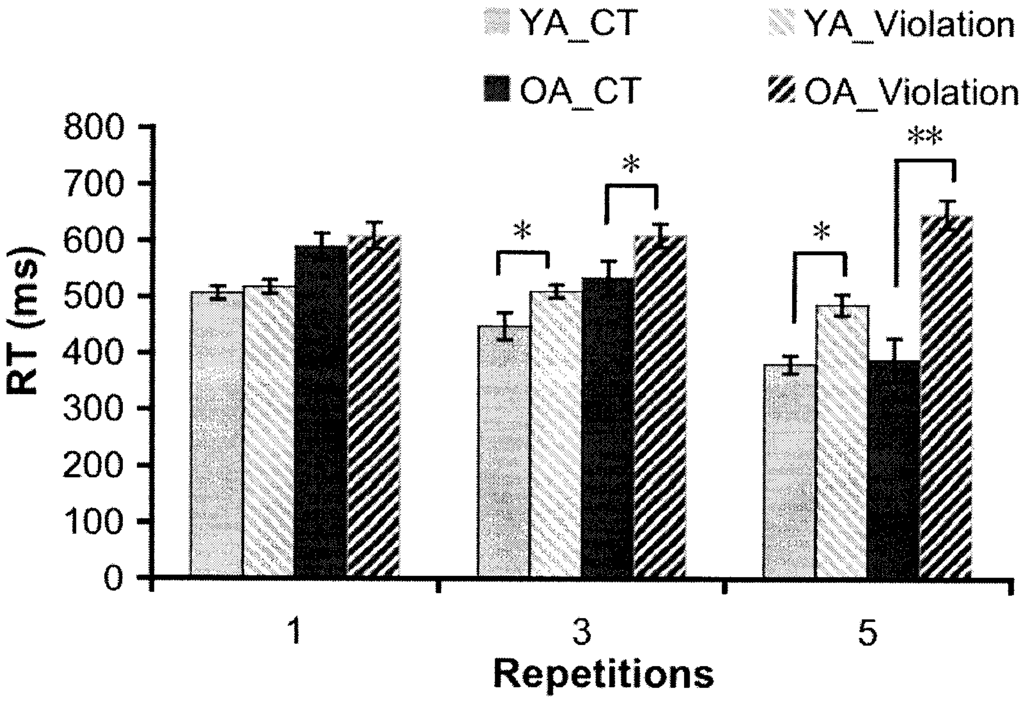


Figure 4. Reaction times (RT) plotted against level of repetition, for critical transitions (CT) during learning and violation transitions (VT) during testing. Both younger (YA) and older (OA) adults perform slower on VT compared to CT with increasing repetition, but the effect is shown to be larger for OA in the 5 Repetition condition.

analysis revealed that more partial movements were made in the 1-Rep block than the 3-Rep block ($p < .05$), but no other significant differences were found. For test, the analysis revealed that there were no significant effects of block, transition type or age. In fact, the proportion of partial movements to the number of stimuli was low for all participants (see Table 4).

Full key presses during training. The kinematic data for full key presses during the training blocks were assessed separately for the four time-course variables and the peak velocity measure. The analysis of the time to peak acceleration is not reported because it revealed the same pattern of results as the time to peak velocity for all comparisons. The CTs during the training blocks were compared across blocks and group for each of the kinematic variables. This set of analyses revealed significant main effects of repetition and age for planning time, $F(2,20) = 9.44$, $p < .01$, $\eta^2 = .48$ and $F(1,21) = 8.73$, $p < .01$, $\eta^2 = .30$ respectively (Figure 5). Post-hoc tests indicated that the participants took less time to plan CTs in the five repetition block than the other two blocks ($p < .01$) and that the one and three repetition blocks did not differ. Also, OA spent more time planning the movements than YA. In terms of the amount of time that it took participants to execute the movement, there was a main effect of repetition, $F(2,20) = 5.69$, $p < .05$, $\eta^2 = .36$, but no age effect ($p = .56$). In addition, there was an interaction between age and repetition, $F(2,20) = 4.52$, $p < .05$, $\eta^2 = .31$, such that YA were slower to press the keys during CTs in the five repetition block compared to the other two blocks ($p < .01$), whereas OA pressed the key at the

Table 4

Mean Proportions of Partial Movements in the Number of Required Responses and Standard Errors for Younger (YA) and Older (OA) Adults for Each Block.

		Learning Blocks		Testing Blocks	
Block	Age Group	Mean (SE) NCT	Mean (SE) CT	Mean (SE) NCT	Mean (SE) VT
1-Rep	YA	.071 (.030)	.008 (.009)	.067 (.030)	.100 (.063)
	OA	.077 (.023)	.042 (.024)	.104 (.040)	.075 (.037)
3-Rep	YA	.088 (.028)	.119 (.074)	.081 (.026)	.033 (.020)
	OA	.152 (.060)	.094 (.044)	.100 (.031)	.033 (.027)
5-Rep	YA	.062 (.023)	.047 (.027)	.013 (.009)	.042 (.020)
	OA	.152 (.069)	.120 (.073)	.028 (.015)	.158 (.066)

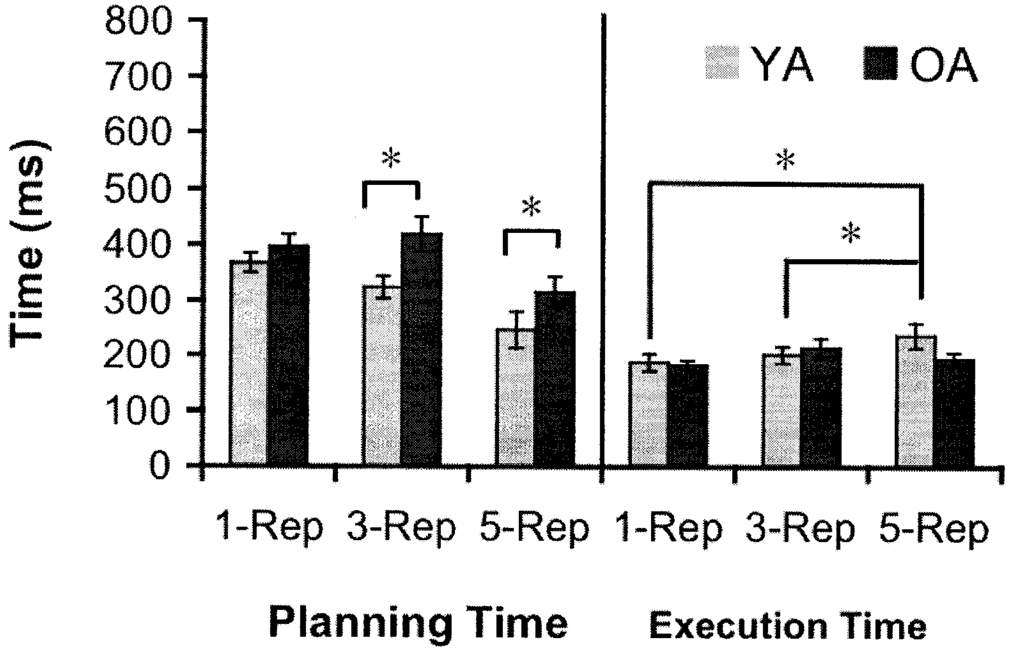


Figure 5. Movement planning time (left panel) and time to full key press (right panel) of critical transitions (CT) plotted across learning blocks for younger (YA) and older (OA) adults. YA decrease planning time with increasing repetition of the CT, but increase time to full key press. OA show a similar pattern in planning time across blocks, but not in execution time in the 5 Repetition condition (5-Rep).

same speed regardless of repetition (Figure 5). In the time that it took to obtain peak velocity of the key press there was a significant effect of repetition, $F(2,20) = 4.66$, $p < .05$, $\eta^2 = .32$, and an interaction between repetition and age, $F(2,20) = 9.01$, $p < .01$, $\eta^2 = .47$. This interaction revealed that YA reached peak velocity more slowly with five repetitions of the CT than with one presentation ($p < .05$), but no other comparisons were significant. On the other hand, OA reached peak velocity more slowly than YA with three repetitions than either one or five repetitions ($p < .01$), but no other comparisons reached significance ($p \geq .30$). In terms of the actual peak velocity that participants reached during CT in the training blocks, there was a significant effect of repetition, $F(2,20) = 41.25$, $p < .001$, $\eta^2 = .81$. Post-hoc analysis on levels of repetition revealed that overall participants reached a smaller peak velocity in the three repetition condition than the other two blocks but no other comparisons were significant.

For each of the kinematic variables the NCTs were again analyzed separately to verify that no systematic differences occurred in these "random" transitions. Specifically, a 2 x 2 mixed factorial ANOVA with the same design as the keyboard analyses was conducted on each of the kinematic variables. In terms of the amount of time spent planning movements no differences were found between the levels of repetition, but there was a significant effect of age such that OA spent more time overall planning NCTs than YA, $F = 8.39$, $p < .01$, $\eta^2 = .29$. For the remaining variables, execution time, peak velocity and time to peak velocity, no significant differences were found for NCTs (Table 3).

Full key presses during testing. For the testing blocks the kinematic analysis was limited to the five repetition condition because the purpose of this analysis was to explain the interaction between age and transition type in the reaction time data. Thus, the analysis was conducted using a 2 x 2 mixed factorial ANOVA in which age was the between groups variable and transition type, CTs during training compared to VTs during testing, as the within groups measure. The planning of movements was found to be significantly longer in the VTs than the CTs overall, $F(2,20) = 78.96$, $p < .001$, $\eta^2 = .79$, and as shown in Figure 6, it was determined that OA spent longer planning movements than YA regardless of transition type, $F(1,21) = 9.39$, $p < .01$, $\eta^2 = .31$. The time that it took for participants to press down on the keys also revealed a significant main effect of transition type such that the execution time was shorter for CTs than VTs, $F(1,21) = 8.37$, $p < .01$, $\eta^2 = .29$. There was also a significant interaction between age and transition type, $F(2,20) = 7.88$, $p < .05$, $\eta^2 = .27$. The post hoc test indicated that YA took longer to press the key for CTs than VT ($p < .001$), whereas OA responded to both transition types equally quickly (Figure 6). The time to peak velocity was found to be shorter overall for CTs than VTs, $F(1,21) = 5.69$, $p < .01$, $\eta^2 = .21$, and there was a significant interaction between transition type and age, $F(2,20) = 12.47$, $p < .01$, $\eta^2 = .37$. This interaction was such that OA were found to be faster on CTs than VTs ($p < .01$) whereas YA did not differ between transition type (see Figure 7). Finally, in the actual peak velocity of the movements there was a main effect of age, $F(1,21) = 4.6$, $p < .05$, $\eta^2 = .18$, and a marginally significant effect of transition type, $F(1,21) = 3.76$, $p = .066$, $\eta^2 = .15$.

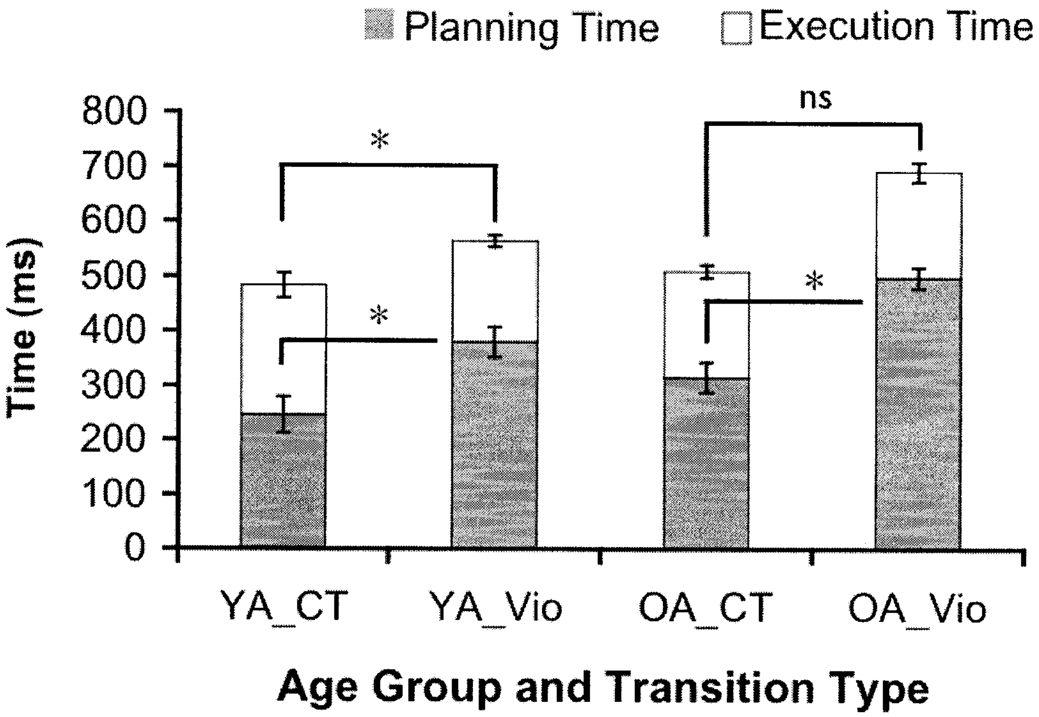


Figure 6. Planning time (bottom section of bars) and time to full key press (top part of bars) plotted for critical transitions (CT) and violation transitions (VT) during the 5 Repetition (5-Rep) condition. YA and OA exhibited a similar pattern of planning time to CT and VT. However, YA took longer to reach the full key press to the CT and a shorter time for the VT. On the other hand, OA reached their full key press rapidly regardless of the transition type.

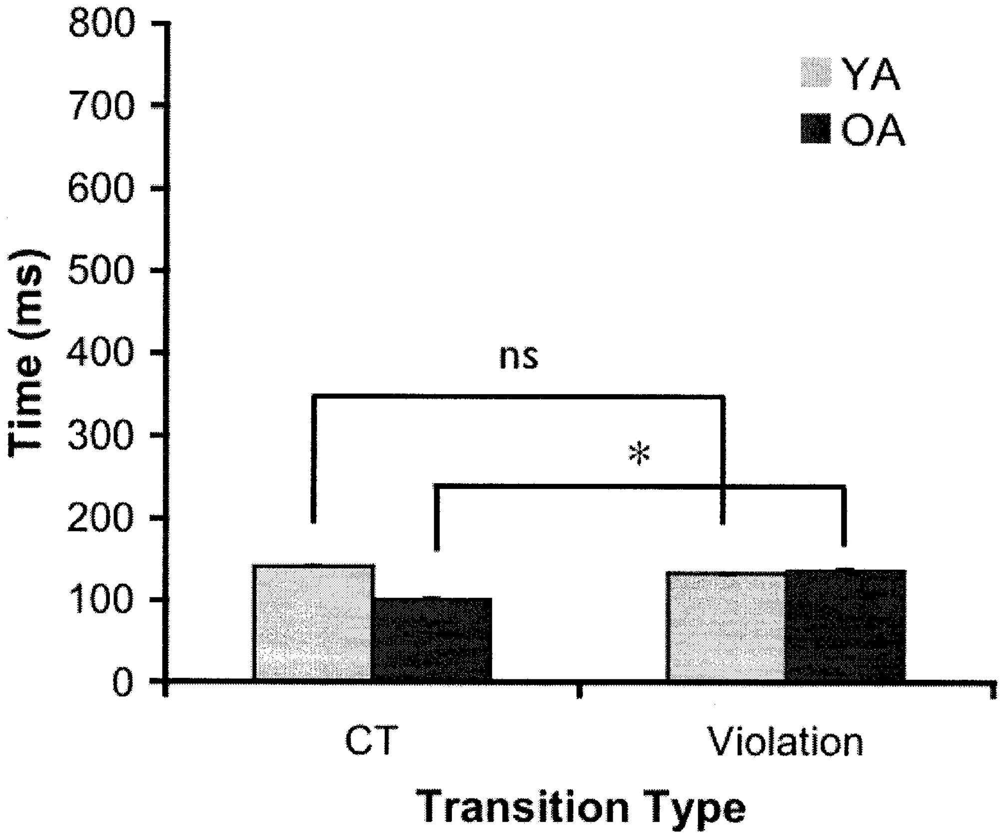


Figure 7. Time to reach peak velocity plotted for younger (YA) and older (OA) adults for the critical transition (CT) and the violation transition (VT) during the 5 repetition condition (5-Rep). YA reached peak velocity at the same time for both CT and VT, whereas OA reached peak velocity faster for CT than VT.

For the NCTs during the testing blocks planning time was found to be longer for OA than YA, $F(1,21) = 8.12$, $p < .05$, $\eta^2 = .28$, and a significant effect of block was also found, $F(1,21) = 9.04$, $p < .01$, $\eta^2 = .48$, where planning time was shorter for the 5-Rep block than the 3-Rep ($p < .05$) and 5-Rep ($p < .05$) blocks. For the execution time there was a significant effect of block, $F(1,21) = 6.10$, $p < .01$, $\eta^2 = .38$, where shorter times were taken for the 5-Rep block than the 3-Rep block ($p < .01$). In addition, there was a significant effect of block in the time to reach peak velocity, $F(1,21) = 3.82$, $p < .05$, $\eta^2 = .28$, such that the 5-Rep block was marginally faster than the 1-Rep block ($p = .06$). Finally, a significant effect of block was found for actual peak velocity, $F(1,21) = 19.18$, $p < .001$, $\eta^2 = .66$, such that peak velocity was faster for the 5-Rep block than the 1-Rep ($p < .001$) and 3-Rep ($p < .01$) blocks. No other significant effects were found for any of the kinematic variables ($p \geq .17$).

Regression Analysis. One of the major goals of this experiment was to assess the relationship between cognitive mechanisms such as executive control (inhibition specifically), and kinematic signatures of motor performance in younger and older adults. In order to attain this goal we conducted a multiple regression to see how well age and a possible measure of inhibitory ability, the Stroop effect, would predict the time that it took participants to plan their responses to violations of well learned sequences. The Stroop interference effect in this study was defined as the number of seconds per correct item in the congruent condition minus the number of seconds per correct item in the incongruent condition. We focused on the planning time parameter for the regression analysis with the assumption that the majority of executive processing would occur just prior to movement initiation. It is possible that executive control mechanisms are also functioning "on-line" or during the execution of a response, however in our data set the lack of significant findings in the partial movement analysis would argue against this interpretation. For the multiple regression analysis, planning time for violation transitions in the five repetition condition was entered as the dependent variable, while age and then Stroop interference scores were entered in a stepwise fashion as predictors. The results revealed that age accounted for a significant amount of variance in the planning time, $R^2 = 0.37$, $F(1,20) = 11.78$, $p < .01$. Moreover, after the effects of age were accounted for, Stroop interference scores accounted for an additional significant amount of the variance in planning time, $R^2 = 0.18$, $F(2,18) = 3.62$, $p < .05$. Together age and Stroop interference scores accounted for more than half of the variance in planning time for violations of well learned sequences ($R^2 = 0.55$). Figure 8 provides a scatterplot of YA and OA planning time scores plotted against Stroop interference scores.

From figure 8, it appears that there is a different correlation between the two measures for YA and OA. In order to assess whether or not Stroop interference scores were predictive of planning time for violation transitions to well learned sequences in the same manner for YA and OA we ran a separate multiple regression for each age group in which Stroop interference scores were entered as the first predictor in the model. We also added participants' difference scores on the Trails A and B tests in order to determine if task set switching ability was also predictive of planning time. For the YA, it was revealed that Stroop interference scores were predictive of planning time ($R^2 = 0.62$, $F(1,10) = 16.02$, $p < .01$), however, performance on the Trails test did not help predict planning time ($p = .59$). For the OA a different story emerged. It was found that neither Stroop interference scores ($p = .55$) or Trails test performance ($p = .22$) were predictive of planning time. Means, standard errors and t-test results for age comparisons of the Stroop test and Trails test are shown in Table 1.

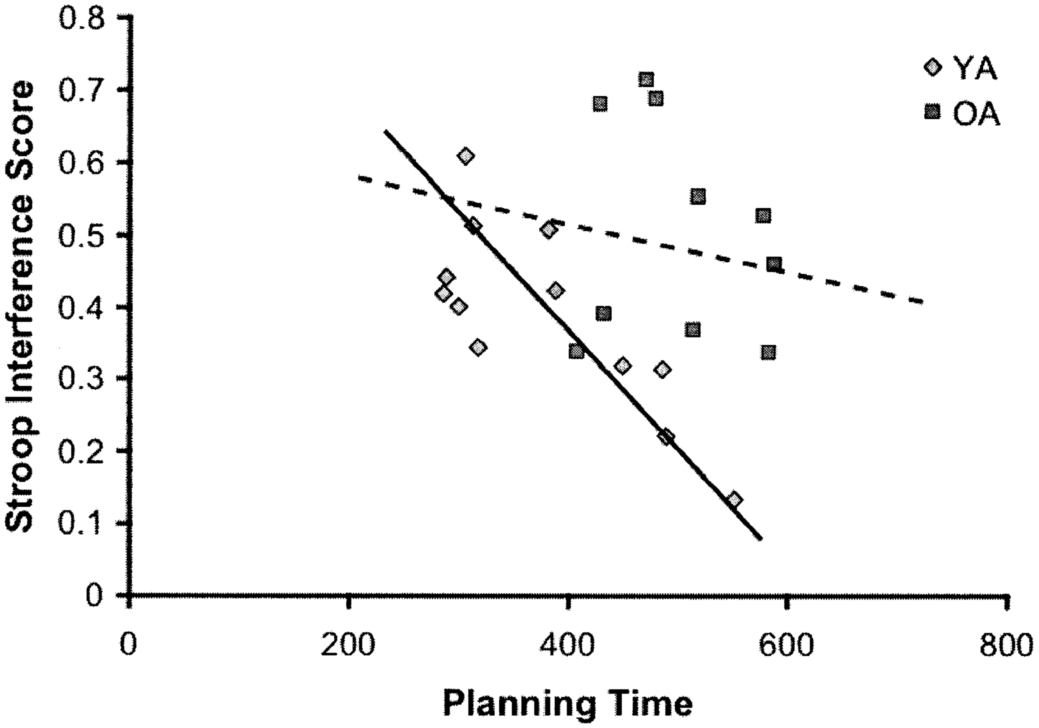


Figure 8. Scatterplot showing Stroop interference scores plotted against planning time separately for younger (YA) and older (OA) adults. This graphs shows that the relationship between these two variables is stronger for YA than OA. Note: Stroop interference scores were calculated as the time per item in the incongruent condition divided by the time per item in the congruent condition. Higher Stroop interference scores indicated less interference and lower scores indicated more interference.

Discussion

The current study employed a variation of the SRT in order to explore the role of executive control processes in YA and OA spatial motor sequencing performance. Traditional reaction time measures revealed that when executive control demands are high, OA are slower to respond, consistent with previous research. In addition, the current study used 3-D motion capture in order to separate the kinematic signatures of performance from reaction time. This analysis revealed that OA spend more time planning each movement than YA regardless of the executive control requirements. Furthermore, YA were slower to complete the full key press when transitions between elements of a series of movements were predictable, and faster to complete the press when they were required to suppress a pre-potent motor response. OA, on the other hand, were equally fast regardless of the predictability of the movements. This finding suggests that YA make slower, more relaxed movements when the response is predictable, and more rapid movements when exerting executive control. OA executed rapid movements regardless of the executive control demands of the response. Finally, regression analyses of the planning time of movements with performance on the Stroop task suggest that YA are employing similar executive control mechanisms when overcoming a pre-potent motor response to those used in the Stroop task. Contrarily, no evidence was found to suggest that OA were using the same executive control processes while overcoming the pre-potent motor responses. These results suggest that OA and YA may be using different executive control mechanisms for sequential motor performance.

The reaction time analysis of the current study was conducted to explore evidence that executive control mechanisms might be recruited for pre-potent motor responses in a spatial sequencing task. Previous research has suggested that executive control mechanisms are crucial for the ability to tap complex rhythms and switch between tapping dominant and non-dominant rhythm patterns. Moreover, OA were found to have more difficulty performing these rhythms than YA (Krampe, et al., 2005). The results of the current study support and also extend those findings into a task that requires spatial rather than temporal learning. Although the current methodology does not require participants to learn an entire sequence of events, the results are in line with the finding that OA have more difficulty with sequence tasks that require greater executive control (Krampe, 2002; and Krampe, et al., 2005). Other researchers have reported similar age-related deficits in performance on higher order, subtle sequencing tasks (e.g., Howard & Howard, 1997; and Howard, et al., 2004), but have not attributed those differences to executive control deficiencies in aging. However, given the more recent findings of Krampe et al., (2005) and the results of the current study, changes in the efficiency of executive control with age seems a viable explanation for age related declines in sequential performance. The differences in methodology between the current study and Krampe, et al. (2005), in combination with the similarity of the findings suggests that the conclusion that age-related decline in executive control can account for age related differences in sequential performance is not a task specific result. Rather, it is more likely that the deficiencies in the executive processing of OA commonly reported in the literature (e.g., Verhaeghen, et al., 2005; and Ettenhofer, et al., 2006) affects their performance on a variety of sequencing tasks.

The current study also extends previous research on sequential performance in aging by employing 3-D motion capture in order to assess kinematic aspects of cognitive/motor performance. The vast majority of cognitive aging research has focused on reaction time as an index of age related differences in performance. Whenever reaction time measures are taken as evidence of age-related decline in executive control there is a major assumption that reaction time differences reflect differences in executive functioning rather than differences in perceptual, mnemonic, or kinematic aspects of performance on cognitive-motor tasks. The analysis of the kinematic variables allowed us to separate the kinematic indices of executive control from reaction time. This analysis was focused on explaining the age related differences in the 5-Rep condition in which the CT was the most pre-potent, and therefore, the VT was the most difficult to overcome. The results indicated that although YA and OA exhibited shorter planning times to CT than VT, OA spent more time planning their movements in both cases than YA, a finding that is consistent with research on aiming movements (e.g., Haaland, et. al., 1993). Furthermore, despite the same pattern of planning time, YA and OA differed in the time that they took to execute a key press on CT and VT. Specifically, YA made slower, more relaxed movements when the finger transition was most predictable and more rapid movements when that pre-potent response was violated. On the other hand, OA made rapid movements regardless of the predictability of the stimuli, and regardless of the amount of time they spent planning (see Figure 6). These results suggest that YA use the information gained during the shorter planning times of CTs in order to make smoother, more relaxed responses. This finding is comparable to a study by Ghilardi, et al., (2003) in which it was shown that YA slow down their reaching movements to highly predictable targets. However, those authors reported the same results for OA which contradicts our findings. In our experiment the OA did not seem to use the information gained during planning of movements to allow more relaxed key presses to CT. Rather, they tended to respond rapidly when the response was highly predictable and when the pre-potent response was violated.

An important question that arises from the kinematic analysis is what cognitive processes are contributing to the differences in the time that it took YA and OA to reach peak velocity. As discussed earlier one of the most difficult challenges facing cognitive aging researchers is to find a way to separate the perceptual, cognitive and kinematic aspects of performance. Motion capture technology has provided a useful way to isolate the kinematic aspects of performance from the other contributing processes, however within the current methodology it was not possible to isolate the cognitive processes from the perceptual processes. Nonetheless, given that the key presses required in the current experiment were executed very rapidly (in less than 200ms) it is unlikely that any cognitive processes were contributing to performance “on-the-fly”, during movement execution. Therefore, it could be assumed that the majority of the cognitive processes recruited for the current task would have occurred during the planning of movements. This assumption is supported by the partial movement analysis in the kinematic data. It was hypothesized that partial movements could represent either anticipatory movements, or corrections of errors during the execution of a response. The analysis revealed that the incidence of partial movements was very low, and found not to vary as a function of the predictability of responses. This relatively infrequent incidence of partial movements, along with the short time in which movements are executed, supports the assumption that cognitive processing was limited to the planning stage of participants' movements in this experiment.

One of the major goals of the current study was to examine the relationship between cognitive processing and kinematic signatures of performance. The relationship between cognitive and motor control processes has been of recent interest to gait and balance researchers. Specifically, this line of research has shown that the gross motor control processes involved in gait and balance require both YA and OA to engage attentional processes, even in simple conditions. Furthermore, this research has shown that OA's balance and gait can be more affected than YA when attentional resources are taxed, for example when concurrently performing a balancing or gait task and an attention demanding cognitive task (for review see Woollacott & Shumway-Cook, 2002). Similarly, kinematic age differences have been revealed in the current study to support a link between cognitive processes, aging and processes of fine motor performance. The finding that YA and OA exhibited the same pattern of planning times to CTs and VTs combined with the differences in the time that each group took to execute the movements can be interpreted in two ways in terms of the cognitive processes involved. One interpretation is that YA are using different executive control processes to overcome the pre-potent CT when executing a VT than OA. It is possible that OA are executing rapid movements to highly predictable stimuli because through the use of different executive control mechanisms, different information is being derived compared to YA. Many executive processes could be involved in this ability, such as inhibitory mechanisms (Hasher, et al., 1999), task switching (Mayr, 2001), or action monitoring processes (Gerhing & Knight, 2000). Which particular processes YA and OA are using to overcome pre-potent motor responses is debatable. The current methodology does not allow any strong conclusions for any one process. The second interpretation is that the difference in time to reach peak velocity is driven by different strategies employed by YA and OA. It may be that both age groups are exercising the same executive control processes during the planning of their movements, but OA are simply employing a "rapid execution" strategy for predictable movements. The results of the correlational analysis seem to favour the former interpretation, although the current methodology does not allow us to rule out the latter. Both the Stroop test and the Trail making test were administered to determine if inhibitory processes or set switching abilities, respectively, would be related to performance on VTs. Different results were found for YA and OA. For the YA it was found that Stroop interference scores were a significant predictor of their ability to suppress the pre-potent CT, whereas performance on the trails test was not. For OA it was found that neither Stroop, nor trails test performance could predict pre-potent response suppression. This finding suggests that YA are using the same processes during the suppression of a motor response in the current task as those used to suppress the tendency to read the words in the Stroop test. As already mentioned, this ability is frequently attributed to inhibitory mechanisms (Troyer, et al., 2006) and so it may be these processes that are involved in YA performance on the VTs. However, there has been considerable debate as to whether Stroop performance is driven by inhibitory processing (e.g., MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). No evidence was found that OA are employing either inhibitory processes or set switching abilities (Arbuthnott & Frank, 2000) in order to suppress the pre-potent CTs in this study. It seems that some other executive control process must be accounting for OA performance. This conclusion is also supported by findings in the literature that suggest that OA recruit different neural networks than YA for motor performance (Mattay, et al., 2002; and Ward & Frackowiak, 2003). The final finding supporting this conclusion is that OA spent more time planning their movements than YA regardless of the predictability of the response in our experiment. This finding might reflect the fact that OA are employing a control process that requires more processing time than the inhibitory mechanisms recruited by YA.

Reaction time measures are frequently taken as indices of cognitive performance and age differences in reaction time commonly support interpretations of age related deficits in cognitive processing. As a consequence, any time that YA and OA are equated in reaction time on a particular task, performance is assumed to be the same. That is, it is assumed that the different age groups are executing their response in the same way. The results of this study call this assumption into question. When OA were equally fast to respond in terms of reaction time they were found to be spending more time planning, but less time executing their movements than YA. The implication of this finding is that equated performance in terms of reaction time does not necessarily mean that YA and OA are performing a task in exactly the same way. With age, different cognitive mechanisms, or strategies for performance could result in the same reaction time in a given task. It is also possible that OA are employing a compensatory mechanism of responding more quickly in order to overcome slower planning time.

Research has suggested that OA may use different strategies in order to compensate for changes in movement efficiency. In studies of OA typing abilities it has been shown that OA have slowed reaction time compared to YA. However, skilled typists seem to make more anticipations of upcoming key presses thereby increasing the span of movements that they are prepared to make, and in turn they may make movement preparations sooner than YA (Salthouse, 1984; and Bosman, 1993). This type of compensatory mechanism of OA makes intuitive sense in light of theories of general slowing in processing speed (Salthouse, 1996). OA may be able to make up for reduced cognitive speed by making changes in the preparation and execution of movements. Furthermore, OA may recruit cognitive mechanisms such as attentional processes to perform simple motor tasks like walking, or balancing in order to compensate for reduced motor functioning (Woollacott & Shumway-Cook, 2002). The current study is consistent with such a compensatory interpretation. OA in this experiment may be using a "rapid execution" strategy in order to make up for changes in the efficiency of executive control mechanisms operating during movement planning. Further research is necessary to fully develop a theory of compensatory motor execution for reduced cognitive efficiency in cognitive/motor tasks.

In conclusion, the current research has provided evidence that spatially defined motor sequence performance requires executive control mechanisms when pre-potent responses must be overcome. In addition, support has been provided for the suggestion that there are age differences in the executive processes employed during such a task. YA may be employing the same executive control processes in pre-potent response suppression of fine motor movements as they use during the Stroop task. However, OA may not be recruiting the same mechanisms. The current study did not provide a way to pinpoint what executive control mechanisms are driving the performance of OA. Isolating the particular executive control mechanisms that are leading to deficits in sequential action for OA is an important challenge for future cognitive aging research.

Measuring kinematic aspects of a cognitive-motor task allows one to assess the contributions of the motor system to participants' reaction time performance. When movements in a fine motor task are highly predictable YA tend to slow down their execution in order to produce smooth responses, whereas they make rapid movements when the responses violate expectations. The same pattern of response execution was not found for OA as they tended to move rapidly regardless of response predictability. The implication of the current findings are that simple reaction time and accuracy measures of performance may not tell the whole story of age related differences in motor and cognitive performance. Although the current methodology provided a way to separate cognitive and kinematic aspects of performance, future research is need to tease apart kinematic and cognitive aspects of performance from perceptual processes in order to get the full picture of the aging process. Fully understanding human aging in cognition will entail accounting for the effects of changes in the visual and auditory systems, as well as changes in movement parameters. Using techniques to isolate particular cognitive mechanisms is essential to improving our understanding of the effects of age on cognition. Perhaps current neuroimaging techniques such as functional magnetic resonance imaging (fMRI), event-related potentials (ERP) and diffusion tensor imaging (DTI) techniques will provide the methodologies necessary to make those separations.

The ability to perform a sequence of motor tasks efficiently is crucial to many activities of daily living (for example driving a car). Difficulties in performing these types of sequences can seriously hamper independence of OA, effecting their quality of life. Understanding the way in which cognitive and motor contributors to performance interact in complex tasks is an important first step for researchers towards the development of strategies and technologies that can assist OA in these tasks. The current study provides evidence that even in healthy OA there are changes in the coordination and execution of sequential actions. Changes in the relationship between the motor and cognitive system may be even more important for everyday task performance in cognitively impaired OA, a relationship that has not yet been investigated. Although the current study has provided a glimpse into the intricate relationship between cognitive and motor processes, much more research is needed to elucidate the nature of this complex relationship, and indeed a comprehensive systems based approach to understanding the aging process will require such an investigation.

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Appendix A

Telephone Screening Survey

Telephone Screening Procedure: MFST study (2006)

Introduce yourself: "Hi, my name is ______. I am calling from the Dept. of Psychology at Concordia University. We are conducting a study on motor learning. You recently participated in study in our lab and indicated that you would be interested in hearing about new studies. Would you like to hear about a new study that we are currently conducting at the Loyola campus?**[If "NO", then ask them if it would be Ok if we call them back another time for another study][If Yes...]** First let me tell you a little bit more about the study. "The study is related to motor learning. We will present you with a display of four boxes on a computer screen that will light up one at a time. Each box corresponds to one of the four fingers on your right hand. Your task will simply be to follow the boxes as they light up and press a key on a piano-type keyboard with the corresponding finger. Thus, you will be making a series of key-presses with the four fingers on your right hand. The study is being conducted at the Penhune lab at Concordia University. (Loyola Campus, SP-250.00). For this study we would need you to come in for one day for approximately 1 hr."You will be reimbursed $10, for your time and participation."**Would you be interested in participating?[If yes...]** Before we book an appointment, I have a few general health questions and questions about musical experience that are relevant to this study. **[If yes to any of the following then suggest that this study may not be the right one for them but perhaps they wouldn't mind if we called them for another study]**

(1) Are you right handed? If they are not sure ask them which hand do they normally hold a pair of scissors in, which hand do they hold a knife when cutting bread?

(**IF NO**...for this particular study we are looking for specifically for right handed individuals. If you like we could call you back for the next study...)

(2) Are you color blind? (If yes, exclude...and say: for this particular study the colors red and green are used frequently and so it would be better if I saved your name for another study...is that Ok?

(3) A. Have you had a serious injury to your hand/arm or medical illness that would affect your movement? (e.g. Parkinson's disease, MS, severe arthritis, etc.)**B. Are you taking any medication that would affect your movement?** If they tell you a certain medication, ask them what they are taking it for...(if they are taking something for neurological disease (i.e. Parkinsons, MS) then exclude.)(**IF YES**...this study requires a lot of repetitive movements of the hands/fingers and so it may not be the best study for you, would you mind if we keep your name on our list for other studies?)

(4) Have you had any head injuries or a stroke? (Exclude if person had a

____, c) ___________________________________

* How old were you when you first started playing/singing/dancing? a) _______, b) _______, c) _______

* How did you learn to play/sing/dance? a) _______________, b) ________________, c) ____________

* For how many years did you play/sing/dance?

0-3 yrs: a) ☐ b) ☐ c) ☐

4-8 yrs: a) ☐ b) ☐ c) ☐

9-13 yrs: a) ☐ b) ☐ c) ☐ **ADD YRS**: ____________________

14 + yrs: a) ☐ b) ☐ c) ☐

If stopped, at what age did you stop? a) _____________, b) _____________, c) _______________

* Are you currently practicing? a) YES ☐ NO ☐ b) YES ☐ NO ☐ c) YES ☐ NO ☐

(What is important here is that the person is excluded if they are currently practicing a musical instrument or have had more than three years of musical experience)If they are currently practicing or have 3+ years musical experience then again tell them that for this study we aren't using people with music experience because we know that they perform better than people without musical experience on this task…perhaps they would like to come in for another study

Appendix B

Demographic/Medical Questionnaire

ID#______________

Demographics Questionnaire

We are interested in your personal history because it may help us to better understand the results of our study. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. Thank you for your help.

Demographics

Date of Birth (D/M/Y):______________ 2. Age:____________

3. Gender: *(circle response)* (1) Male (2) Female

4. Handedness: *(circle response)* (1) LEFT (2) RIGHT (3) BOTH

5. Present marital status: *(circle response)*
   - (1) Single – never married
   - (2) Married
   - (3) Separated
   - (4) Divorced
   - (5) Widowed
   - (6) Cohabit

Language

6. Place of Birth:____

7. Languages Spoken (in order of fluency):__________________________________

8. Primary Language/Language of choice:__________________________________

9. Language at home:________________________ 8. At Work (if applicable):______________

10. Language of Education:______________________________________

11. At what age did you first learn English? _______________________

12. At what age did you become fluent in it?_______________________

13. How many years of education do you have at this time? (i.e., your highest level achieved?)

1 2 3 4 5 6	7 8 9 10 11	12 13	14 15 16	17 18 19 20 21 22 23 24 25
Elementary	Secondary	Cegep	Undergrad	Graduate Professional

14. What is or was your main occupation?

____

Medical History

15. Do you have now, or have you had in the past -*(please circle your response)*

Vision:				
A	(i) **Nearsighted**	NO / YES	(ii) **Farsighted**	NO / YES
B	(i) **Glasses**	NO / YES	(ii) **Contact lenses**	NO / YES
C	**Cataract**	LEFT / RIGHT / BOTH / NEITHER		
D	**Colour blind**	NO / YES		
Hearing:				
E	**Hearing Trouble**	NO / YES		
F	**Hearing Aid**	LEFT / RIGHT		

16. Have you ever been unconscious, had a head injury or had blackouts?
    A) NO / YES
    B) Cause:____________________________________
    C) Duration:__________________________________
    D) Treatment:_________________________________
    E) Outcome:__________________________________

17. Have you been seriously ill or hospitalized in the past 6 months?
    A) NO / YES
    B) Cause:____________________________________
    C) Duration:__________________________________

Do you have now, or have you had in the past:

18	a) a stroke	No / Yes	When?
	b) transient ischemic attack	No / Yes	
19	Heart disease	No / Yes	Nature (MI, angina, narrowing of arteries):
20	High blood pressure	No / Yes	If yes, is it controlled?
21	High cholesterol	No / Yes	
22	Bypass surgery	No / Yes	
23	Other surgery	No / Yes	Nature:
24	Seizures	No / Yes	Age Onset_____, Frequency__ Cause______, Treatment_____
25	Epilepsy	No / Yes	
26	a) Diabetes	No / Yes	Type 1/ Type 2 Age Onset______ Treatment_________________
	b) Insulin Dependent	No / Yes	
27	Thyroid disease	No / Yes	
28	Frequent headaches	No / Yes	Tension / Migraine
29	Dizziness	No / Yes	
30	Trouble Walking (unsteadiness)	No / Yes	
31	Arthritis	No / Yes	
32	Any injuries to the lower limb (e.g., hip, knee, ankle)	No / Yes	
33	Serious illness (e.g., liver disease)	No / Yes	
34	Neurological Disorders	No / Yes	
35	Exposure to toxic chemicals	No / Yes	
36	Depression	No / Yes	
37	Anxiety	No / Yes	
38	(Other) psychological difficulties	No / Yes	
39	Hormone Replacement	No / Yes	
40	Steroids	No / Yes	

Continued...

37. Medication: Please list the medication you are currently taking and any other medication that you have taken in the past year

	Type of Medication	**Reason for Consumption**	**Duration of Consumption and Dose**
A			
B			
C			
D			
E			
F			

38. Approximately how many drinks of alcohol do you have per week?
(1 drink = 1 beer, 1 glass of wine, 1 oz of liquor)

____

39. Do you use non-prescription drugs for recreational purposes? NO / YES
If YES, How many times per week: (A) 1 - 3 (B) 4 - 6 (C) more than 6

40. Do you smoke? NO / YES
If YES, How many packs a day? ____________________

41. Present Problems - Are you currently troubled by any of the following?

A	Concentration / Attention Problems	No / Yes	Nature:
B	Memory Problems	No / Yes	Nature:
C	Difficulties finding words	No / Yes	Nature:

42) How would you rate your health? 1) poor 2) fair 3) good 4) very good 5) excellent

43) How would you rate your level of familiarity with computers and/or electronic devices requiring manual manipulation? 1) poor 2) fair 3) good 4) very good 5) excellent

Comments: ____
____
____
____
____

Appendix C

Consent Form