Dual Mechanisms of Control in Fine Motor Response Inhibition: A Comparison Between Young and Older Adults

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Abstract

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While past studies have proposed that age differences in fine motor response inhibition can be partly explained by age-related declines in proactive cognitive control, this association has never been formally investigated. The present study thus aimed to examine the extent to which fine motor response inhibition relies on specific modes of cognitive control. To do so, 34 younger adults (YA) and 26 older adults (OA) completed a novel visual-motor finger sequencing task incorporating the AX-CPT paradigm, a common test of cognitive control processes. Participants were first trained on a short sequence of key presses to develop a prepotent visual-motor pattern. Then, they completed mixed blocks of sequences composed of 70% prepotent sequences and 30% conflict sequences, for which successful performance relied on response inhibition and reprogramming to override the prepotent pattern. In the final two blocks, stimulus onsets were preceded by an asterisk cue to promote the use of proactive control. Results from linear mixed effects models showed that cueing improved reaction time performance across all sequence types, and particularly so for the conflict sequence causing the most proactive interference ($\eta_p^2 = 0.03$). However, the effect of cueing did not significantly differ across age groups. Moreover, OAs' reaction patterns across sequence types resembled YAs'. This implies that inducing proactive control through cueing may be a viable means of improving fine motor response inhibition. However, given our high-performing OA sample, further investigation is needed to determine whether promoting proactive control will help *all* OAs as much as YAs.

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Introduction

The Canadian population is aging. In 2016, seniors (defined as older adults over the age of 65) outnumbered children and youth under age 15 – a first in Canada's history (Public Health Agency of Canada, 2021). In 2019, there were 6.6 million seniors in the country, making up almost 20% of the overall population. By 20, it is estimated that there will be about 10.7 million seniors, and that population aging will continue to accelerate over the next two decades. Nationally and internationally, these trends are due to a combination of decreasing fertility and mortality rates, and the aging of baby boomers (Public Health Agency of Canada, 2021; Rudnicka et al., 2020).

In response to these demographic trends, there has been a focus on the concept of healthy aging, which the World Health Organization (2015) defines as "the process of developing and maintaining the functional ability that enables well-being in older age", and on how to promote healthy aging. Functional ability is conceptualized as one's intrinsic capacity (i.e., physical and mental abilities), one's environment (i.e., physical, social supports), and their interactions (World Health Organization, 2015; Zhou & Ma, 2022). Recent work on how to maintain, evaluate and predict intrinsic capacity in older adults has grouped those abilities into five key domains: locomotion, cognition, vitality, psychological, and sensory (Beard et al., 2019, 2022; Cesari et al., 2018). A large body of research shows that the sensory, motor, and cognitive systems, as well as their coordinated integration, decline even in the context of typical aging (Oh-Park, 2017; Paraskevoudi et al., 2018; Park et al., 2001; T. Salthouse, 2012; T. A. Salthouse, 2019; Tuokko et al., 2005). Declines in those systems can in turn have a negative impact on older adults' daily functioning, productivity, independence, and in some case, survival (Burton et al., 2006; Gopinath et al., 2012; Gross et al., 2011; Han et al., 2016; Lewis & Miller, 2007; Lin et al., 2004; Njegovan et al., 2001; Studenski et al., 2011; Tomaszewski Farias et al., 2009; Wood et al., 2005).

Moreover, as digital technology continues to become more ubiquitous in our society, there is a growing need for older adults to become familiar and interact with digital devices such as computers, smartphones, touch pads, and other digital interfaces. Indeed, the number of older adults who own a computer and/or a smartphone has sharply increased within the past decade, and this upward trend has been further accelerated since the COVID-19 pandemic (Mace et al., 2022). Consequently, there is a growing need for older adults to maintain good cognitive abilities, fine motor control, and fine motor coordination (Charness & Boot, 2009; Czaja et al., 2006).

Thus, there is a growing interest and need to further our understanding of the processes underlying functional independence so that it can be maintained for as long as possible. The present thesis will focus on the cognitive and motor systems in typical aging; specifically, on the interplay between cognitive control and fine motor control.

Cognitive Aging – Behavioural and Neural Changes

It is well-established that in the context of typical aging, some cognitive processes experience more significant declines than others, while other processes are maintained and sometimes even improve over time (Park et al., 2001). Cognitive aging theories commonly categorize one’s various cognitive abilities as being either crystallized or fluid in nature (Baltes, 1993; Cattell, 1971; Horn, 1970). Crystallized abilities are based on experience and reflect the cumulative, overlearned, well-practiced, and familiar knowledge one gains throughout their life such as vocabulary, language comprehension, and general knowledge. In contrast, fluid abilities require one to attend, process, manipulate, and/or learn new information from their environment, and include abilities such as processing speed, memory, and executive functions or cognitive control processes (Ackerman, 1996; Baltes, 1993; Harada et al., 2013; Paraskevoudi et al., 2018; Park et al., 2001; Spreng & Turner, 2019).

While crystallized abilities are well preserved in old age or even improve, fluid abilities reach their peak in the second decade of life and show a steady and near linear decline as one becomes older (Baltes, 1993; Paraskevoudi et al., 2018; Park et al., 2001; Spreng & Turner, 2019; Verhaeghen, 2003; Verhaeghen & Cerella, 2002). Additionally, it has been shown that to compensate for declines in fluid abilities, older adults increasingly rely on crystallized abilities to maintain their cognitive performance and to solve everyday problems (Baltes et al., 1999; Chen et al., 2017). These changes are demonstrated by the way performance on various neuropsychological tasks and everyday problems evolve with increasing age. For instance, performance on measures of world knowledge (crystallized, accumulated knowledge) have been shown to be relatively well preserved, and there is evidence that social reasoning improves with age (Gross et al., 2011; Park et al., 2001; Spreng & Turner, 2019). Conversely, steady declines in performance are observed on measures of working memory, long-term memory, processing speed, and cognitive control processes such as inhibitory control and task-switching (Chalfonte & Johnson, 1996; Hedden & Park, 2001; Kramer et al., 1999; Park et al., 2001; Spreng & Turner, 2019; Zacks & Hasher, 1994).

Age-related decline in fluid abilities is also paralleled by changes in the neuroanatomy and function of the brain. Aging is associated with widespread decreases in gray and white matter volume in regions like the prefrontal cortex, hippocampus, caudate, cerebellum, and association cortices, as well as with loss of white matter integrity (Buckner, 2004; Kaup et al., 2011; Paraskevoudi et al., 2018; Raz et al., 2005; Spreng & Turner, 2019, 2019). It is also correlated with disruptions in major functional neuronal networks such as the default network and the frontoparietal network, and these disruptions are in turn associated with cognitive and motor deficits including impairments in response inhibition, attentional processes, processing speed, and working memory (Andrews-Hanna et al., 2007; Paraskevoudi et al., 2018). Moreover, many studies have observed an age-related enhanced bilateral recruitment of the lateral prefrontal cortices, which are critically involved in the implementation of cognitive control processes when completing goal-directed tasks. However, there remains debate as to whether this increased prefrontal activity serves as a compensatory mechanism for age-related declines in cognitive resources or is simply an age-related difference in brain activity due to neural inefficiency or dedifferentiation (Cabeza et al., 2018).

Cognitive Control and Its Underlying Processes

As discussed previously, executive/cognitive control processes are part of one's fluid abilities that decline with age, and they are a critical aspect of human cognition and everyday functioning. Control processes enable one to regulate, coordinate, or plan their thoughts and actions in accordance to their goal and in an everchanging environment (Manard et al., 2014; Miller & Cohen, 2001). Examples of situations that require cognitive control include: doing groceries and mentally keeping track of the items you already have and the items you need to buy, shifting your attention between two tasks you need to complete in parallel, driving a car and paying attention to the road instead of getting distracted by the radio, and writing a manuscript while resisting the urge to watch a riveting animal documentary. Moreover, it is widely acknowledged that impairments in cognitive control are a significant feature of numerous psychological and neurocognitive disorders such as Alzheimer's disease, Parkinson's disease, depression, among others (Braver et al., 2021; McTeague et al., 2016).

Various definitions of executive control functions have been proposed and debated in the literature thus far (Baddeley & Hitch, 1974; Chan et al., 2008; Diamond, 2013; Friedman et al., 2006; Karr et al., 2018; Miyake et al., 2000; T. A. Salthouse et al., 2003). Miyake et al. (2000)'s model is among the most commonly cited and replicated (Baggetta & Alexander, 2016; Jurado & Rosselli, 2007; Lehto et al., 2003). In this model, executive function is thought to be both a unitary construct with a common underlying mechanism and three separate but moderately correlated components: shifting, updating, and inhibition (Miyake et al., 2000). Shifting refers to the ability to flexibly switch between tasks or mental sets, while updating involves actively monitoring and manipulating the contents of working memory such that information that is no longer relevant is replaced by newer, more relevant information. Finally, inhibition (response inhibition) refers to the ability to *deliberately* suppress a prepotent or automatic response when necessary, and to subsequently reprogram a more appropriate action (Miyake et al., 2000).

Response Inhibition in Older Adulthood

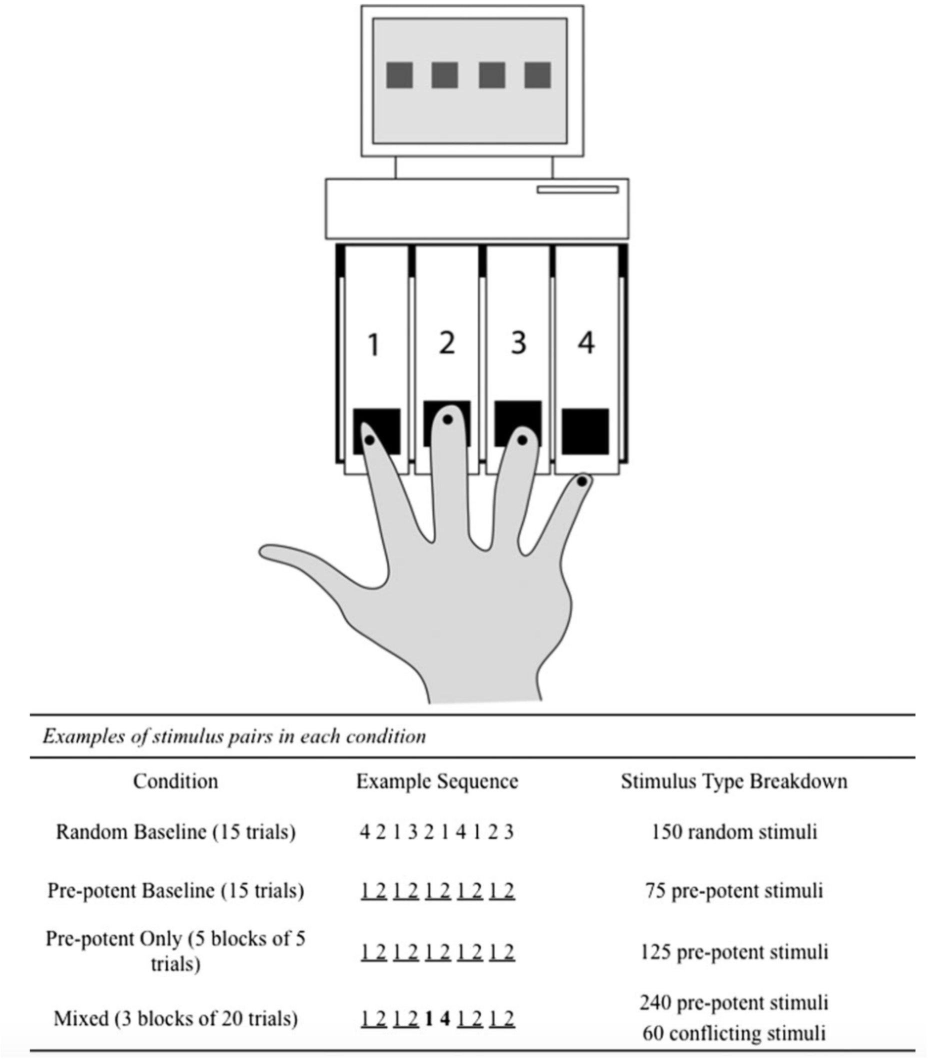
The ability to inhibit prepotent responses applies to both habitual thoughts and habitual motor actions (Hasher & Campbell, 2020). For example, if one's dominant arm were injured, reaching for objects with the other arm would require response inhibition to avoid movements of the injured dominant arm. In the cognitive domain, when a cue triggers many responses at once, failure to suppress the irrelevant competing responses may result in retrieval failures (Lustig &

Jantz, 2015). Age-related declines in response inhibition are well documented in the literature using tasks such as the Stroop, go/no-go and stop-signal tasks (Andrés et al., 2008; Comalli et al., 1962; Dorfman, 1998; Hasher & Campbell, 2020; Rey-Mermet & Gade, 2018; Troyer et al., 2006). Inhibition with respect to gross motor control has also been investigated extensively within older adults, with studies showing that decreasing response inhibition capabilities is associated with worse postural control, step initiation and suppression, and gait (Cohen et al., 2011; England et al., 2021; Potocanac et al., 2015; Sparto et al., 2013). However, the aging of response inhibition with respect to complex fine motor tasks is a relatively understudied area despite the upper limbs being the most active part of the human motor system and their marked age-related degradation (Frolov et al., 2020).

Past studies conducted at Concordia University have used a finger-sequencing paradigm to examine age differences in fine motor response inhibition (Korotkevich et al., 2015; Trewartha et al., 2009, 2011, 2013). Shown in Figure 1, the task involved younger and older adult participants making key presses using four fingers from their right hand on a piano-type keyboard, while viewing a computer monitor. Four dark gray boxes were presented horizontally on the screen, and each box represented a particular finger as well as one of four consecutive keys on the keyboard. The boxes on the screen changed color one at a time, and participants were instructed to follow along and press the corresponding key with the assigned finger as quickly and accurately as possible. Participants first learned a prepotent action by repeating the same pair of key presses for 15 trials. In the subsequent condition, trials were heterogenous, containing both the prepotent sequence and conflict sequences (see Figure 1 for example). Conflicting sequences consisted of the first key press from the prepotent pair followed by an

Figure 1

Finger Sequencing Task Apparatus and Sample Trials for Each Task Condition



Examples of stimulus pairs in each condition

Condition	Example Sequence	Stimulus Type Breakdown
Random Baseline (15 trials)	4 2 1 3 2 1 4 1 2 3	150 random stimuli
Pre-potent Baseline (15 trials)	1 2 1 2 1 2 1 2 1 2	75 pre-potent stimuli
Pre-potent Only (5 blocks of 5 trials)	1 2 1 2 1 2 1 2 1 2	125 pre-potent stimuli
Mixed (3 blocks of 20 trials)	1 2 1 2 **1 4** 1 2 1 2	240 pre-potent stimuli 60 conflicting stimuli

Note. Finger sequencing task used in Trewartha et al. (2011, 2013) and Korotkevich et al. (2015)'s studies. When a box on the monitor changed colour, participants pressed on the corresponding key with the corresponding finger. Illustration taken from Trewartha et al. (2013).

unexpected alternate second key press, and required the inhibition of the prepotent finger sequencing action and reprogramming to the appropriate motor response. Results from those studies showed that older adults experience significant declines in fine motor response inhibition and reprogramming, as well as in conflict adaptation. Moreover, those age-related declines were proposed to be associated with reduced cognitive capacity and with older adults favoring an increasingly more reactive form of cognitive control (Braver, 2012), but this speculation was not formally investigated in terms of age-related declines in proactive control.

Proactive and Reactive Control – A Dual Mechanisms View of Cognitive Control

The dual mechanisms of control (DMC) framework is a prominent model that focuses on the temporal dynamics of cognitive control processes (Braver, 2012). The central hypothesis of the DMC model is that cognitive control operates in two distinct modes: proactive and reactive. Proactive control is employed in anticipation of cognitively demanding events in order to optimally bias attention, perception, and action systems in a goal-driven manner, and requires the active and sustained maintenance of goal-relevant information in one's working memory. As such, proactive control enables one to anticipate and prevent interference before it occurs to optimize performance. In contrast, reactive control is akin to a late correction mechanism that is employed as needed and in response to a conflict or high interference event. In other words, reactive control is deployed after the onset and detection of interference, and goals are transiently reactivated. Each mode of cognitive control is also associated with its unique neural signature. Proactive control is associated with sustained activation of the prefrontal cortex (PFC), which reflects the active maintenance of goal-related information. By contrast, reactive control is associated with transient activation of the lateral PFC and brain regions involved in conflict monitoring or episodic/associative cueing such as the anterior cingulate cortex, posterior parietal cortex, and medial temporal lobe (Botvinick et al., 2001; Braver et al., 2009, 2021).

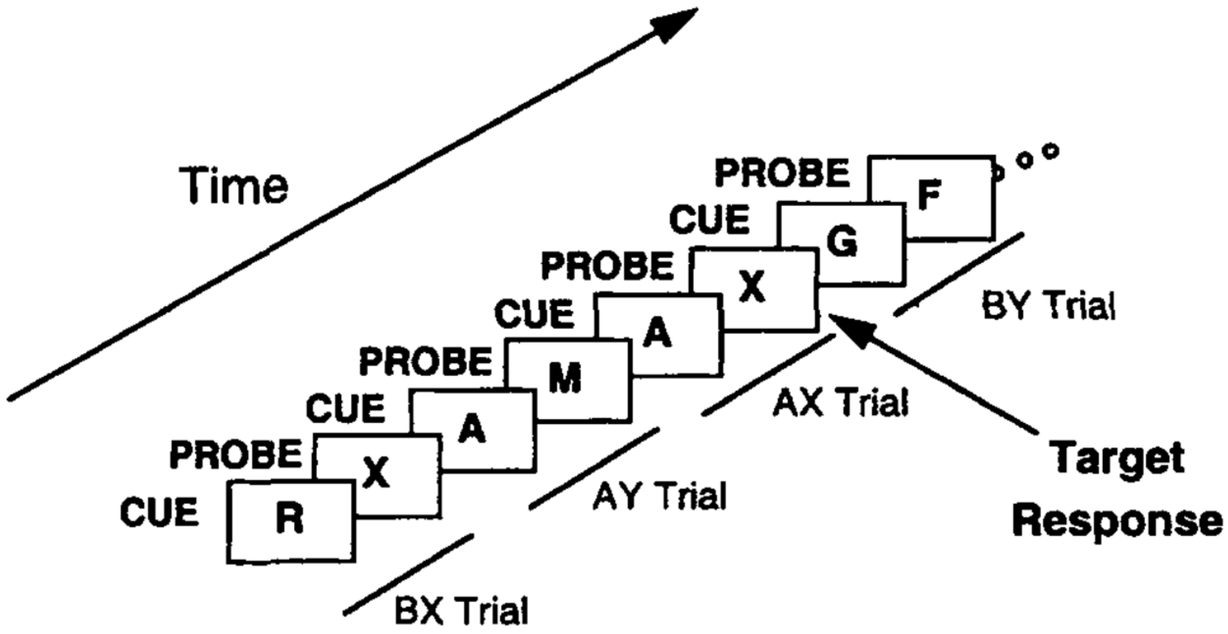
While proactive control optimizes performance, it is more cognitively taxing compared to reactive control due to the sustained activation of goal-relevant information. Therefore, successful cognition relies on an adaptive mixture of proactive and reactive control (Braver, 2012). However, there is variation within and between individuals in terms of which mode of cognitive control is favored over the other (task and state related versus trait related), and between different age groups (Braver, 2012). Previous studies have shown that overall, while younger adults have a bias toward proactive control, typical older adults have a bias toward reactive control due to decreasing cognitive resources such as working memory capacity and processing speed. Moreover, there is evidence that while there is an age-related decline in proactive control, reactive control is relatively spared in old age (Ball et al., 2023; Braver, 2012; Bugg, 2014; Czernochowski et al., 2010; Manard et al., 2014).

Assessing Proactive and Reactive Control – The AX-CPT

The AX-Continuous Performance Test (AX-CPT), shown in Figure 2, is a paradigm that has been commonly used to investigate proactive and reactive control due to its simplicity and applicability in a wide range of populations (Barch et al., 2009; Braver et al., 2001; Chatham et al., 2009; Gonthier et al., 2016; Iselin & DeCoster, 2009; Paxton et al., 2008). In this task, participants are presented with a series of single letters that are grouped as cue-probe pairs; in each trial, a cue letter is presented, followed by a probe letter after a delay period. There are four types of cue-probe pairs: the target AX (an A cue followed by an X probe), AY (an A cue followed by any letter other than X), BX (any non-A cue followed by an X probe), and BY (any non-A cue followed by any non-X probe). Participants respond “yes” to AX pairs, and “no” to

Figure 2

Schematic of AX-Continuous Performance Test (AX-CPT) Paradigm



Note. Single letters are displayed as a series of cue-probe pairs. The target requiring a response is defined as an X probe when and only when it is preceded by an A cue. The task has three types of non-target trials: AY, BX, and BY (Y refers to any non-X probe, and B refers to any non-A cue). Illustration taken from (Braver et al., 2001).

the other combinations. Importantly, 70% of the trials consist of the AX sequence while the remaining 30% are equally divided between the non-target sequences (AY, BX, BY), leading participants to strongly associate A cues with X probes. This strong association, in turn, leads participants to an increased expectancy of a target following an A cue, and to a prepotent response tendency when an X probe is presented to them.

Due to the delay between the offset of the cue and the onset of the probe, one can complete the AX-CPT using either a more proactive or reactive strategy. For instance, individuals who rely more on proactive control can prepare their response after seeing a cue by actively maintaining both the goal of the task (respond only to AX pairs) and the nature of the cue (A or B cue) during the delay period. Alternatively, individuals who favour a more reactive strategy can simply wait until the target is presented. Should the probe be an X, they can "in-the-moment" retrieve the cue that was presented before to determine whether they should make a response or not. In the event that a Y probe is presented instead, there would be no need to retrieve information about the cue in order to choose the appropriate answer.

The extent to which one tends to employ one mode of cognitive control over the other can be assessed through the AX-CPT because they favour and impair different sequences. Proactive control is beneficial for BX because the B cue can facilitate the inhibition of the dominant but inappropriate response when an X probe is shown subsequently. However, it is detrimental to performance on AY sequences because the A cue triggers a false expectation that the following probe will be an X probe. Conversely, reactive control is beneficial for performance on AY because the impact of the cue is lessened, but performance on BX is impaired because the prepotent X response needs to be overridden on the spot, without a strong representation of the preceding cue. Older adults typically show impaired performance on BX trials, but relatively spared performance on the AY trials compared to younger adults (Braver et al., 2001). Moreover, older adults' impaired performance on BX trials were primarily in terms of slower reaction times rather than increased errors, which further suggests that reactive control may be relatively intact (Braver et al., 2005).

Summary and Open Questions

A large body of research has shown that cognitive control processes (switching, updating, inhibition) are subject to decline in typical aging, and that those abilities are crucial to one's everyday functioning. Previous studies of response inhibition and fine motor sequencing have proposed that age-related declines in proactive control may underlie the age-related performance declines. However, this association has not been formally assessed.

The Current Study

To address this gap, the present study used the DMC framework and AX-CPT method to examine the extent to which fine motor response inhibition relies on specific modes of cognitive control. To do so, younger (YA) and older (OA) adults completed a newly programmed task that combined the finger sequencing task (Korotkevich, 2015; Trewartha, 2011, 2013) with the AX-CPT paradigm. Like the finger sequencing task, participants were first trained on a sequence of two key presses, thus developing a prepotent motor response. Participants next completed mixed blocks primarily composed of the prepotent sequence and less frequently occurring conflict sequences, for which successful performance relied on response inhibition and reprogramming. The number of prepotent and conflict sequences in each block followed the same proportions as the four different cue-probe pairs in the AX-CPT. In the last two blocks of the task, stimulus onsets were preceded by a cue (asterisk above the box), to promote the use of proactive control.

Based upon the literature showing that YAs have a propensity to employ proactive control whereas OAs tend to use reactive control, three hypotheses were put forward. We expected that 1) promoting proactive control through cueing would improve reaction time performance for the YA group more so than for the OA group, as we believed that YAs would be better equipped to utilize the cues than the OAs. We also predicted that 2) the presence of a cue prior to each box changing color will help performance on the AY sequences the most, as it is the one that causes the most proactive interference. Lastly, we hypothesized that 3) although an incongruent/invalid cue would negatively impact performance for both age groups, this negative effect should be more prominent in the YAs due to their greater reliance on proactive control.

Methods

Participants

The data were collected in person at Concordia University (Montreal, QC, Canada). Preliminary power analyses using G*Power recommended a minimum total sample size of 29 participants in order to achieve 0.95 power to detect an effect of $\beta = 0.40$ with three predictors (Faul et al., 2009). Sixty-two participants were recruited, including 34 younger adults (ages 18-31) from the undergraduate population at Concordia University and 28 older adults (ages 63-79) from the community in the general Montreal area. However, two older female adult participants were excluded from further analyses due to a large number of incorrect trials on the computerized task, resulting in a final sample size of 60 participants. Of those 60 participants, there were 8 males (four in each age group) and 52 females (30 in the younger adult group and 22 in the older adult group).

Inclusion criteria were: right-handedness and absence of cognitive, mood, and/or physical conditions that could affect their cognitive or fine motor performance. Participants had less than

3 years of musical training, and must not have practiced regularly in the past 10 years (see Appendix A for telephone screening survey). Additionally, older adult participants were excluded if they received a score of 24 or less on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). Due to the design of the computerized task, participants were also screened for red-green color blindness.

The study was reviewed and accepted by the Concordia University Human Research Ethics Committee. All participants gave their verbal consent to participate in the telephone screening as well as their written consent to participate in the full experiment. As compensation, younger adults were given course credits, and older adults were given an honorarium of $30.

Background Measures

Following the written consent stage, participants were given a background demographic questionnaire (see Appendix B), which included questions regarding their physical and mental health history, as well as questions about their sociodemographic characteristics and their daily computer usage. Older adult participants were also given the MoCA to screen for possible mild cognitive impairment (MCI). Paper-and-pencil neuropsychological tests were administered to get an overview of some of their baseline cognitive abilities, and included: the Color-Word Interference Test (CWIT) from the Delis-Kaplan Executive Function System (D-KEFS) battery for inhibition (Delis et al., 2001), the Coding subtest from the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008) for processing speed, and the Letter-Number Sequencing (LNS) subtest from the WAIS-IV for working memory (Wechsler, 2008a).

Montreal Cognitive Assessment (MoCA)

The MoCA is a brief cognitive screening tool primarily used in clinical settings to diagnose possible MCI in older adults (Nasreddine et al., 2005). Version 7.3 of the test was used for the older adult participants only. The MoCA is designed to assess several cognitive domains, including: visuospatial processing (drawing two- and three-dimensional figures); verbal memory (learning and recall of words); executive functions (trail making, phonemic fluency, and verbal similarity); attention (digit span forward and backward, sentence repetition, and tapping to a target letter among a sequence of letters); working memory (mental arithmetic); visual recognition (animal naming); and orientation with respect to time and space. An individual who obtains a score of less than 26 out of 30 is suspected of having MCI. Older adult participants with 12 years or less of education were given an additional point as a corrective factor (Nasreddine et al., 2005). The MoCA has been shown to have good test-retest reliability ($r = 0.9$) and internal consistency reliability (Cronbach's alpha of 0.83), as well as high sensitivity and specificity (Nasreddine et al., 2005). However, a recent meta-analysis showed that the original cut-off score of 26 may overestimate cognitive impairment, especially among older adults and those with a lower education level, and that using a cut-off score of 24 leads to a lower false positive rate and to a better overall diagnostic accuracy (Carson et al., 2018). Therefore, the less stringent cut-off score of 24 out of 30 was used for this study.

Color-Word Interference Test (CWIT)

The CWIT was administered to assess participants' inhibition abilities (Delis et al., 2001). In the first two baseline conditions, they were asked to name the color of the presented visual stimuli (Color Naming) and to read words (Word Reading) as quickly and accurately as possible. Subsequently, participants had to inhibit an overlearned verbal response (reading printed words) in order to name the dissonant ink color in which the words were printed in (Inhibition condition). For example, if participants saw the word "RED" printed in blue ink, they should say "blue" instead of "red". On the last condition (Switching), participants were asked to switch between naming the dissonant ink color and occasionally reading the words (indicated by a surrounding box). Completion time (in seconds) per condition was recorded, as well as the number of mistakes made. The CWIT has been shown to have adequate internal consistency (r = 0.70-0.79), and test-retest reliability (r = 0.62-0.76; Delis et al., 2001).

Coding (Digit Symbol)

The Coding subtest (previously known as the Digit Symbol) from the WAIS-IV was included to evaluate participants' processing speed (Wechsler, 2008a). The participant views a key showing the numbers one to nine paired with corresponding abstract symbols. They are instructed to refer to the key to fill in the symbols associated with the numbers below. Participants are given 120 seconds to fill in the squares as quickly and accurately as they can without skipping any squares. The number of correct symbols drawn by the end of the allotted time is converted into a score, minus the number of incorrect symbols filled in if any. As such, the highest possible score is 135. This measure has been found to have great internal consistency reliability (r = 0.84+) and test-retest reliability (r = 0.86; Wechsler, 2008).

Letter Number Sequencing (LNS)

The LNS is another subtest from the WAIS-IV, and is a measure of working memory (Wechsler, 2008a). It has been found to have high internal consistency (r = 0.85-0.90) and good test-retest reliability(r = 0.76; Wechsler, 2008). The examiner reads out several sequences of random letters and numbers to the participants, and after each sequence they must respond by rearranging the sequence such that the numbers appear first in ascending order, followed by the letters in alphabetical order. For example, if participants hear the sequence “Q-1-T-6-Z”, they correct response should be “1-6-T-Q-Z”. The test begins with a sequence of two characters, and progresses all the way to sequences of nine characters. It is composed of 10 items, and each item includes three trials. Participants must provide a correct response to at least one trial within an item before they can progress to the next item. As such, the test is terminated if a participant fails to answer correctly to all three trials within an item. The total number of correct responses is recorded, with a maximum score of 30.

Computerized Task

The computerized task was created using the software Inquisit (Milliseconds, 2022). Stimuli were presented on a 22-inch monitor screen powered by a Windows 7 Dell desktop computer, and participants responded with their right hand using a computer keyboard onto which four red stickers were placed to denote the keys to be used during the task. To account for differences in the inherent strength and coordination between fingers (index, major, ring, and little), four versions of the task were created. In each task version, the overlearned motor action involved a different key press sequence (see Appendix C). For each age group, task versions were assigned to participants in rotation. As such, within the total sample, 16 participants completed Version 1, 16 participants completed Version 2, 15 participants completed Version 3, and 14 participants completed Version 4.

Stimuli

Four grey boxes (2.5 cm x 2.5 cm) were displayed horizontally over a black background on the computer screen. Each box was associated with a specific key on the keyboard: the leftmost square with the “F” key, the second square with the “G” key, the third square with the “H” key, and the rightmost square with the “J” key. Throughout the task, the boxes lit up one at a time, changing to a deep red colour. Whenever participants saw a particular box change color, they had to press the corresponding key as quickly and accurately as possible. For example, if they saw the third box from the left turn red, they had to press on the “H” key. Participants had

800 ms to make a response once a box changed color. Once those 800 ms were up, the red box would return to its original grey color (see Figure 3).

Trial composition – Incorporating the AX-CPT paradigm into the task

Each trial was made up of 10 events, thus requiring 10 key press responses per trial. In keeping with Braver's AX-CPT paradigm (Braver, 2012), those 10 key presses were grouped into five pairs, each pair being either an AX, AY, BX, or BY type of key press sequence. The composition of each trial was created in a quasi-random fashion. The order of appearance of each type of key press sequence throughout the task was first randomized in Excel for each version. Then, trials were examined to ensure that there were at least two AX pairs, and that participants would not encounter more than three conflicting key press sequences (AY, BX, BY) in a row.

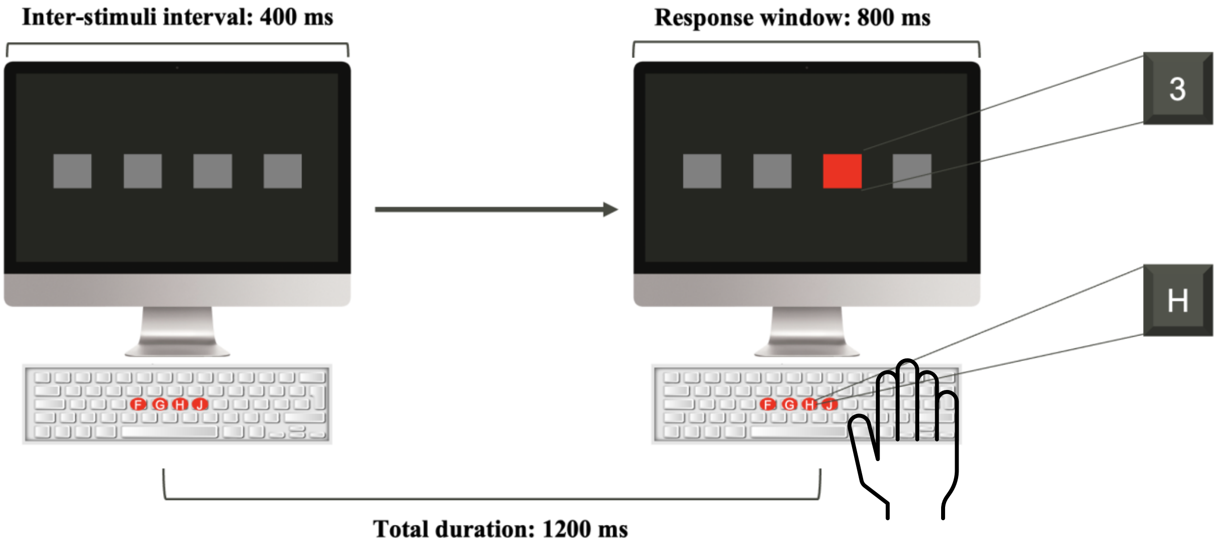
Task Conditions

The computerized task was made up of six parts in fixed order: a practice phase (one trial composed of 15 random key presses), the prepotent block (15 trials), two conflict blocks without cueing (20 trials/block), and two conflict blocks with cueing (20 trials/block). Instructions were presented on the screen before the start of each block, and participants were able to take short breaks in between each block.

Practice phase. To help participants become familiar with the setup prior to the actual start of the task, the practice phase consisted of 15 quasi-random key presses with feedback. After each key press, participants saw a message appear below the four boxes, stating whether they pressed the correct key, and if they responded too early or too late. A response was considered "too late" and marked as incorrect if it was made after the 800 ms response time window. On the other hand, a response was considered "too early" and counted as incorrect if it was made within the first 100 ms after stimulus onset, as it has been shown that it takes about

Figure 3

Example of a Task Stimulus and the Correct Key Press Response



Note. The inter-stimuli interval refers to the duration between each colour change, when all four squares were grey. For explanatory purposes, and not in the experiment, the boxes are labeled here using the numbers 1-4, from left to right.

100 ms for visual information to be processed for object recognition (Johnson et al., 2023; Masquelier et al., 2011). This phase was the only one with feedback; for the remainder of the experiment, no feedback was given to participants.

Prepotent block. In this portion of the task, a specific sequence of two key presses was repeated 75 times (for a total of 150 key presses) to have participants overlearn a simple fine motor action sequence. This prepotent sequence is labelled as “AX” in reference to the AX-CPT paradigm. For example, in one version of the task, Box 1 would turn red followed by Box 3, 75 times. Thus, for the participants who completed this version of the task, pressing on the “F” key with their index finger and then on the “H” key with their ring finger became a prepotent action sequence. Furthermore, participants were primed to expect Box 3 to turn red whenever they saw Box 1 change color, akin to how in the AX-CPT task (Braver, 2012) individuals expected to see an “X” probe following an “A” cue.

Conflict blocks without cueing. Following the prepotent block, participants completed two blocks of 20 trials, totalling 200 pairs of key presses. Among those, 70% were the overlearned key press sequence (AX). The remaining 30% were equally divided among the three conflicting key press sequences in which: the ending key press differed (AY), the leading key press differed (BX), and both the leading and ending key presses differed from the prepotent sequence (BY). Those conflicting pairs were meant to introduce instances in which participants had to inhibit the overlearned motor action and reprogram it to the indicated action sequence. For a breakdown of the number of each sequence type within a block, see Table D1 in Appendix D.

Conflict blocks with cueing. The last two blocks of the computerized task were similar to the previously described uncued conflict blocks: they included 200 pairs of key presses, with 70% being the AX sequence, and 30% being one of the conflict sequences (BX, AY, BY).

Different from the uncued blocks, participants saw an asterisk appear above one of the boxes prior to a box changing color. Participants were instructed that the asterisk indicated which box had a high likelihood of turning red, and were asked to pay attention to it and only respond after they saw a box turn red. The asterisk remained on the screen for 300 ms, followed by a delay period of 400 ms and then a box changing colour (see Figure 4). The asterisk served as a cue and was meant to promote the use of proactive control. Additionally, to encourage participants to withhold responding until they saw a box changing color, and to assess the extent to which they made use of the cues presented to them, a small portion of the cues for X and Y were misleading, or in other words incongruent with the color change (see Figure 4b). To be consistent with the AX-CPT paradigm, for each type of key press sequence (AX/BX/AY/BX), 70% of them were preceded by a congruent cue, while the other 30% were preceded by an incongruent cue. For a full breakdown of the total number of each type of key press with congruent and with incongruent cueing, see Table D2 in Appendix D.

Procedure

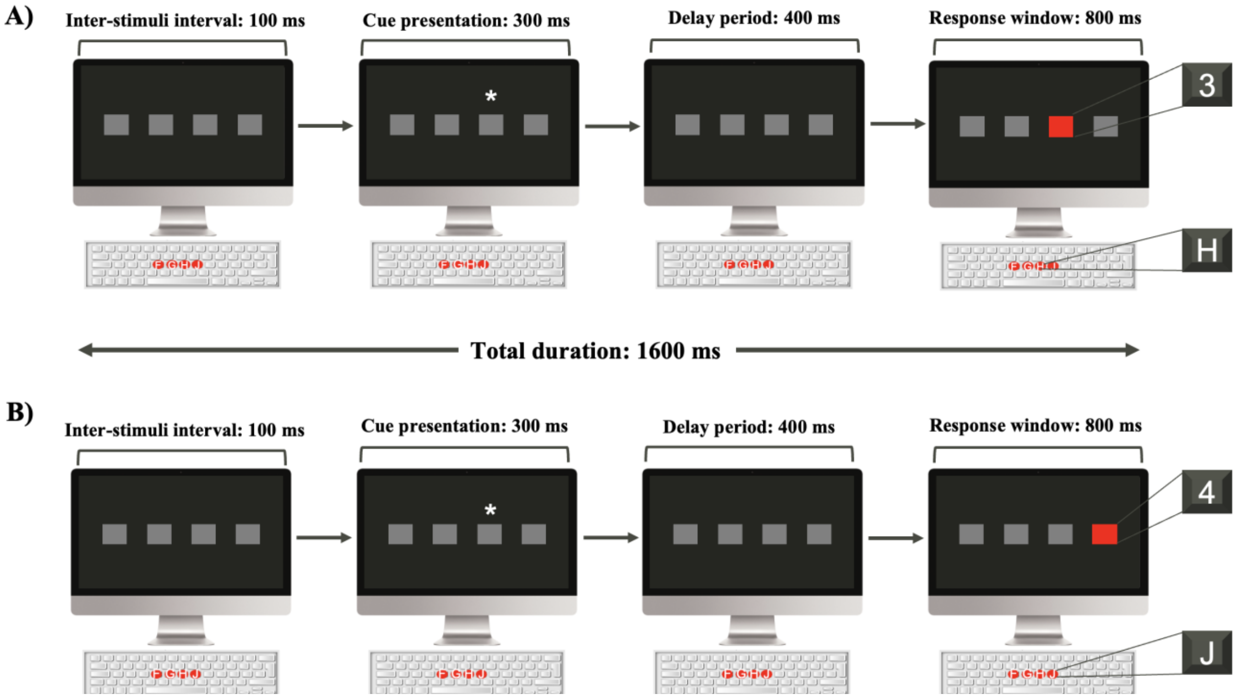
Participants' eligibility for the study was confirmed through the telephone screening interview. During the in-person testing session, participants completed a consent form, and then the examiner administered the background demographic questionnaire followed by the neuropsychological tests. Lastly, participants completed the computerized task. The main outcome variable of interest for the computerized task was participants' reaction time (ms) for each key press they made. The entire experiment lasted between 1 and 1.5h.

Data Analysis

All data processing and analyses were done using R version 4.3.0. (R Core Team, 2023) and Rstudio (Posit team, 2023). For all data, outliers were identified using the boxplot method.

Figure 4

Example of Stimulus Preceded by a Cue and the Correct Key Press Response



Note. Figure 2a shows a stimulus onset preceded by a congruent cue. Figure 2b shows a stimulus onset preceded by an incongruent cue.

Any score with values 1.5*IQR above the third quartile (Q3) and with values 1.5*IQR below the first quartile (Q1) were considered as extreme outliers. No extreme values were detected in either age groups when inspecting the main outcome variable of interest for the computerized task (reaction time) and the baseline neuropsychological scores. Because the main statistical technique used for this study is robust toward non-extreme outliers, those data points were not removed. Additionally, each outcome measure grouped by age group had a skew index below |3| and a kurtosis value below |10|, and were thus considered to not be severely non-normal (Kline, 2020). There were no missing data.

The sociodemographic characteristics of each age group, along with their performance on the neuropsychological measures, were compared using Student t-tests for continuous variables (or Welch t-tests if the homogeneity of variance assumption was not met) and Fisher's exact test for the categorical variable *sex*. Age group comparisons of each sequence type's mean reaction time were examined for each task condition using Student *t* tests or Mann-Whitney U tests (also referred to as Wilcoxon rank-sum tests) if the normality assumption was not met, as the latter are robust against non-normality (Zimmerman & Zumbo, 1990). Preliminary analyses of the accuracy rate data identified several extreme outliers in both age groups (five data points out of 240 in the OA group and 11 data points out of 240 in the YA group), which were removed for subsequent statistical analyses. Age group comparisons of each sequence type's mean accuracy rate were examined for each task condition using Welch *t* tests or Mann-Whitney U tests if non-normality was present.

Additionally, in keeping with previous AX-CPT research, a Proactive Behavioural Index for reaction time, calculated as $(AY - BX)/(AY + BX)$, was derived for each age group and for each task condition. With values ranging from -1 to +1, positive PBI reflects a higher level of interference on the AY sequences, indicating a tendency toward proactive control, whereas a negative PBI reflects higher interference on the BX sequences and is indicative of a propensity for reactive control (Gonthier et al., 2016; Qiao et al., 2018). PBIs for each task condition were compared across age groups using Student *t* tests.

Linear mixed effects modeling was used for the main analyses of the data from the computerized task with the *lmerTest* function (Kuznetsova et al., 2017) from the *lme4* package (Bates et al., 2015). This approach was used because it enables data analysis at the level of individual key presses instead of using averaged means, all while accounting for within-subject grouping of the data. As such, inherent inter-individual differences in response speed and in the way predictor variables affect performance can be accounted for.

Two sets of linear mixed model analyses were conducted, with RTs for the key presses in the conflict blocks as the dependent variable. The first set included trials from all four conflict blocks, with congruently and incongruently cued key presses pooled together. The main fixed effects of interest were Age Group (YA vs. OA), Cue Presence (no cue vs. with cue), and Sequence Type (AX, BX, AY, BY). The second set of analyses only included trials from the conflict blocks with cueing, and the main fixed effects of interest were Age Group, Sequence Type, and Cue Congruency (congruent cueing vs. incongruent cueing). For all mixed effects analyses, models included random intercepts by participants, as well as random slopes for cue presence/cue congruency to take into account the possibility that they may impact each participant’s performance to a varying extent.

To avoid overfitting, analyses always began with a null model that only included the random effect structure. Fixed effects were then progressively added, and each model was compared against the previous one to determine whether the added effect significantly improved model fit. To determine the best model, likelihood ratio tests were used to obtain AIC and BIC values, as well as *p*-values. When comparing models, the more complex one was only retained if its additional fixed effect significantly improved model fit over the simpler one. In cases when two models did not significantly differ from one another with respect to model fit, the one with the lower AIC/BIC values was retained.

Once the best fitting model was determined, omnibus *F*- and *p*-values were calculated using the *Anova* function from the *car* package (Fox & Weisberg, 2019) and Kenward-Roger's method to estimate degrees of freedom (Halekoh & Højsgaard, 2014). When a statistically significant interaction effect was detected, post-hoc comparisons using the Bonferroni adjustments for multiple comparisons were made using the *emmeans* package (Lenth, 2023). Contrasts involving continuous variables were estimated using the *emtrends* function from the *emmeans* package. All plots were generated using *ggplot2* (Wickham, 2009), *wesanderson* (Ram & Wickham, 2018).

Results

Sample Characteristics

Sample characteristics are shown in Table 1 below. Both age groups were female-skewed (85% female for the OAs and 88% female for the YAs) in a comparable way, and also had similar education levels, $t(58) = 1.67$, $p = 0.10$. However, OAs on average spent significantly fewer hours than YAs using their computers on a daily basis, $t = -4.65$, $df = 58$, $p = 0.00002$. They also spoke significantly fewer languages than the YA group, $t = -3.00$, $df = 58$, $p = 0.004$. With respect to neuropsychological performance, OAs did not significantly differ from YAs on working memory capacity (LNS), $t = 1.30$, $df = 58$, $p = 0.20$, but did exhibit slower processing speed (Coding), $t = -4.65$, $df = 58$, $p < 0.0001$. The OA group was also significantly slower than

Table 1

Sociodemographic and neuropsychological characteristics of participants

	Older Adults ($n = 26$)		Younger Adults ($n = 34$)		Statistics [b]	
	M	*SD*	*M*	*SD*	Student (Welch) t [c]	p
Sex (Female) [a]	0.85	0.37	0.88	0.33	—	ns
Age (years)	71.69	3.37	22.05	3.37	51.40	< 0.001
Education level (years)	16.62	3.14	15.39	2.53	1.67	0.10
Number of languages spoken	2.30	0.93	3.00	0.85	-3.00	0.004
Average daily computer use (hours)	3.32	2.10	6.72	3.24	-4.65	< 0.0001
MoCA (Total Score /30)	27.27	1.28	—		—	—
WAIS-IV – Coding (Raw Score/120)	68.65	12.54	85.47	9.15	-6.01	< 0.0001
WAIS-IV – LNS (Raw Score/30)	19.77	2.61	18.79	3.05	1.30	0.20
D-KEFS – CWIT Color (s)	31.35	6.01	27.68	3.83	2.88	0.006
D-KEFS – CWIT Reading (s)	22.92	3.74	20.41	3.10	2.84	0.006
D-KEFS – CWIT Inhibition (s)	60.04	15.46	44.29	8.95	(4.63)	< 0.0001
D-KEFS – CWIT Switching (s)	65.81	17.47	50.15	8.87	(4.18)	0.0002
CWIT Inhibition Cost (s)	28.69	13.56	16.62	7.29	(4.64)	< 0.0001
CWIT Switching Cost (s)	5.77	12.27	5.85	7.99	(-1.05)	0.30

Note. MoCA = Montreal Cognitive Assessment; WAIS-IV = Wechsler Adult Intelligence Scale, 4th Edition; LNS = Letter-Number Sequencing; D-KEFS = Delis-Kaplan Executive Function System; CWIT = Color Word Interference Test; s = seconds; CWIT inhibition cost derived from subtracting Color time from Inhibition time; CWIT switching cost derived from subtracting Inhibition time from Switching time.

[a] Fisher's exact test was used for the variable *sex*. To obtain a mean and standard deviation, males were assigned a value of 0 and females were assigned a value of 1. A mean value closer to 1 would indicate that the group is primarily composed of females, whereas a mean value closer to 0 would indicate that the group is primarily composed of males.

[b] Statistical contrasts refer to contrasts of the older adults against the younger adults.

YAs on the measure of inhibition (CWIT) across all conditions (*ps* < 0.006), with the exception of the CWIT Switching Cost contrast ($p = 0.30$).

Age Differences in Global Performance on Computerized Task

Participants' global performance on the computerized task is shown in Tables 2 and 3 for reaction time and accuracy rates, respectively. Across all conditions, OAs showed significantly slower reaction times than YAs on all key press sequences (*ps* < 0.0001). OAs were also significantly less accurate than YAs on AX, BX, and BY sequences (*p*s < 0.03) in the No Cue condition, but showed comparable accuracy rates on AY sequences, $U = 425$, $p = 0.80$. When stimuli were congruently cued, OAs were significantly less accurate than YAs on AX and AY sequences (*ps* < 0.07), but the age groups performed similarly on BX and BY sequences (*ps* > 0.13). When stimuli were incongruently cued, OAs had lower accuracy rates than YAs on AX and BX sequences (*ps* < 0.03), but the groups were similarly accurate on AY and BY sequences (*ps* > 0.08). Both groups had a positive PBI that suggested a slight bias for proactive control. While OAs had a significantly lower PBI compared to YAs in the No Cue condition, $t = -2.03$, $df = 58$, $p = 0.05$, the age groups had similar PBIs (*ps* > 0.55) in the With Cue condition, regardless of cue congruency.

Performance on Computerized Task – Mixed Model Analyses

Reaction time performance on the computerized task was analyzed in 1) across all experimental conditions (No Cue and With Cue conditions), and 2) within the cued trials only. To account for multicollinearity issues when continuous variables were added into the mixed models, performance on the Coding and LNS subtests were mean-centered. Additionally, initial models with untransformed reaction time data had a high number of influential data points. A log10 transformation was therefore applied to the reaction time data, which solved for this issue.

Table 2

Summary Statistics of Computer Task Across Age Groups – Reaction Time (ms)

	Older Adults (*n* = 26)		Younger Adults (*n* = 34)		Group Contrasts [a]	
	M	*SD*	*M*	*SD*	*t*, *U* [b]	*p*
Trials Without Cue						
AX	420.34	124.75	322.65	99.95	(817)	< 0.0001
AY	573.84	110.91	466.13	99.71	5.89	< 0.0001
BX	525.90	119.79	395.03	98.01	7.54	< 0.0001
BY	532.90	124.71	439.00	119.07	5.07	< 0.0001
PBI Index	0.04	0.08	0.08	0.06	-2.03	0.05
Trials With Congruent Cue						
AX	367.85	107.40	275.91	89.24	6.93	< 0.0001
AY	417.91	117.72	318.66	106.82	5.62	< 0.0001
BX	383.44	114.74	287.87	94.01	(766)	< 0.0001
BY	399.24	126.15	299.98	105.28	5.36	< 0.0001
PBI Index	0.04	0.09	0.05	0.09	-0.56	0.55
Trials With Incongruent Cue						
AX	542.56	120.45	400.62	104.38	9.40	< 0.0001
AY	620.70	91.21	487.23	101.77	7.92	< 0.0001
BX	560.18	95.46	426.48	104.63	8.18	< 0.0001
BY	602.22	98.62	475.37	104.97	6.36	< 0.0001
PBI Index	0.06	0.06	0.06	0.08	-0.01	0.99

Note. PBI = Proactive Behavioural Index (ranges from -1 to +1, with positive numbers indicating a bias for proactive control and negative numbers indicating a bias for reactive control)

[a] Statistical contrasts compare older adults against the younger adults.

[b] Contrast values in parentheses were calculated using Mann-Whitney *U* tests, while contrast values without parentheses were calculated using Student *t* tests.

Table 3

Summary Statistics of Computer Task Across Age Groups – Accuracy Rate

	Older Adults (n = 26)		Younger Adults (n = 34)		Group Contrasts [a]	
	M	*SD*	*M*	*SD*	*t*, *U* [b]	*p*
Trials Without Cue						
AX	0.93	0.10	0.97	0.04	(296)	0.03
AY	0.83	0.13	0.85	0.11	-0.45	0.66
BX	0.85	0.14	0.95	0.08	(209)	0.0003
BY	0.82	0.15	0.90	0.09	-2.47	0.02
Trials With Congruent Cue						
AX	0.83	0.22	0.92	0.12	-1.80	0.08
AY	0.82	0.24	0.91	0.13	-1.79	0.08
BX	0.85	0.24	0.91	0.14	-1.09	0.28
BY	0.84	0.21	0.91	0.15	-1.45	0.16
Trials With Incongruent Cue						
AX	0.76	0.20	0.85	0.15	-1.97	0.06
AY	0.67	0.31	0.79	0.19	-1.69	0.10
BX	0.69	0.26	0.86	0.16	-2.95	0.005
BY	0.59	0.30	0.80	0.18	-3.20	0.003

Note. Analyses were conducted after removing extreme outliers identified in the mean accuracy rate of each sequence type in each age group.

[a] Statistical contrasts compare the older adults against the younger adults.

[b] Contrast values in parentheses were calculated using Mann-Whitney *U* tests, while contrast values without parentheses were calculated using Student *t* tests.

For data visualization purposes, reaction time values were then untransformed back to their original scales. Model fit information for all the analyzed models can be found in Appendix E.

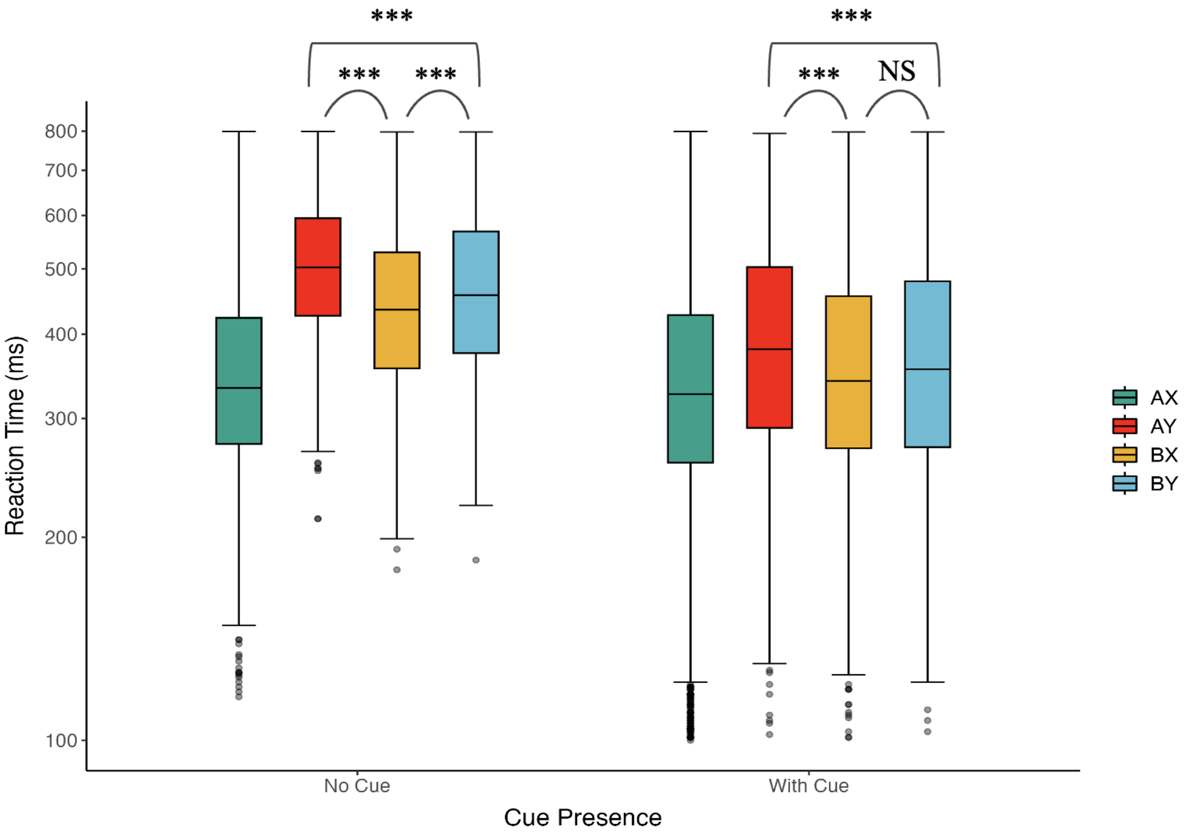
Across uncued and cued conditions

To examine whether the presence of a cue prior to stimulus presentation would help YA's performance more than OA's (Hypothesis 1) and whether cueing helped performance on AY sequences the most (Hypothesis 2), mixed effect models with Age Group, Cue Presence, Sequence Type, and their interaction terms as fixed effects were compared against each other. The selected model (Model 1; conditional $R^2 = 0.41$, marginal $R^2 = 0.25$) included the following 6 fixed effects: Age Group, Cue Presence, Sequence Type, Age Group × Cue Presence, Age Group × Sequence Type, and Cue Presence × Sequence Type (see Table F1 in Appendix F for supplementary information on the model).

Contrary to Hypothesis 1, while cueing was associated with an overall decrease in reaction time for all sequence types ($ps < 0.0001$), its effect was similar for both age groups ($p = 0.52$). However, there was a significant interaction between Cue Presence and Sequence Type, $F(3, 21165.13) = 201.26$, $p < 0.001$, $\eta_p^2 = 0.03$, shown in Figure 5 below. Post-hoc comparisons showed that in the No Cue condition, conflict sequences were associated with significantly higher reaction times than AX (*p*s < 0.0001). AY produced the most interference ($ps < 0.0001$), followed by BY ($p < 0.0001$) and then BX. With the presence of a cue, participants still had higher reaction times for conflict sequences than for AX ($ps < 0.0001$) and AY remained the most interfering sequence ($ps < 0.0001$), but BY was no longer significantly more interfering than BX ($p = 0.11$).

Figure 5

Reaction Time (ms) of Each Sequence Type in No Cue and With Cue Conditions



Note. Reaction time of AX (green), AY (red), BX (yellow), and BY (blue) sequences in No Cue and With Cue conditions of the computerized task. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range (difference between 75th and 25th percentile). Untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots (e.g., AY and BX), while square brackets compare non-neighboring boxplots (e.g., AY and BY). NS = non-significant; '***' indicates $p \leq 0.001$.

Importantly, estimated marginal means ratios of each sequence type across conditions (e.g., $AX_{No\ Cue}/AX_{With\ Cue}$) showed that cueing decreased reaction time for AY sequences the most compared with the other sequences (see Appendix G for exact values and Figure 6). The ratio $AY_{No\ Cue}/AY_{With\ Cue}$ had the highest value, indicating that the reaction time difference between No Cue and With Cue conditions was the largest for AY, which is in line with Hypothesis 2. There was also a significant interaction between Age Group and Sequence Type, $F(3, 21165.44) = 5.91, p < 0.001, \eta_p^2 = 0.0008$, shown in Figure 7 . Post-hoc comparisons show that for OAs BX and BY sequences were similarly interfering ($p = 1.00$), whereas for YAs BY sequences caused more interference than BX ($p < 0.0001$).

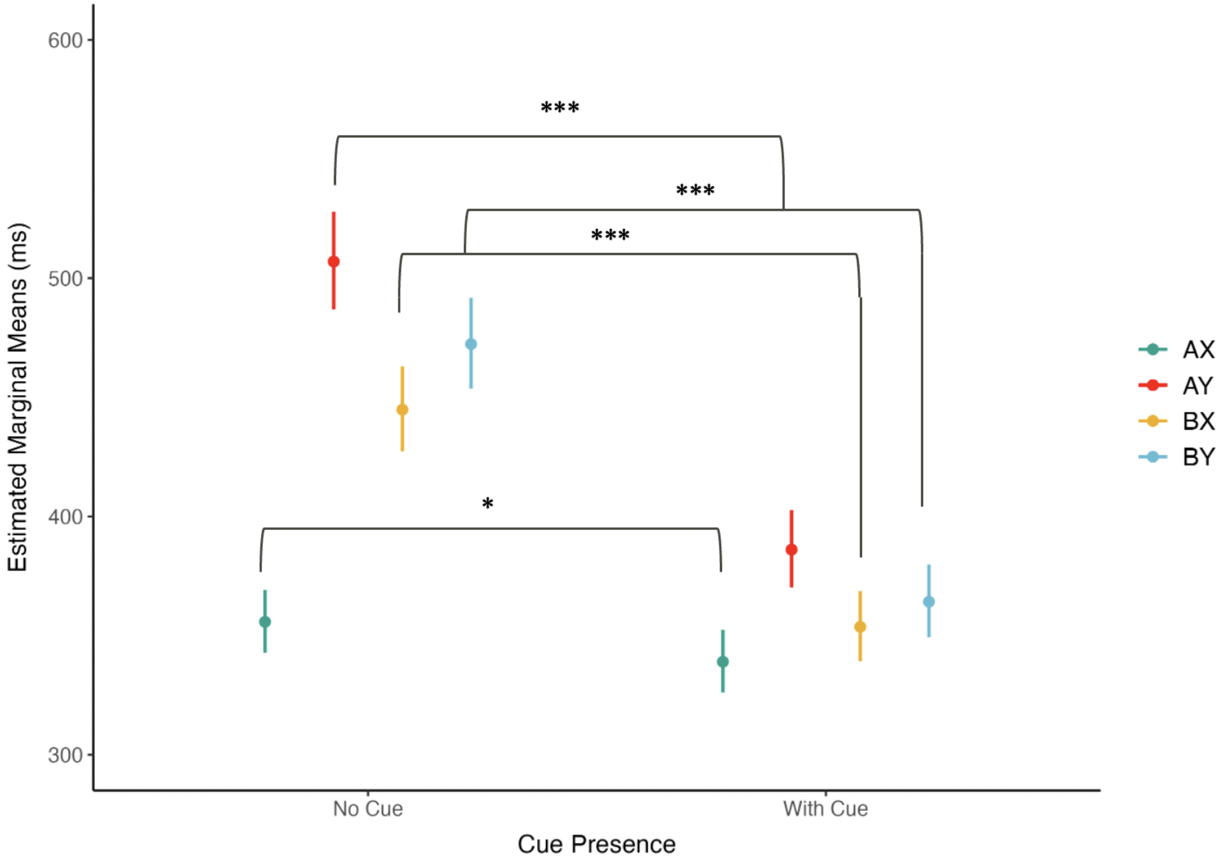
A Closer Look at Cued Trials

To encourage participants to respond only after they saw a box changing color and to examine the extent to which they relied on the cues, a small portion of the cues for X and Y key presses were incongruent with the color change. To investigate whether incongruent cueing affected YAs' performance more than the OA's (Hypothesis 3), mixed effect models with Age Group, Cue Congruency, Sequence Type, and their interaction terms as fixed effects were compared against each other. The selected model (model 2; conditional $R^2 = 0.57$, marginal $R^2 = 0.40$) included the following 4 fixed effects: Age Group, Cue Congruency, Sequence Type, and Cue Congruency × Sequence Type. See Table F2 in Appendix F for supplementary information on model 2.

Contrary to Hypothesis 3, while incongruent cueing was associated with an overall decrease in reaction time for all sequence types ($ps < 0.0001$), its effect was similar for both age groups ($p = 0.64$). However, there was a significant interaction between Cue Congruency and Sequence Type, $F(3, 10111.28) = 5.82, p < 0.001, \eta_p^2 = 0.002$, shown in Figure 8. Post-hoc

Figure 6

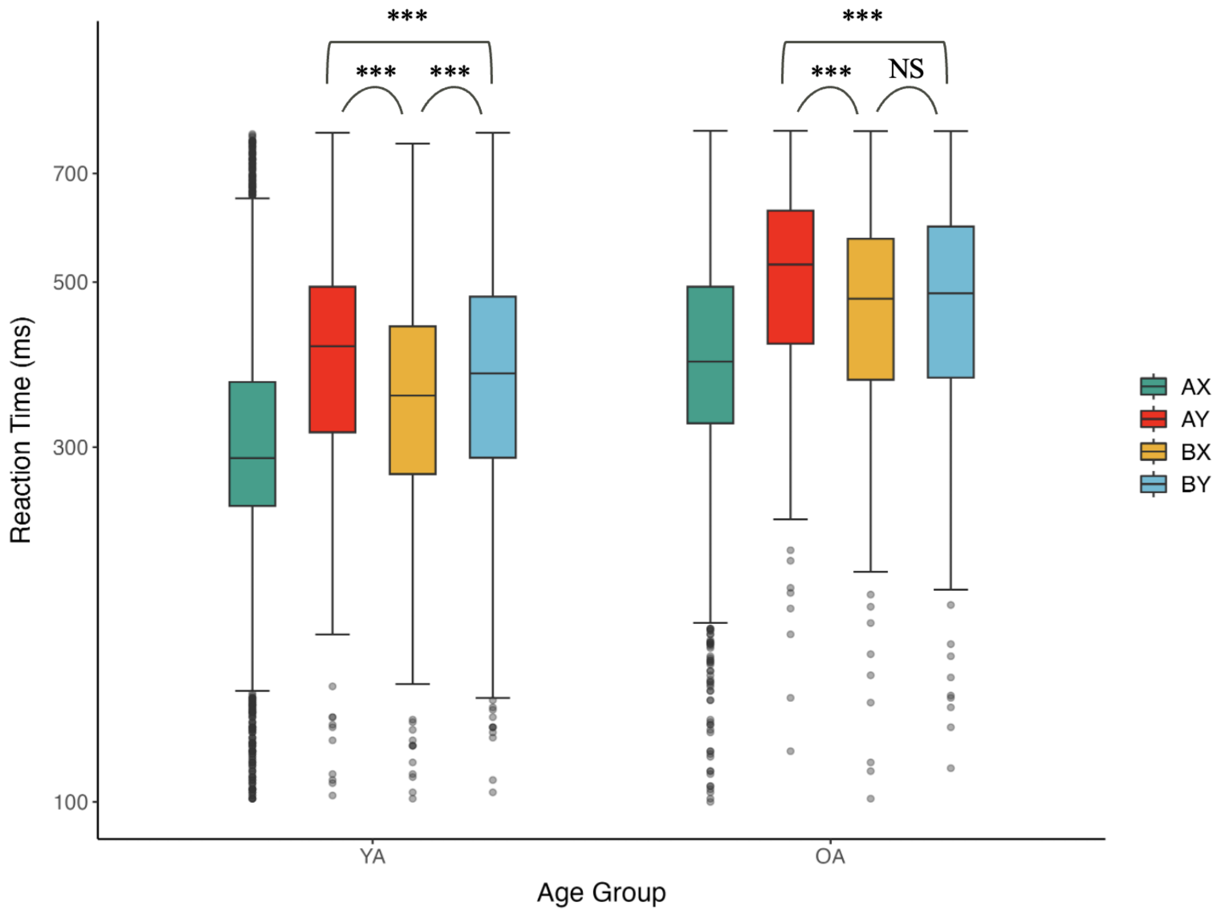
Estimated Marginal Means of Reaction Time (ms) by Cue Presence and Sequence Type



Note. Estimated marginal means of reaction times for AX (green), AY (red), BX (yellow), and BY (blue) in the No Cue and With Cue conditions of the computerized task. Error bars correspond to the 95% confidence intervals of the estimated marginal means. Untransformed values were used for data visualization purposes. Square brackets compare non-neighboring boxplots (e.g., AY in No Cue condition and AY in With Cue condition). '*' indicates $p \leq 0.05$; '***' indicates $p \leq 0.001$.

Figure 7

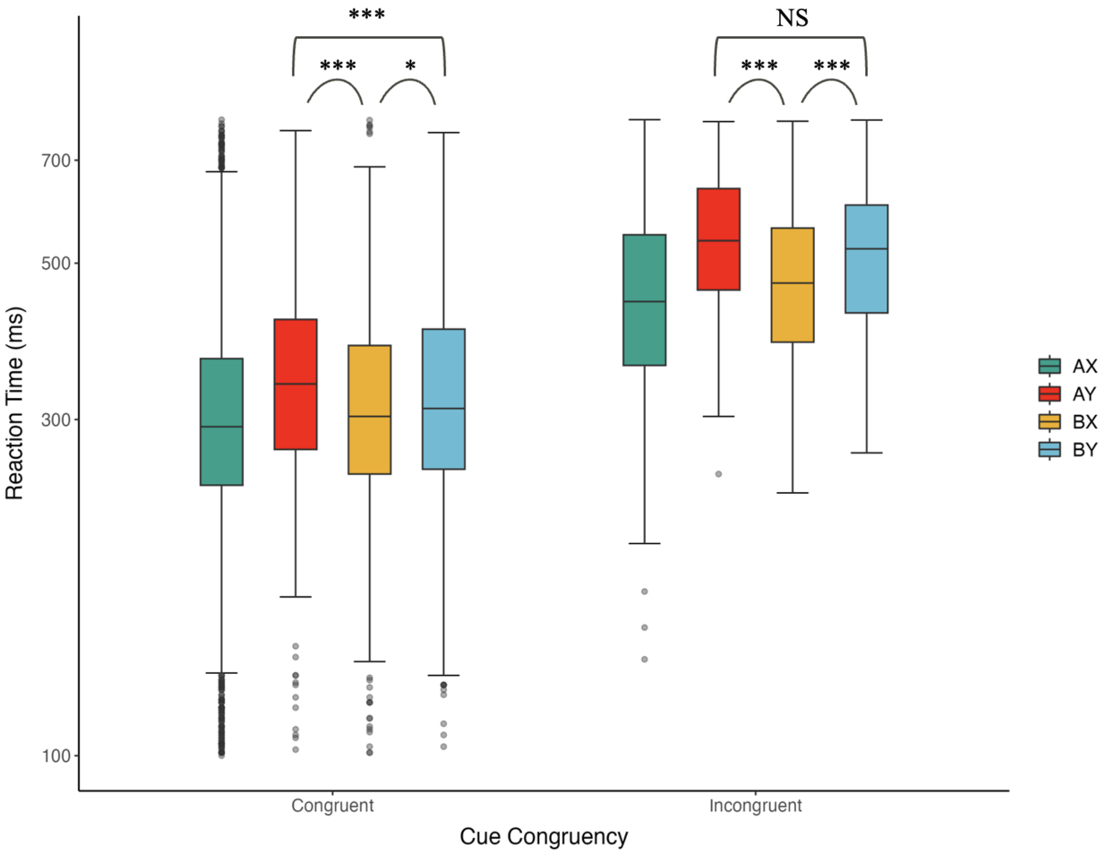
Reaction Time (ms) of Each Sequence Type for Younger and Older Adults



Note. Reaction time of AX (green), AY (red), BX (yellow), and BY (blue) sequences for younger (YA) and older (OA) adult participants. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range (difference between 75th and 25th percentile). Untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots (e.g., AY and BX), while square brackets compare non-neighboring boxplots (e.g., AY and BY). NS = non-significant; '***' indicates $p \leq 0.001$.

Figure 8

Reaction Time (ms) of Each Sequence Type Within the Cued Condition



Note. Reaction time of AX (green), AY (red), BX (yellow), and BY (blue) sequences within the With Cue condition of the computerized task, grouped by congruent and incongruent cueing. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range (difference between 75th and 25th percentile). Untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots (e.g., AY and BX), while square brackets compare non-neighboring boxplots (e.g., AY and BY). NS = non-significant; '*' indicates $p \leq 0.05$; $p <$ '***' indicates $p \leq 0.001$.

comparisons show that when X and Y key presses were preceded by a congruent cue, AY was the most interfering conflict sequence (*ps* < 0.0001). When stimuli were incongruently cued however, performance on BY sequences was comparable to that of AY sequences ($p = 1.00$).

Additional Analyses – Effect of Task Version on Performance

Because preliminary data visualization showed that performance on the computerized task may vary across the four versions, Task Version (1 vs. 2 vs. 3 vs. 4) was added as an additional fixed effect into the selected hypothesis-driven models. In other words, Model 1 was used as a base when looking across all task conditions, while Model 2 was used as a base when examining the cued condition only. Its potential interactions with the other fixed effects (Age Group, Cue Presence/Congruency, and Sequence Type) were also considered when selecting the best fitting model.

Across All Conditions

The selected model (Model 3; conditional $R^2 = 0.42$, marginal $R^2 = 0.26$) included the following additional 6 fixed effects: Task Version, Age Group × Task Version, Cue Presence × Task Version, Sequence Type × Task Version, Age Group × Sequence Type × Task Version, and Cue Presence × Sequence Type × Task Version. See Appendix H for supplementary information on model 3.

A significant 3-way interaction between Age Group, Sequence Type, and Task Version was observed, $F(9, 21138.46) = 5.19$, $p < 0.001$, $\eta_p^2 = 0.002$. The YAs' and OAs' performance on the four sequences across task versions are shown in Appendix L. Post-hoc comparisons showed that for YAs, the only significant difference among the four task versions was that BX similarly interfering in Version 2 ($p = 1.00$) unlike in other versions, where BY was significantly more interfering than BX (*ps* < 0.04). Within the OAs however, the response patterns in Version

3 differed significantly from all other task versions. Specifically, in Version 3 BX was significantly less interfering than both AY ($p < 0.0001$) and BY ($p < 0.0001$). In contrasts, conflict sequences did not significantly differ from one another in terms of reaction time in Version 1 and Version 2 ($ps > 0.14$), and in Version 4 BX was only significantly less interfering than AY ($p = 0.008$).

Additionally, a significant three-way interaction between Cue Presence, Sequence Type, and Task Version was observed, $F(9, 21138.03) = 4.47$, $p < 0.001$, $\eta_p^2 = 0.002$. Performance on the four sequences between the No Cue and With Cue conditions are shown in Appendix M for each task version. While cueing was associated with a similar decrease in reaction time for each sequence type across all task versions ($p > 0.06$), there were several differences across the four versions with respect to the difference in level of interference between sequence types. Specifically, post-hoc comparisons showed that in the No Cue condition, AY is significantly more interfering than BY in Versions 1 and 4 ($p < 0.04$), but the two sequences were comparable in Versions 2 and 3 ($ps > 0.19$). Moreover, while AY is significantly more interfering than BX in Versions 2-4, they do not significantly differ in Version 1. While in Versions 1, 2, and 4 BX and BY have comparable reaction times, BX is significantly less interfering than BY in Version 3 ($p < 0.0001$). In the With Cue condition, conflict sequences have similar levels of interference ($ps > 0.052$) in Version 2, unlike in the other versions where AY is consistently more interfering than BX ($ps < 0.04$).

Within Cued Trials

The effect of Task Version was also examined within the cued condition only to assess whether the effect of Cue Congruency varied across task versions. However, when selecting the best fitting model for the cued trials, models with Cue Congruency × Task Version interaction terms were not significantly different from models without those terms. Ultimately, a model without any interaction terms involving Cue Congruency × Task Version was selected, as it had lower AIC values. Thus, the selected model (Model 4; conditional $R^2 = 0.57$, marginal $R^2 = 0.41$) included the following additional 4 fixed effects: Task Version, Age Group × Task Version, Sequence Type × Task Version, and Age Group × Sequence Type × Task Version. See Appendix I for supplementary information on model 4.

A significant three-way interaction between Age Group, Sequence Type, and Task Version, $F(9, 10083.13) = 4.22$, $p < 0.001$, $\eta_p^2 = 0.004$, was observed. Each age group's performance on the four sequences across task versions are shown in Appendix N. Post-hoc comparisons showed that for YAs, BY was significantly more interfering than BX in Version 1 ($p = 0.006$), whereas they were comparable in the other versions ($ps > 0.93$). For the OAs, AY was significantly more interfering than BY in Version 2 ($p = 0.04$), whereas they were comparable in all other versions ($ps = 1.00$). Moreover, while AY was significantly more interfering than BX in Versions 3 and 4 ($ps < 0.03$), they were similarly interfering in Versions 1 and 2 ($p > 0.16$). BX was significantly less interfering than BY in Version 3 ($p = 0.0013$), but they two sequence types were comparable in all other versions ($ps = 1.00$).

Exploratory Analyses with Neuropsychological Measures

To examine whether participants' performance on certain neuropsychological measures had any effect on their performance on the computerized task above and beyond the hypotheses-driven factors and the effect of task version, exploratory models with mean-centered scores on the Coding and the LNS were analyzed. While LNS did not appear to have a significant effect, interaction effects involving Coding scores were observed.

Across All Conditions

The selected model (model 5; conditional $R^2 = 0.42$, marginal $R^2 = 0.26$) had a significant interaction between Sequence Type and Coding score, $F(3, 21134.31) = 4.69$, $p < 0.003$, $\eta_p^2 = 0.0007$ (See Appendix J for supplementary information on model 5). As shown in Appendix O, higher processing speed was associated with higher reaction times on AX, AY, and BY sequences, but with lower reaction times on BX sequences. Post-hoc comparisons also showed that the magnitude of the slope for AX, AY, and BY did not significantly differ from one another (*ps* = 1.00).

Within Cued Trials

Within the cued trials, the selected model (Model 6; conditional $R^2 = 0.57$, marginal $R^2 = 0.41$) included a significant interaction between Sequence Type and Coding score, $F(3, 10078.51) = 3.38$, $p < 0.02$, $\eta_p^2 = 0.001$ (See Appendix K for supplementary information on model 6). Higher processing speed was again associated with higher reaction times for AX, AY, and BY, but with lower reaction times for BX, as shown in Appendix Q. Post-hoc comparisons showed that the magnitude of the slope for AX, AY, and BY did not significantly differ from one another (*ps* = 1.00)

Discussion

To date, there is ample evidence suggesting that cognitive control processes such as response inhibition are subject to decline in the context of typical aging. As the global population continues to age at an increasingly faster rate and as digital technology continues to become an integral part of daily life, the need to further our understanding of the processes underlying typical cognitive and motor aging will only become more relevant as time goes on. Previous work has proposed that age-related impairments in fine motor response inhibition can be explained by age-related declines in proactive control, but this association has not been formally assessed until now. Overall, our findings suggest that promoting proactive control through cueing led to significant decreases in reaction time across all key press sequences, and especially so for AY and BY. Conversely, incongruent cueing of X and Y key presses negatively affected performance on all sequences, but particularly so for AY and BY. However, we did not observe differential effects of cueing across our younger and older adult groups.

Sample Characteristics and General Performance Patterns

Our younger and older adult groups were well matched in terms of their sociodemographic profiles, although younger adults on average spent significantly more hours using a computer and as a group spoke more languages than the older adult group. While both age groups had comparable working memory capacity, the older adult group showed significantly slower processing speed and worse performance on a measure of verbal inhibition than the younger adults. The experimental task data showed that overall, older adults responded more slowly and less accurately compared to the younger adults. For both age groups, AY sequences proved to be the most interfering, likely because the A cue raised the expectation of the second keypress of the prepotent pair (X). While this form of AY interference was expected for the YAs, it was not anticipated that OAs would exhibit comparable levels of interference (Braver et al., 2001). However, our older adult group's PBI index was positive (0.04-0.06), suggesting that overall, they had a balanced use of proactive and reactive control with a slight bias for proactive control. That the measure of working memory, LNS, was comparable across age groups is compatible with the observed age-invariance in PBI index, given that proactive control is thought to require working memory capacity for the maintenance of task-relevant cue information. These age-comparable effects have important implications for the hypotheses, which were based upon assumptions of age differences in cognitive control strategies. Detailed discussion of the hypothesis-driven analyses must therefore take into consideration the age-equivalences observed in proactive control biases.

Hypothesis-Driven Analyses

The first goal of the present study was to assess whether the presence of a cue preceding each stimulus onset, which was meant to promote proactive control, would improve reaction time performance for younger adults more than for older adults. We predicted this based on past evidence showing that younger adults have a higher tendency to use proactive control when performing cognitively demanding tasks, whereas older adults have been shown to have bias toward reactive control due to decreasing cognitive resources (Braver, 2012). Our results show that contrary to Hypothesis 1, the effect of cueing did not significantly differ between younger and older adults. For both age groups, cueing led to a significant decrease in reaction time for all sequence types, particularly so for the conflict sequences AY, BX, and BY. However, the magnitude of performance improvement for each sequence type was similar between the younger and older adults. Moreover, AY sequences were found to be the most interfering for both younger and older adults. This finding differs from past studies using the AX-CPT paradigm, which show that older adults experience the most interference on BX trials due to their tendency to use a more reactive form of cognitive control (Braver, 2012; Braver et al., 2001). However, one study using a modified version of the Stroop task found that although the neural networks associated with proactive and reactive control differed between younger and older adults, behaviourally there were no significant differences with respect to the implementation of proactive control during the task (Manard et al., 2017).

Many studies have used experimental paradigms that allowed proactive control to be induced or that encouraged the use of proactive control. Notably, one study showed that when older adults received additional training on how to prepare themselves for the probes in the AX-CPT task in a way that encouraged the use of a more proactive strategy, they made more errors on the AY pairs, showing a response pattern similar to that of younger adults (Paxton et al., 2006). This suggests that a shift to a more proactive form of control can be induced in older adults, which is consistent with our results. Moreover, a study with younger adults using a modified version of the Stroop task whereby stimuli were preceded by a cue indicating whether a stimulus would be congruent or incongruent showed that cueing was able to reduce interference both in terms of reaction time and error rate (Olsen, 2014). Olsen (2014)'s study suggests that promoting proactive control via a cueing procedure leads to improvements in inhibitory control, which is in line with our findings.

Our second objective was to examine whether cueing improved performance on select key press sequences more so than for others. We hypothesized that when comparing performance in the No Cue and With Cue conditions, we would observe the largest decrease in reaction time for AY. Among the four sequence types, AY was designed to cause the most proactive interference (in the form of increased reaction time) by being composed of the prepotent leading key press and a non-prepotent ending key press. We expected that cueing would encourage participants to proactively anticipate the non-prepotent ending key press and prepare the appropriate non-prepotent response, thereby mitigating its interfering effect. Conversely, since AX was already an overlearned response, we expected that even if cueing led to lower reaction times, the improvement would be lesser in magnitude. Our findings indicate that although AY remained the most interfering sequence type in the With Cue condition, the observed improvement in performance was also the greatest for AY, in line with Hypothesis 2. This finding also suggests that cue-related facilitation of proactive control may benefit response inhibition and reprogramming in particular.

The decrease in reaction time for BY sequences was also particularly noteworthy. While in the No Cue condition, BY sequences were significantly more interfering than BX, this significant difference was no longer present with cueing. We believe that BY was the second sequence to benefit the most from cueing because it is the most different from AX (non-prepotent leading and ending key presses), and hence the most unfamiliar of the four sequence types.

The third aim of this study was to determine the extent to which participants made use of the cues, and whether incongruent cueing on the X and Y key presses would negatively affect younger adults' performance more than older adults'. Due to younger adults' inherent bias for proactive control and to the With Cue condition deliberately encouraging its use, we predicted that younger adults would rely on the cues more than older adults. Consequently, when cueing was incongruent with the actual stimulus, we anticipated that younger adults' performance would decrease to a greater extent than for older adults. Results from Model 2 show that incongruent cueing was associated with a global decrease in performance, suggesting that participants were indeed using the cues to guide their responses. However, contrary to Hypothesis 3, incongruent cueing impaired younger and older adults' performance on the task to a similar extent. This is attributable to the observed age-equivalence in PBI index. Moreover, BY and AY sequences were the most negatively impacted by incongruent cueing, with both sequences showing significantly larger increases in reaction times of comparable magnitude. The non-prepotent Y ending key press is relatively unfamiliar to participants and is thus likely to have been more vulnerable to incongruent cueing compared to the prepotent X ending key press.

Age Equivalence, Cognitive Reserve, and Cognitive Control

It is important to note that the above results must be interpreted with the caveat that although our older adult participants were recruited from the community, they showed an overall cognitive profile and sociodemographic characteristics that are not typical of older adults from the general population. First, our older adult participants are highly educated (*M* = 16.62 years), and their education level was comparable to that of our younger adult sample which consisted exclusively of undergraduate students. Most of them also spoke two or more languages (*Mdn* = 2). Even though working memory is part of the fluid abilities that show substantial decline with aging (Baltes, 1993; Paraskevoudi et al., 2018; Park et al., 2001; Spreng & Turner, 2019; Verhaeghen, 2003; Verhaeghen & Cerella, 2002), our older adult group's working memory performance was similar to that of our younger adult group. Furthermore, although our older adult sample had significantly lower raw scores on the measures of processing speed (Coding) and inhibition (CWIT) than the younger adults, standardized scores based on the WAIS-IV's Canadian age norms (Wechsler, 2008b) suggest that our older adults overall formed a higher-than-average performing group. For example, our older adult sample had an average and median standardized score of 14 on Coding, which would place an individual in the 91st percentile within their respective age bracket. In contrast, our younger adult group had an average and median standardized score of 12 on Coding, which would put an individual in the 75th percentile of their respective age bracket.

These characteristics suggest that our older adult group may possess a higher cognitive reserve than the average older adult. Reserve can be broadly defined as a cumulative improvement of neural resources due to genetic and/or environmental factors that help mitigate age-related cognitive decline in later adulthood despite neural degeneration or neuropathology (Bialystok, 2021; Cabeza et al., 2018; Stern, 2009). Education, for one, is a factor that promotes reserve, and education level is commonly used as a proxy measure for reserve (Cabeza et al., 2018). Bilingualism has also been shown to contribute to cognitive reserve, and has been associated with better performance on measures of interference/conflict resolution in young and older adults (Bialystok, 2021; Bialystok et al., 2004; Costa et al., 2009, 2009; Perani & Abutalebi, 2015; Zhang et al., 2020).

There is evidence that older adults with higher cognitive reserve (as indexed by measures such as education level, frequency of second language use, and IQ) show performance levels on cognitive tasks such as the Stroop task comparable to middle-aged adults or even younger adults (Gajewski et al., 2020). Importantly, high performing older adults also had enhanced proactive and reactive control, suggesting that older adults with higher cognitive reserve may experience a more attenuated decline in proactive control (Gajewski et al., 2020). High cognitive reserve in healthy older adults has also been associated with greater proactive cognitive preparation in simple visual-motor response tasks as well as preserved motor preparation (Quinzi et al., 2020), further supporting this line of thought. Moreover, studies have reported or shown that specific aspects of bilingualism such as greater language switching abilities and lower unwanted language switching are associated with greater reliance on proactive control strategies (Chauvin, 2015; Zhang et al., 2015). Therefore, the age-equivalence observed in our results could be due to our older adult participants having relatively high cognitive reserve. A more formal examination of the role of cognitive reserve on the association between modes of cognitive control and fine motor response would be needed to test the present interpretation, and future studies could do this by dividing participants into high and low cognitive reserve subgroups.

Results From Additional Analyses – Processing Speed and Task Version

Additional variables were considered following the primary hypotheses-driven analyses. Notably, the neuropsychological measures most closely associated with proactive/reactive control were considered, namely processing speed and working memory. As discussed previously, declines in working memory capacity and processing speed have been associated with the age-related decline in proactive control (Braver, 2012; Manard et al., 2014). While models including working memory as a fixed effect did not improve model fit and were hence not retained for further analyses, we found that the effect of processing speed on reaction time performance varied across sequence types. For both the No Cue and With Cue conditions, higher processing speed was associated with longer reaction times for AX, AY, and BY, but with shorter reaction times for BX sequences. The positive correlation between processing speed and performance on the AX sequence was an unexpected finding. However, participants with higher processing speed having a lower performance on AY sequences can be explained by the association between processing speed and proactive control use, since individuals who tend to use a more proactive strategy would experience the most interference on AY sequences. As participants are primed to expect an X ending key press, those with faster processing speed were likely to also have experienced greater interference when a Y ending key press was presented instead. Conversely, those participants were likely able to process the non-prepotent leading key press B and recover from its interfering effect faster, leading to a faster response on the following prepotent ending key press X. For the cued condition, it is possible that we see following prepotent ending key press X. For the cued condition, it is possible that we see similar patterns because both congruent and incongruent cueing were pooled together.

Another factor under consideration was the task version, given the biomechanical differences between the relevant fingers. Four versions of the computerized task were created and assigned to participants randomly as a counterbalancing measure, and we did not expect significant variations in performance across task versions. However, the secondary analyses suggest otherwise. We observed that across the four versions, there were variations in 1) the overall level of interference caused by AY, BX, and BY in the No Cue condition, 2) the relative differences in interference level of the conflict sequences within each age group, and 3) the way cueing improved performance on the conflict sequences. One recurring pattern was that in Version 3, BX caused significantly less interference than BY, as evidenced by much faster reaction times compared to the other versions (see Appendices L-N). In particular, the older adult participants assigned to Version 3 showed significantly faster reaction times for BX when compared against their performance on BY sequences. Moreover, in the No Cue condition, BX was only significantly less interfering than BY in Version 3. During data analysis, it was found that five of the 10 older adult participants with the highest Coding scores were assigned to Version 3, making up a third of the older adult sample who completed this version of the task. As higher processing speed has been found to be correlated with lower reaction time for BX, it is possible that Version 3 differed from the other versions in part because of this uneven randomization of high-performing older adults. Another possibility is more biomechanical in that Version 3 was the only one in which the key presses associated with BX did not involve neighbouring fingers, but rather the little and index fingers, thus facilitating performance (see

Appendix C). It is possible that the combination of biomechanical differences and participant characteristics jointly contributed to the observed Version effects and interactions.

Study Limitations

The present study has a few limitations that should be considered. First, our younger adult sample comes from a very specific subpopulation (undergraduate students studying psychology or a related discipline from the same university). Moreover, while our older adult participants were recruited from the community, they showed higher than average baseline cognitive performance and education level, forming a high performing group that is not representative of the average older adult. Consequently, the generalizability of our findings, particularly with respect to older adults, may be limited. Future studies should thus strive to diversify the ways in which they recruit their younger and older adult participants.

Another limitation is that due to the strictly behavioural nature of this study, participants' proactive versus reactive control strategies were indirectly observed by deriving their PBI index. A more direct approach would be to use fNIRS (functional near-infrared spectroscopy) or EEG (electroencephalogram) neural imaging to observe participants' prefrontal activity while they completed the computerized task under cued and uncued conditions. As previous research has shown, more sustained neural activity in the prefrontal cortex is indicative of a more proactive strategy, whereas more transient prefrontal activity suggests a bias towards reactive control (Braver, 2012).

Concluding Notes and Future Directions

In summary, young and older adult adults completed a computerized finger sequencing task that assessed fine motor inhibition and that incorporated the DMC framework and AX-CPT method. Our findings suggest that promoting proactive control with cueing led to similar improvements in reaction time performance for both young and older adults. The older adults' reaction time pattern across sequence types was also similar to that of the younger adults, with AY sequences being the most interfering. This pattern differs from previous research showing that due to their increasing bias toward reactive control and age-related decline in proactive control, older adults should experience the most interference for BX sequences. However, because our older adult group showed higher-than-average cognitive capacities that were in part comparable to that of our younger adult group, evidence of possessing high cognitive reserve, and a propensity for proactive control, one can argue that they are substantially different from the average older adult at a cognitive level. Therefore, we cannot definitively conclude that promoting proactive control through cueing will help *all* older adults as much as younger adults with respect to fine motor inhibition. Nonetheless, our results do lend support to the idea that specific modes of cognitive control are associated with fine motor response inhibition, as promoting a more proactive strategy led to significant improvements in fine motor response inhibition performance.

Future studies may extend this work in several ways. Functional neuroimaging would provide additional evidence of proactive control in use, by showing a pattern of sustained prefrontal activity rather than the more intermittent pattern associated with reactive control. Secondly, a more in-depth assessment of bilingualism/multilingualism and deliberate recruitment of older adult participants into a high- or low- cognitive reserve subgroups would allow a more direct test of the effects of cognitive reserve on the present experimental paradigm. Third, while the computerized task designed for this study involved more complex fine motor actions than in previous studies of DMC theory, it is still rather simple in nature considering the broad range of fine motor actions one executes in their daily life (e.g., object manipulation or longer sequential actions). Future work could involve fine motor tasks with varying levels of complexity. Lastly, many of one’s everyday actions involve the more general use of their upper limbs, such as reaching and grabbing objects, pushing and pulling objects, etc. Investigating the interplay between cognitive control and upper-limb gross motor control would be a novel avenue of research. Although this study was able to add to the growing body of knowledge on cognitive and fine motor control, much more research is needed to elucidate the nature of their intricate relationship in the context of typical aging; especially in light of population aging and the growing importance of maintaining and enhancing cognitive and motor abilities.

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Appendix A: Telephone Screening Survey

********************************* SCREENING INTERVIEW *********************************

Today's date: ___________________ Time(s) booked: ___________________
Interviewer: ____________________

1. PERSONAL INFORMATION:

Last Name: ______________________ **First Name**: ______________________

What is your biological sex?	M	F	Intersex	Do not wish to respond
What gender do you identify as?	Male	Female	Non-Binary	Do not wish to respond

What is your date of birth? Day _____ / Month _______ / Year _______

Do you write with your left hand, right hand, or both hands? Left Right Ambidextrous

2. HEALTH INFORMATION

Do you have normal or corrected vision?	YES	NO
Are you red-green colorblind?	YES	NO
Do you have normal or corrected hearing?	YES	NO

If YES, participant is ineligible

End interview

Do you have any condition that would it make it difficult for you to come to campus, concentrate for an extended period of time, and/or work on a computer task using a keyboard for 30-45 minutes?

(<u>Examples of conditions</u>: neurodegenerative disorder like MCI or dementia, multiple sclerosis, epilepsy, malignant brain tumour, Parkinson's, Down's syndrome or other neurodevelopmental disorders, traumatic brain injury [TBI] with loss of consciousness lasting longer than 30 min., unmedicated ADHD, any musculoskeletal condition significantly affecting mobility of hands/wrist/fingers)

YES NO

If YES, participant is ineligible
End interview

3. LANGUAGE

If NOT FLUENT, participant is ineligible
End interview.

What is your proficiency level in English?	Fluent	Conversational	Slightly fluent

4. MUSICAL EXPERIENCE

If over 3 years of training OR practiced regularly within the last 10 years, participant is ineligible
End interview.

Do you have more than 3 years of musical training? (Includes all instruments + voice)	YES	NO

IF THEY ANSWERED YES TO PREVIOUS QUESTION

When was the last time you practiced that instrument REGULARLY?

i. Yesterday
ii. Last week
iii. Last month
iv. Last year
v. Five years ago
vi. 10 years ago or more

5. DECISION

○ ELIGIBLE

○ INELIGIBLE

○ UNSURE (Contact supervisor)

Reason (If ineligible or unsure)

____

************************* END OF SCREENING INTERVIEW *********************************

Appendix B: Background History 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

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

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

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. Place of birth: ________________________________

Ethnicity

Please indicate your ethnic origin by choosing one of the ten categories listed below. Ethnic origin refers to the ethnic or cultural group(s) to which your recent ancestors belonged. If you have multiple ethnic origins, then please select the one with which you most strongly identify; if this is not possible, then please choose option 11.

1 – European (including British Isles)
2 – East and Southeast Asian (e.g., China, Japan, Korea, Vietnam)
3 – South Asian (e.g., India, Pakistan, Bangladesh, Sri Lanka)
4 – Middle Eastern
5 – African
6 – Latin, Central, and South American
7 – Caribbean
8 – Pacific Islands
9 – Aboriginal
10 – Canadian
11 – Other

Language

1. Languages spoken (in order of fluency):
____

2. Primary Language/Language of choice: _______________________________
3. Language of education: _______________________________
4. At what age did you first learn English? ___________________________
5. At what age did you become fluent in English? ______________________

Education and Work

Level of Education	**Please circle how many years of education you completed at each level.**
Elementary (starting at Grade 1)	1 2 3 4 5 6 7 8
Secondary (i.e., high school)	1 2 3 4 5 6 7 8
CÉGEP	1 2 3 4 5 6
Undergraduate	1 2 3 4 5 6
Graduate	1 2 3 4 5 6 7 8
Professional	1 2 3 4 5
Total number of years of education	
Occupation: What is or was your main occupation?	

Vision

1. Do you wear glasses (indicate whether it's for reading, bifocal, etc.)? YES NO
2. If yes, when was the last time your prescription was updated? _________________________
3. Have you had/ do you currently have:
   A) Glaucoma YES NO
   B) Cataract(s) YES NO
   C) Macular degeneration YES NO

4. Do you currently receive medical treatment for your eyes? YES NO

   If **YES**, what kind? ____

5. Have you ever seen a doctor for an eye injury? YES NO

   If **YES**, what kind? ____

Injuries

1. Have you ever been unconscious, had a head injury, or had blackouts? YES NO

   A) Cause: ____________________________________

   B) Duration: __________________________________

2. Have you ever been seriously ill or hospitalized in the past 6 months? YES NO

   A) Cause: ____________________________________

   B) Duration: __________________________________

   A) Cause: ____________________________________

   B) Duration: __________________________________

Hearing and Hearing loss

1. Do you have normal hearing? YES NO
2. Can you have a phone conversation without difficulty? YES NO
3. Can you carry on a conversation with another person when you are in a noisy place, such as a restaurant or a party? YES NO
4. Do you feel any difficulty with your hearing limits and does it hamper with your persona or social life? YES NO

5. Do you have ringing in your ears? SOMETIMES ALWAYS NEVER

Smoking and Alcohol usage

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

2. Do you smoke? YES NO

   If yes, how many packs a day? ____

General health

<u>Do you have now, or have you had in the past</u>:

1. A stroke? YES NO

   If yes, when: _________________________

2. Transient ischemic attack? YES NO

   If yes, when: _________________________

3. Heart disease? YES NO

   If yes, nature: ________________________

4. High blood pressure? YES NO

   If yes, is it controlled? ________________

5. High cholesterol? YES NO
6. Bypass surgery? YES NO
7. Other type of surgery? YES NO

   If yes, nature: ________________________

8. Seizures? YES NO

   If yes, Age of onset: __________________

   Frequency: ____________________

   Cause: ________________________

   Treatment: ____________________

9. Epilepsy? YES NO

10. Diabetes? YES NO

If yes, type: TYPE I TYPE II

Age of onset: ______________________

11. Insulin dependent? YES NO

12. Thyroid disease? YES NO

13. Frequent headaches? YES NO

If yes, is it TENSION or MIGRAINE

14. Dizziness? YES NO

15. Trouble walking/Unsteadiness? YES NO

16. Have you fallen in the last year? YES NO

If yes, how many times? _____________

Were you seriously injured? __________

Did you require hospitalization
due to your fall? ___________________

17. Have you had any near falls in the last year? YES NO

If yes, how many times? ____________

18. Arthritis? YES NO

19. Any injuries to the arms/wrists/hands/fingers? YES NO

If yes, nature: ____________________

20. Any injuries to the lower limbs (hip/knee/ankle)? YES NO

If yes, nature: ____________________

21. Serious illness (e.g., liver disease)? YES NO

If yes, nature: ____________________

22. Neurological disorders? YES NO

23. Exposure to toxic chemicals (that you know of)? YES NO

24. Depression? YES NO

25. Anxiety? YES NO

26. Other psychological difficulties (e.g., ADHD)? YES NO

27. Hormone replacement? YES NO

28. Steroids? YES NO

29. Reached menopause? YES NO

If yes, age: _____________________

Medication

Please list all medications you are currently taking:

Type of medication	Reason for consumption	Duration of consumption and Dose

Present problems

Are you currently troubled by any of the following?

1. Concentration or Attention problems? YES NO
2. Difficulty finding words. YES NO
3. Do you feel like your memory or thinking is becoming worse? YES NO
   If yes, does this worry you? YES NO
4. Do you feel like your memory or thinking is worse than that of other people who are the same age as you? YES NO

Musical experience

Do you know how to play any musical instrument? YES NO

If yes, how many years of experience do you have? ______________________________

When was the last time you practiced that/those musical instrument(s) REGULARLY?

i. Yesterday
ii. Last week
iii. Last month
iv. Last year
v. Five years ago
vi. 10 years ago

Daily computer use

Do you use a computer? YES NO

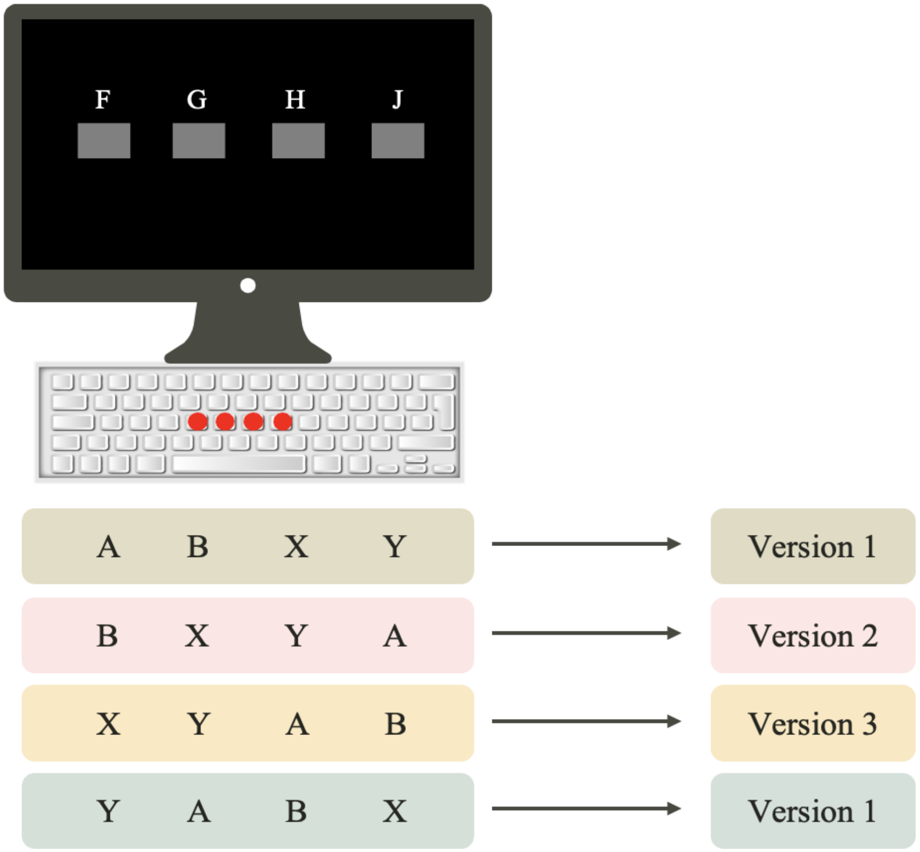
If yes, how often do you use this device (in a day)?

i. Less than 1 hour
ii. 1 hour
iii. 2 hours
iv. 3 hours
v. 4 hours
vi. 5 or more hours

What kind of activities do you do on the computer every day? Circle all the options that apply to you and indicate the amount of time you spend doing each activity every day.

i. Gaming (e.g., League of Legends, Genshin Impact, etc.): _______________
ii. Social media (e.g., Facebook, Twitter, Instagram, etc.): ________________
iii. Online chess, sudoku, or other similar activities: _____________________
iv. Work-related (e.g., e-mails, coding, etc.): __________________________
v. Communication (e.g., Zoom, FaceTime, Teams, etc.): ________________
vi. Browsing the internet : __________________
vii. Reading/watching the news : __________________

Appendix C: Four Versions of the Computerized Task



Note. For Explanatory purposes, the key corresponding to each box are indicate on top of the boxes. The cue/probe from the AX-CPT paradigm associated with a key press is shown for each version. For example, in Version 1, Box 1 (leftmost box) is associated with the F key on the keyboard, and corresponds to an A cue from the AX-CPT paradigm; Box 2 is associated with the G key and corresponds to a B cue from the AX-CPT, Box 3 is associated with the H key and corresponds to the X probe from the AX-CPT, and finally Box 4 is associated with the J key and corresponds to the Y probe from the AX-CPT.

Appendix D: Composition of Task Blocks in No Cue and With Cue Conditions

Table D1

Number of Key Press Sequences in the No Cue Condition (2 Blocks of 100 Sequences), by Sequence Type.

Sequence Type	Block 1	Block 2	Total Number
AX	70	70	140
AY	10	10	20
BX	10	10	20
BY	10	10	20

Table D2

Number of Congruently and Incongruently Cued Key Press Sequences in the With Cue Condition (2 Blocks of 100 Sequences), by Sequence Type.

Sequence Type	With Congruent Cueing	With Incongruent Cueing	Total Number
AX	98	42	140
AY	14	6	20
BX	14	6	20
BY	14	6	20

Appendix E: Model Fit Information for All Linear Mixed Effects Models

Table E1

Model Fit Information for Hypotheses-Driven Linear Mixed Effect Models

Model	AIC	BIC	Conditional R^2	Marginal R^2
Model 1 (for Hypotheses 1 and 2)	-29351.14	-29215.72	0.41	0.25
Model 2 (for Hypothesis 3)	-15957.55	-15863.53	0.57	0.40

Note. Conditional R^2 indicates the amount of variance explained by both fixed and random factors, while marginal R^2 indicates the amount of variance explained by only the fixed factors.

Table E2

Model Fit Information of Linear Mixed Effect Models for Additional Analyses

Model	AIC	BIC	Conditional R^2	Marginal R^2
Model 3 (Task Version)	-29169.17	-28746.97	0.42	0.26
Model 4 (Task Version in WC only)	-15788.86	-15499.57	0.57	0.41
Model 5 (Coding)	-29120.47	-28666.40	0.42	0.26
Model 6 (Coding in WC only)	-15737.62	-15419.40	0.57	0.41

Note. WC = With Cue Condition. Models 3 and 5 analyze trials from both No Cue and With Cue conditions. Conditional R^2 indicates the amount of variance explained by both fixed and random factors, while marginal R^2 indicates the amount of variance explained by only the fixed factors.

Appendix F: Statistics of Linear Mixed Effects Models for Hypotheses-Driven Analyses

Table F1

Statistics of Linear Mixed Effect Model 1 Used to Test Hypotheses 1 and 2

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	59.86	69.08	< 0.001	0.54
Cue Presence	1	62.6	98.36	< 0.001	0.61
Sequence Type	3	21165.48	665.63	< 0.001	0.09
Age Group * Cue Presence	1	58.09	0.41	0.52	0.0002
Age Group * Sequence Type	3	21165.44	5.91	< 0.001	0.0002
Cue Presence * Sequence Type	3	21165.13	201.26	< 0.001	0.03

Table F2

Statistics of Linear Mixed Effect Model 2 Used to Test Hypothesis 3

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	58.14	84.48	< 0.001	0.59
Cue Type	1	63.02	457.34	< 0.001	0.88
Sequence Type	3	10098.41	77.92	< 0.001	0.02
Cue Type * Sequence Type	3	10111.28	5.82	< 0.001	0.002

Note. The symbol '*' denotes an interaction. η_p^2 = Eta squared partial, with values ranging from 0 to +1. η_p^2 indicates the effect size of a variable after accounting for the variance explained by other variables.

Appendix G: EMM Ratio of Each Sequence Type Across Task Condition

Estimated Marginal Means Ratio (ms) of Each Sequence Type Across Task Conditions

Sequence Type	EMM (No Cue)	EMM (With Cue)	Ratio (No Cue/With Cue)	SE	df	*t*	*p*
AX	365	339	1.05	0.02	59.80	2.39	0.02
AY	507	386	1.31	0.03	106.00	11.70	< 0.0001
BX	445	354	1.26	0.03	101.60	9.95	< 0.0001
BY	472	364	1.30	0.03	105.50	11.18	< 0.0001

Note. EMM = estimated marginal means (ms); SE = standard error. A ratio with a value lower than 1 indicates that the average reaction time for a particular sequence is higher in the With Cue condition compared to the No Cue condition. A ratio with a value higher than 1 indicates that the average reaction time for a particular sequence is lower in the With Cue condition compared to the No Cue condition.

Appendix H: Statistics of Linear Mixed Effects Model 3

Statistics of Linear Mixed Effects Model 3 Used to Examine the Effect of Task Version Across No Cue and With Cue Conditions

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	53.61	68.31	< 0.001	0.56
Cue Presence	1	59.23	97.40	< 0.001	0.62
Sequence Type	3	21138.40	661.84	< 0.001	0.09
Task Version	3	53.62	0.84	0.48	0.05
Age Group * Cue Presence	1	55.10	0.46	0.50	0.008
Age Group * Sequence Type	3	21138.48	6.55	< 0.001	0.009
Age Group * Task Version	3	53.62	0.46	0.71	0.02
Cue Presence * Sequence Type	3	21138.09	206.81	< 0.001	0.03
Cue Presence * Task Version	3	59.21	1.48	0.28	0.07
Sequence Type * Task Version	9	21138.46	5.19	< 0.001	0.002
Age Group * Sequence Type * Task Version	9	21138.59	4.98	< 0.001	0.002
Cue Presence * Sequence Type * Task Version	9	21138.03	4.47	< 0.001	0.002

Note. The symbol '*' denotes an interaction. η_p^2 = Eta squared partial, with values ranging from 0 to +1. η_p^2 indicates the effect size of a variable after accounting for the variance explained by other variables.

Appendix I: Statistics of Linear Mixed Effects Model 4

Statistics of Linear Mixed Effects Model 4 Used to Examine the Effect of Task Version Across in the With Cue Condition

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	52.62	26.63	< 0.001	0.34
Cue Type	1	62.99	456.89	< 0.001	0.88
Sequence Type	3	10078.09	42.10	< 0.001	0.01
Task Version	3	52.41	1.10	0.36	0.06
Age Group * Sequence Type	3	10079.22	8.13	< 0.001	0.002
Age Group * Task Version	3	53.11	0.30	0.83	0.02
Cue Type * Sequence Type	3	10089.42	5.89	< 0.001	0.002
Sequence Type * Task Version	9	10080.05	2.69	0.004	0.002
Age Group * Sequence Type * Task Version	9	10083.13	4.22	< 0.001	0.004

Note. The symbol '*' denotes an interaction. η_p^2 = Eta squared partial, with values ranging from 0 to +1. η_p^2 indicates the effect size of a variable after accounting for the variance explained by other variables.

Appendix J: Statistics of Linear Mixed Effects Model 5

Statistics of Linear Mixed Effects Model 5 Used to Examine the Effect of Coding Score Across No Cue and With Cue Conditions

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	56.86	16.81	< 0.001	0.23
Cue Presence	1	56.07	0.53	0.47	0.009
Sequence Type	3	21133.27	162.49	< 0.001	0.02
Task Version	3	59.09	0.61	0.61	0.03
Coding	1	51.59	1.16	0.29	0.02
Age Group * Cue Presence	1	55.11	0.45	0.50	0.008
Age Group * Sequence Type	3	21133.19	8.10	< 0.001	0.001
Age Group * Task Version	3	51.61	0.62	0.61	0.03
Cue Presence * Sequence Type	3	21133.17	31.56	< 0.001	0.004
Cue Presence * Task Version	3	56.55	0.26	0.86	0.01
Sequence Type * Task Version	9	21133.88	4.55	< 0.001	0.002
Sequence Type * Coding	3	21134.31	4.69	0.003	0.007
Age Group * Sequence Type * Task Version	9	21135.54	4.49	< 0.001	0.002
Cue Presence * Sequence Type * Task Version	9	21134.02	4.47	< 0.001	0.002

Note. The symbol '*' denotes an interaction. η_p^2 = Eta squared partial, with values ranging from 0 to +1. η_p^2 indicates the effect size of a variable after accounting for the variance explained by other variables. Coding scores were mean centered.

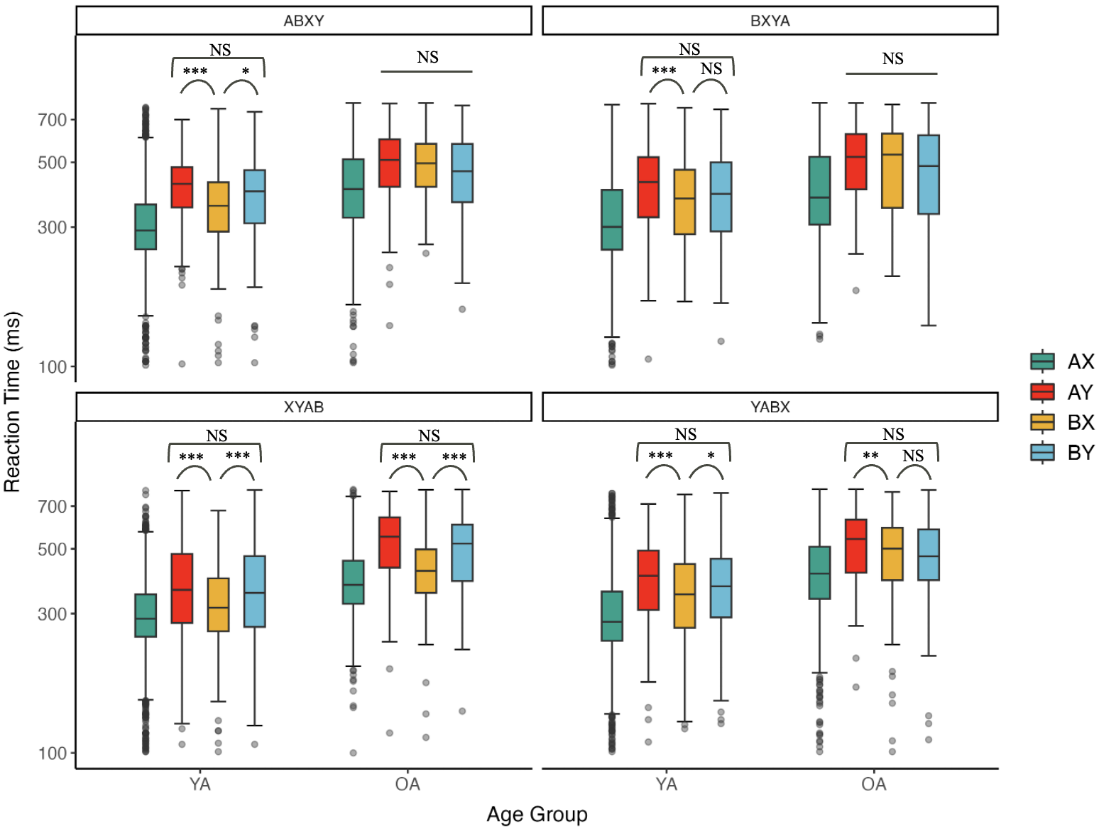
Appendix K: Statistics of Linear Mixed Effects Model 6

Statistics of Linear Mixed Effects Model 6 Used to Examine the Effect of Coding Score in the With Cue Condition

Parameter	df	df_{res}	F	p	η_p^2
Age Group	1	51.51	23.63	< 0.001	0.31
Cue Type	1	62.98	456.14	< 0.001	0.88
Sequence Type	3	10076.17	33.66	< 0.001	0.01
Task Version	3	51.47	0.87	0.46	0.05
Coding	1	52.07	0.78	0.38	0.01
Age Group * Sequence Type	3	10076.26	4.43	0.004	0.001
Age Group * Task Version	3	52.11	0.39	0.76	0.02
Cue Type * Sequence Type	3	10086.14	5.90	< 0.001	0.002
Sequence Type * Task Version	9	10077.13	2.87	0.002	0.003
Sequence Type * Coding	3	10078.51	3.38	0.02	0.001
Age Group * Sequence Type * Task Version	9	10080.02	3.68	< 0.001	0.003

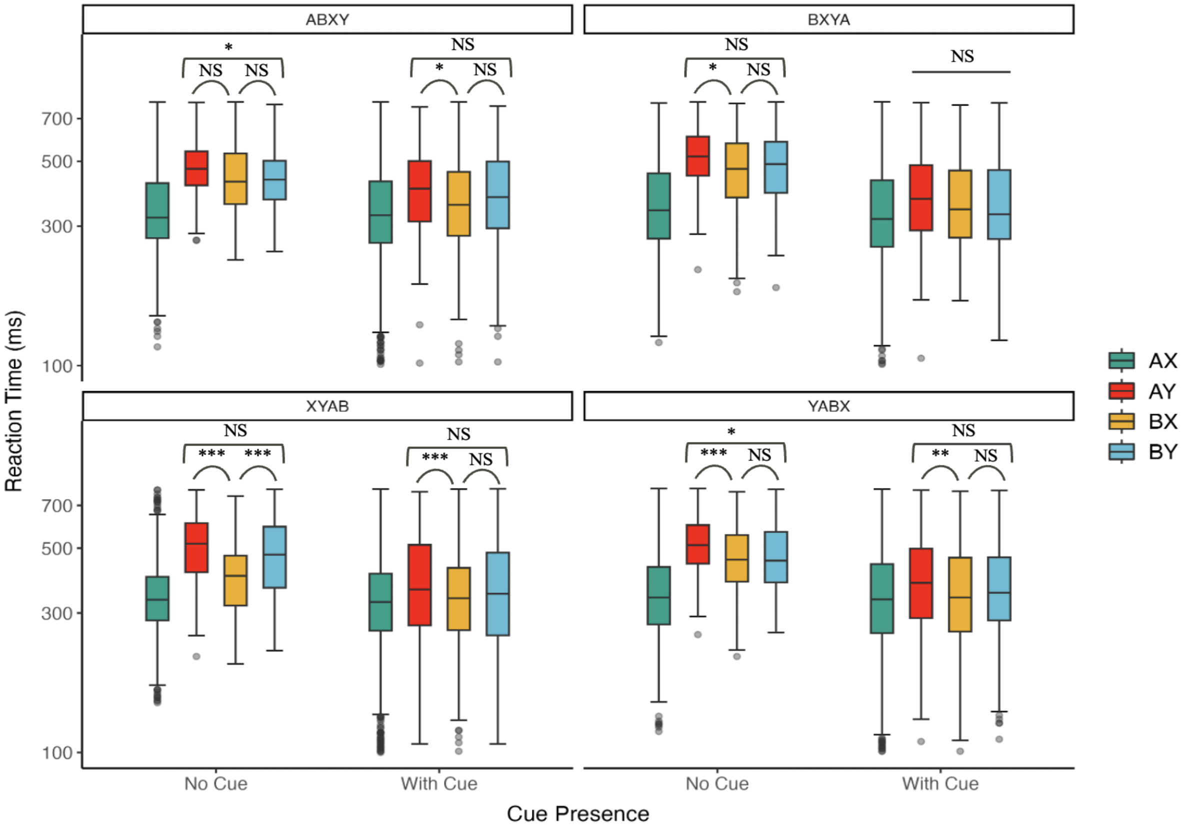
Note. The symbol '*' denotes an interaction. η_p^2 = Eta squared partial, with values ranging from 0 to +1. η_p^2 indicates the effect size of a variable after accounting for the variance explained by other variables. Coding scores were mean centered.

Appendix L: Reaction Time of Each Sequence Type for Younger and Older Adults, Across Task Versions



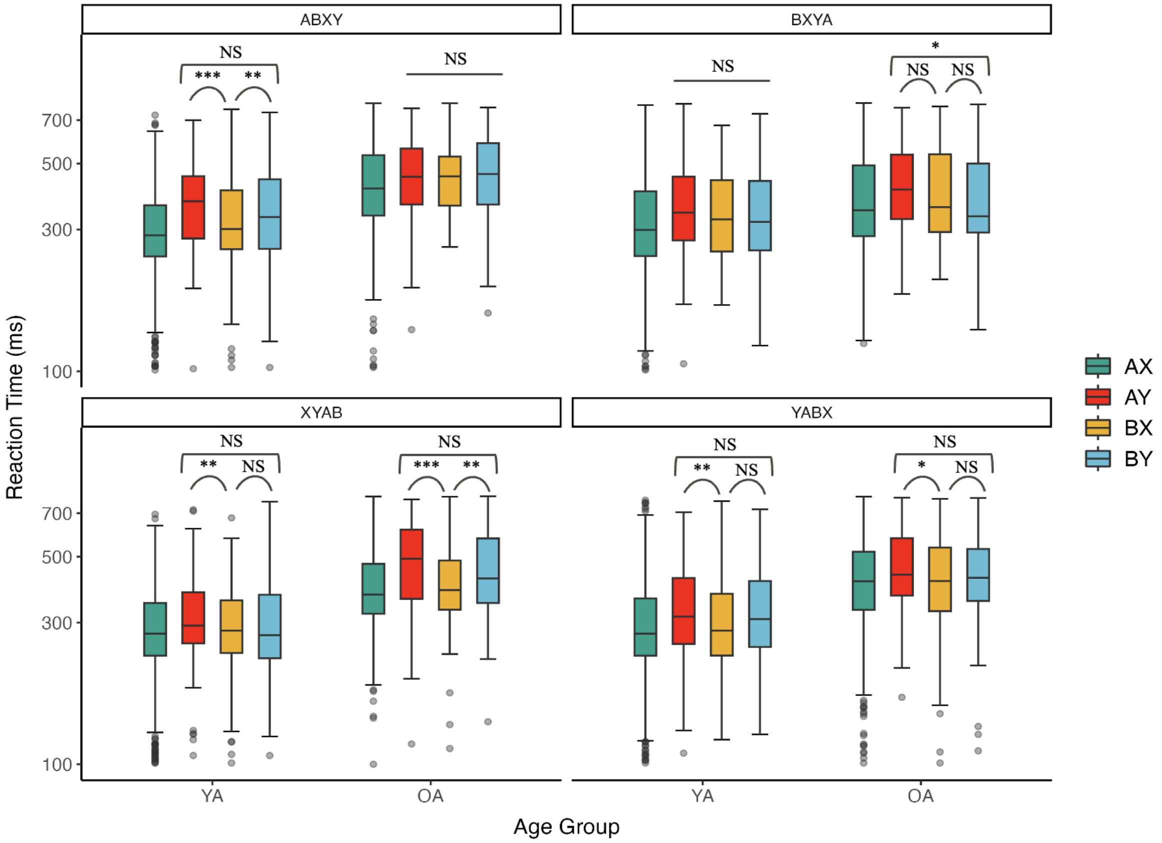
Note. Reaction time (ms) of AX (green), AY (red), BX (yellow), and BY (blue) sequences for younger (YA) and older (OA) adult participants, across all four versions of the task. ABXY = Version 1; BXYA = Version 2; XYAB = Version 3; YABX = Version 4. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range. The untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots, while square brackets compare non-neighboring boxplots (e.g., AY and BY). Horizontal line compares all boxplots underneath. NS = non-significant; '*' indicates $p \leq 0.05$; '**' indicates $p \leq 0.01$; '***' indicates $p \leq 0.001$.

Appendix M: Reaction Time of Each Sequence Type in No Cue and With Cue Conditions, Across Task Versions



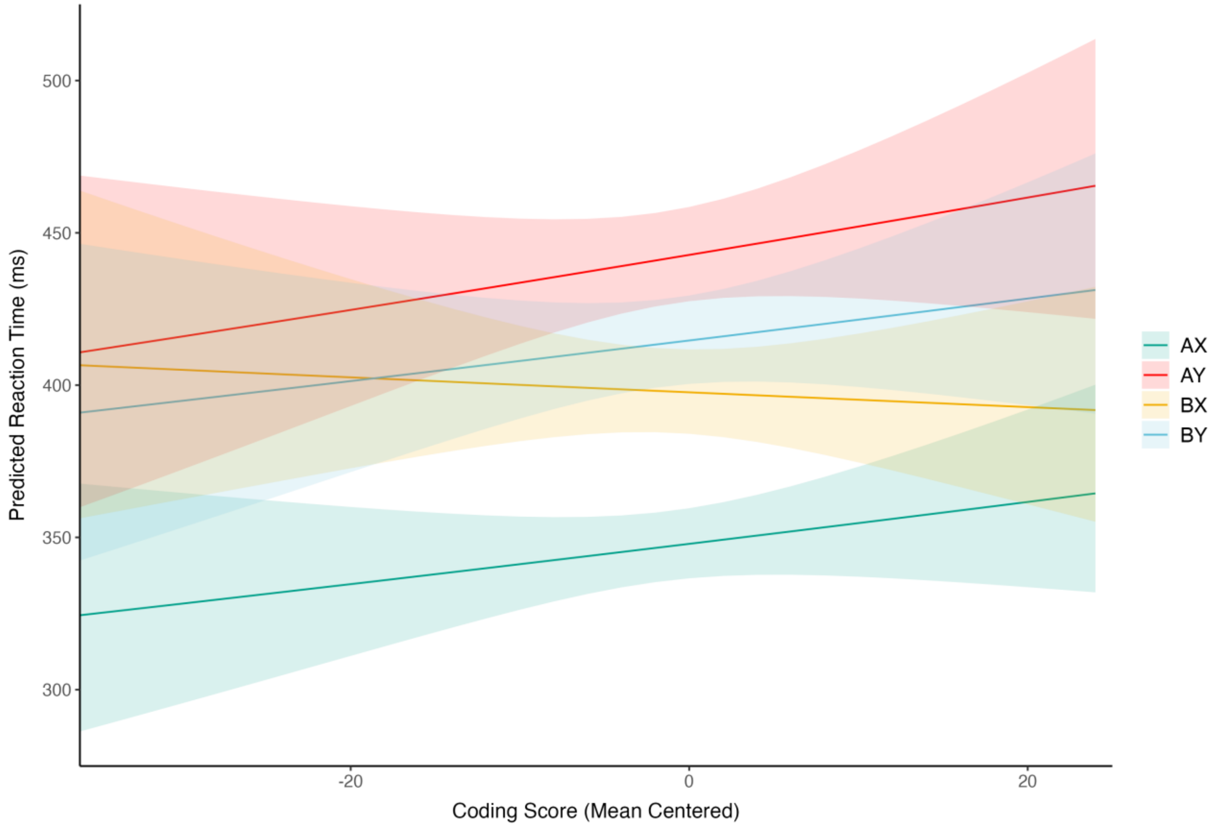
Note. Reaction time (ms) of AX (green), AY (red), BX (yellow), and BY (blue) sequences in No Cue and With Cue conditions across all four task versions. ABXY = Version 1; BXYA = Version 2; XYAB = Version 3; YABX = Version 4. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range. The untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots while square brackets compare non-neighboring boxplots (e.g., AY and BY). Horizontal line compares all boxplots underneath. NS = non-significant; '*' indicates $p \leq 0.05$; '**' indicates $p \leq 0.01$; '***' indicates $p \leq 0.001$.

Appendix N: Reaction Time of Each Sequence Type for Younger and Older Adults in the With Cue Condition, Across Task Versions



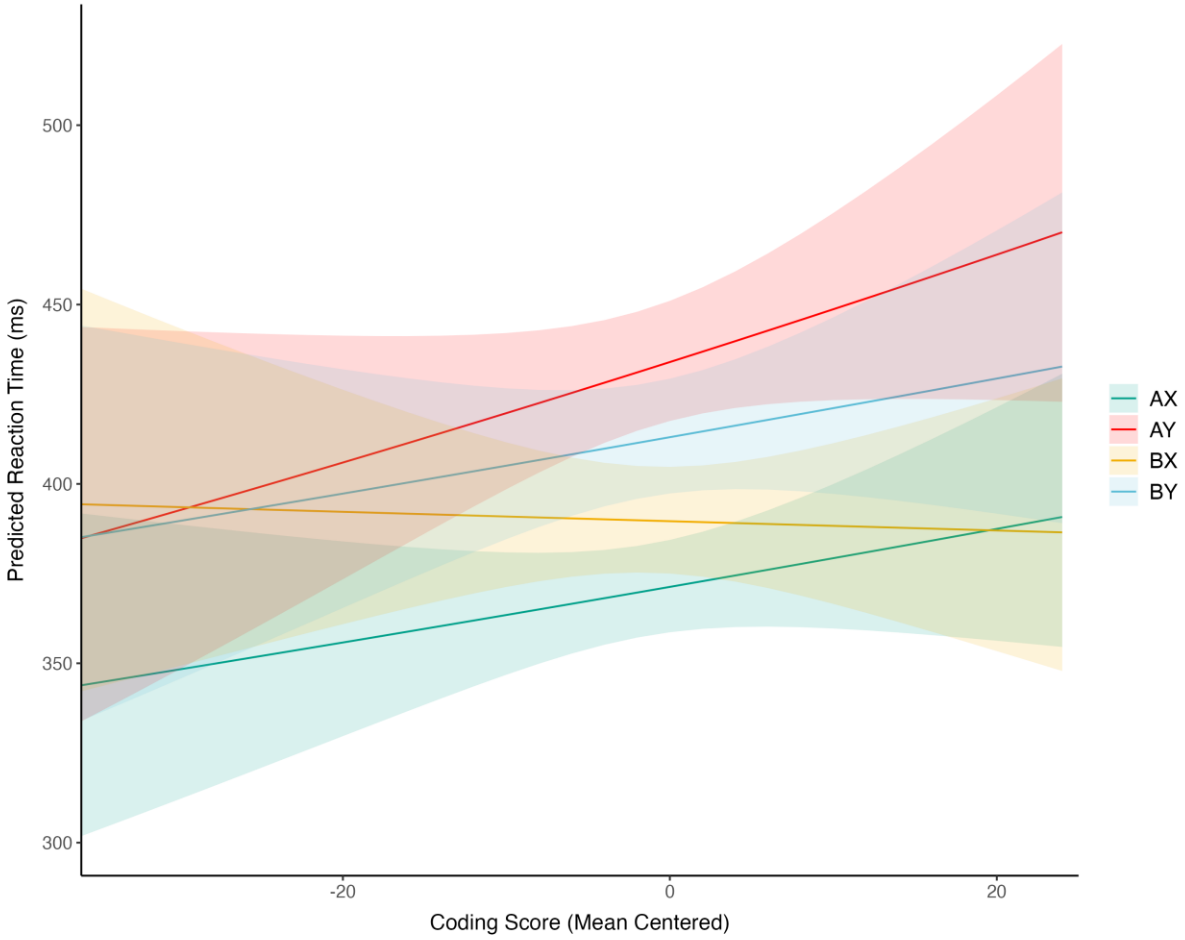
Note. Reaction time (ms) of AX (green), AY (red), BX (yellow), and BY (blue) sequences in the With Cue condition for younger (YA) and older (OA) adult participants across all four task versions. ABXY = Version 1; BXYA = Version 2; XYAB = Version 3; YABX = Version 4. The horizontal lines of the boxes correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively. The length of the box corresponds to the interquartile range. The untransformed values were used for data visualization purposes. Curved brackets compare neighboring boxplots while square brackets compare non-neighboring boxplots (e.g., AY and BY). Horizontal line compares all boxplots underneath. NS = non-significant; ‘*’ indicates $p \leq 0.05$; ‘**’ indicates $p \leq 0.01$; ‘***’ indicates $p \leq 0.001$.

Appendix O: EMMs of Reaction Time by Coding Score and Sequence Type



Note. Estimated marginal means (EMMs) of reaction times (ms) for AX (green), AY (red), BX (yellow), and BY (blue) by mean centered performance on the Coding subtest of the WAIS-IV. Error bars correspond to the 95% confidence intervals of the estimated marginal means.

Appendix P: EMMs of Reaction Time by Coding Score and Sequence Type in the With Cue Condition



Note. Estimated marginal means (EMMs) of reaction times (ms) for AX (green), AY (red), BX (yellow), and BY (blue) in the With Cue condition by mean centered performance on the Coding subtest of the WAIS-IV. Error bars correspond to the 95% confidence intervals of the estimated marginal means.