Intraindividual Variability of Proactive Control in Cognitive Aging *

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Executive functions are known to decline as a function of healthy aging. The Dual Mechanisms of Control model characterizes age-sensitive executive functions by positing two mechanisms: proactive and reactive control. Proactive control recruits cognitive resources such as maintenance of goal-relevant information in working memory, allowing for the anticipation of a forthcoming interference. Given the known age-related declines in working memory, I investigated the role of intraindividual variability of proactive control in relation to working memory processes in 25 young adults (18-30 years old, M = 25.72) and 26 older adults (60-80 years old, M = 71.19) using a computerized AX-CPT paradigm. A working memory index (Letter Number Sequencing) significantly predicted intraindividual variability of proactive control (t = -3.01, p = .004, 95 % CI for t [-17.49, -3.47], s_r^2 = .167). The present findings provide preliminary evidence that working memory processes are involved in age-related intraindividual variability of proactive control.

Healthy aging is often accompanied by declines in memory, attention, and inhibition [1, 2, 3]. These cognitive changes in older adults (OA) may be a result of normative age-related declines in executive functioning [4, 5]. Higher order cognitive control processes, such as executive functions, supervise and regulate incoming information to achieve goal-intended behaviors [6]. One classification of these executive control processes includes three divided components. The first includes working memory updating, which involves adding and deleting information from working memory. The second is response inhibition, which is defined as suppressing goal-irrelevant information. The third is task-switching which consists of being able to flexibly alternate between mental tasks [7]. Among all cognitive processes, executive functions are known to be especially age-sensitive [8]. For instance, deficits in working memory updating and response inhibition account for a significant portion of the age-related variance in working memory [9]. The current study was designed to examine the role of executive functions in relation to the variable nature of cognition in aging. Specifically, the influence of intraindividual variability of proactive control was investigated with regards to the maintenance of goal-relevant information in working memory.

One candidate model of executive functions that may be applicable to understanding age differences in cognitive control is Braver's Dual Mechanisms of Control (DMC) model [10]. Braver posited that when individuals are faced with goal-irrelevant information, they use two main modes of cognitive control to resolve the interference and accomplish their task. In proactive control, goal-relevant information is maintained early on in working memory, in order to anticipate and adjust for an incoming interference. Proactive control is highly demanding on cognitive resources due to the need to maintain goal-relevant cue information in working memory in anticipation of a later target event. At the same time, this cue maintenance also serves to suppress goal-irrelevant information. For example, if an individual is standing on a bus and sees a stop sign coming up ahead, they may use the goal-relevant information (the stop sign) to anticipate

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a change in movement, allowing them to adjust ahead of time. Conversely, reactive control is a late stimulus-driven reflexive response after the interference or stimulus is presented to correct and readjust for the goal-intended behavior. Reactive control is less cognitively demanding than proactive control, as there is not the same need to maintain goal-relevant information in working memory. In the same example, the individual may have failed to maintain the goal-relevant information (that there is a stop sign coming up ahead) in working memory and had to rely on a reflexive behavior. Researchers have found that older adults exhibit a greater use of reactive control compared to young adults (YA), as a result of age-related declines in executive functions, such as working memory. Young adults, on the other hand, exhibit a greater use of proactive control compared to older adults [11].

To measure proactive and reactive control in older and young adults, Braver used the AX-Continuous Performance Task (AX-CPT) [11]. This computerized reaction time task evaluates participant engagement in proactive and reactive control when faced with goal-irrelevant information. The AX represents a cue-stimulus pairing. In each trial, a letter cue (either A or B) is presented on a screen for a short period of time, followed by a cue-stimulus interval (CSI). This time delay engages the maintenance of goal-relevant information (the cue) in working memory. Following the CSI, a letter stimulus (X or Y) is presented for a limited duration and participants are asked to respond as quickly as possible. The presentation of an AX (cue-stimulus) pairing requires a target button response (left mouse click), while presentation of any of the three other possible pairings (AY, BX, and BY) requires a non-target button response (right mouse click).

The trial type distribution is as follows: 70% AX, 10% AY, 10% BX, and 10% BY. A greater proportion of AX trials creates a response bias towards the A cue over trials. On 70% of trials, an X stimulus follows an A cue, requiring a target response. The A cue becomes associated with the need to make a target response. Intact proactive control leads to the successful maintenance of the A cue in working memory and the anticipation of the target response. The presentation of a B cue, regardless of the stimulus type, elicits a non-target response. In contrast, reliance on reactive control may be caused by a failure to maintain the A cue in working memory. As a result, the presentation of an X stimulus is more likely to elicit a reflexive target response (false positive), regardless of the initial cue type.

Due to the A cue response bias eliciting an X stimulus expectancy, participants utilizing proactive control are more prone to making false target response errors on AY trials. This tendency is greater in young adults as a consequence of their greater engagement in proactive control [11]. Conversely, participants engaging in reactive control are more susceptible to false target response errors on BX trials, as a result of reactive responding upon the presentation of an X stimulus. This greater tendency observed in older adults is attributed to an increased use of reactive control [11]. Lastly, BY trials are considered to be a control trial type as there is no A cue to trigger a response bias, nor an X stimulus to engage a reactive response.

Age-related differences have been observed in the use of proactive control in a cognitive setting and in working memory capacity [9, 11]. However, there is little research addressing the role of intraindividual differences (within-person change) in the cognitive applications of the DMC theory. There is experimental evidence suggesting that individual differences in working memory may lead to differences in the ability to maintain consistent cognitive control [12]. Specifically, young adults with a lower working memory capacity exhibit greater intraindividual variability of proactive control, resulting in more AX errors on the AX-CPT, compared to those with a higher working memory capacity [13]. However, Weimers and Redick defined intraindividual variability, in the context of the DMC framework, as a general inconsistency in responding on the overall task, rather than the variable application of both cognitive control processes (proactive and reactive control). In their study, variability was specifically calculated as a function of mean differences in accuracy scores across testing blocks [13]. Previous research also suggests an age-related increase in general intraindividual variability [14, 15, 16]. The nature of this variability has also been suggested to be both adaptive and maladaptive [17]. Increased variability offers more opportunity for practice-related gains, which becomes an adaptive learning tool. Alternatively, intraindividual variability can be maladaptive in nature due to the overall inconsistency of responding [17]. The work of Weimers and Redick [13] identifies working memory as a key influence but does not explore whether working memory is linked to any age-related differences in the intraindividual variability of the specific application of proactive control on the AX-CPT. These questions are warranted, given the known age-related declines in working memory capacity in healthy aging, and the importance of cognitive control in the aging population. The present study was designed to examine the role of intraindividual variability in a cognitive application of the DMC model. Specifically, cognitive age-related differences in intraindividual variability of proactive control were investigated using the computerized AX-CPT. Given the known age-related differences in general intraindividual variability and working memory capacity, it was hypothesized that older adults would exhibit greater cognitive intraindividual variability of proactive control compared to young adults.

Method

Participants

The current study used archival data collected from May to October 2018 in the Li Lab at Concordia University. The study was approved by the Human Research Ethics Committee of Concordia University. An a priori power analysis using G Power revealed that 25 participants were needed per age group to achieve a power of .80, at a moderate effect size ($\eta p^2 = .15$) [18]. This sample size requirement was met for the current analyses. Participants were comprised of 26 community-dwelling older adults, between the ages of 60 and 80 years old, and 25 young adults between the ages of 18 and 30 years old (see Table 1 for sample characteristics). Older adults were recruited through advertisements placed around the Montreal community and young adults were recruited through Concordia University's Psychology participant pool. The inclusion criteria required all participants to be English-speaking, with no prior history of cognitive impairment. Participants also had to be free of any self-reported visual and auditory impairments. All participants were screened for exclusion criteria by telephone prior to testing. Further screening was conducted upon arrival at the lab. Older adults were excluded if they scored less than or equal to 26 out of 30 on the Montreal Cognitive Assessment (MoCA), which screens for mild cognitive impairment in combination with falling below age normative ranges on one or more neuropsychological measure [19]. All participants provided written and verbal consent. As shown in Table 1, participants did not significantly differ in terms of the years of education they possessed. Older adults' mean MoCA score was above the cutoff of 26 for potential mild cognitive impairment. Most notably, older adults did not significantly differ from young adults on the Letter Number Sequencing task, which assesses auditory working memory, $t(52) = 1.79$, $p = .079$, 95% CI = [-0.12, 2.17], $d = 0.49$.

Table 1

Sample Characteristics on Background Measures

	Young Adults		Older Adults		*p*
	M	*SD*	*M*	*SD*	
Age (years)	25.72	5.50	71.19	4.35	-
Education (years)	16.48	2.22	15.90	3.21	.449
MoCA (max.30)	-	-	27.39	2.14	-
LNS (max.30)	19.79	1.89	18.77	2.24	0.79

Note. Sample characteristics of participant age in years, number of years of education, performance on the Montreal Cognitive Assessment (MoCA) scored out of 30, and performance on the Letter Number Sequencing (LNS) task scored out of 30. Independent sample *t*-tests were conducted to examine group differences between young and older adults. $*p < .05$

Measures

Participants completed a demographic questionnaire that included information such as age, gender, medical history, and level of education to gain more knowledge on the characteristics of the sample. Additional background measures were also administered for a second separate study. Relevant to the current research, the MoCA was used to screen for potential cognitive impairment in older adults [19]. This measure had good internal reliability with a Cronbach's α of .79, comparable to the reported norms (Cronbach's α = .83) [19]. To examine participants' auditory working memory, Letter Number Sequencing was used [20]. Assessors auditorily presented a random list of letters and numbers and asked participants to recall them in alpha-numeric order. A total Letter Number Sequencing score was derived by averaging out the number of correct responses in each item. Measures of internal consistency revealed good reliability with a Cronbach's α of .76, falling slightly below the reported norms (Cronbach's α = .87) [20]. Finally, the Computerized AX-CPT was used as a measure of cognitive control processes from the DMC model [11].

Computerized AX-CPT. The computerized AX-CPT followed a similar experimental design as the one previously employed in Braver's study [11]. Participants focused their attention on a computer screen. A letter cue (either A or B) was presented for a duration of 300 milliseconds (ms), followed by a CSI of 4900 ms. This maintenance period was designed to be lengthy to engage working memory processes. Following the delay, participants were presented with a stimulus (either X or Y) for 300 ms and subsequently given 1300 ms to respond with either a target or non-target button click. To indicate the end of a trial, a screen with the text "Trial is over, get ready for next one" was displayed for 1000 ms (see Appendix A). Participants were told in advance that when an AX pair was presented, they should press the target button (left mouse click). When any other cue-stimulus pairing (AY, BX, or BY) was presented, they should press the non-target button (right mouse click). Accuracy scores (probability score out of 1.00) and reaction times (ms) were recorded for each trial. The experiment was made up of four blocks containing 50 trials each, for a total of 200 trials. Trial type frequencies were consistent with Braver et al.'s [11] study: 70% AX, 10% AY, 10% BX, and 10% BY. All letter cues and stimuli were presented in a white bolded uppercase font, using 36-point Helvetica, on a black background [21]. Inquisit 4 software was used to present the AX-CPT (Millisecond Software, Seattle).

Procedure

The study was comprised of one experimental session. This session took place in Concordia University's Psychology Department and lasted an average of 1.5 hours. Participants signed the consent form upon arrival. Participants then completed the demographic questionnaire, followed by the background measures and neuropsychological assessments (MoCA, Computerized AX-CPT, Letter-Number Sequencing). Older adults were compensated with a $20 honorarium, while young adults were solely compensated with participant pool credits.

Analyses

The hypothesis relating to intraindividual variability of proactive control was analyzed using Weimers and Redick's [13] measure of proactive shift in the computerized AX-CPT paradigm. Mean accuracy and reaction time of the second half of trial blocks (3 and 4) was subtracted from the first half of trial blocks (1 and 2), to obtain measures of change in accuracy and reaction time for trial types AY and BX. These trial types were most relevant in evaluating the use of proactive control, as they reveal behavioral patterns indicative of each mode of cognitive control. For accuracy, a positive value for mean change is indicative of an increased shift to proactive control over time. A negative value indicates a shift away from proactive control across blocks. For reaction time, the inverse is true. A positive value is indicative of decreased proactive control, while a negative value indicates increased proactive control over time. These analyses capture global intraindividual variability on the AX-CPT. However, Weimers & Redick fail to give a complete representation of proactive control as their analyses were originally designed to measure an overall inconsistency of responding in the task, in combination with measures of hits and false alarms for AX and BX trials, rather than variability specific to proactive control. Going beyond the Weimers and Redick analyses, a Proactive Behavior Index (PBI) was also derived for each participant, with the equation (AY-BX)/(AY+BX) [21]. The Weimers & Redick [13] and Braver et al. [21] analyses were considered as they both offered a unique measure of intraindividual variability. The PBI represents a quantitative measure of interference between AY and BX trials. A positive PBI is indicative of proactive control, while a negative PBI is indicative of reactive control. The PBI was obtained for reaction time and error rate averages on AY and BX trials. For error rate computations, the log-linear correction (number of errors + 0.5) / (number of trials + 1) was applied to correct for trials where the error rate was 0 [22]. Intraindividual variability was obtained by subtracting the PBI of the first two blocks from the last two blocks, in a similar manner to the Weimer's and Redick analyses. Greater intraindividual variability indicates a greater inconsistency in the use of cognitive control, as predicted for older adults.

Independent samples t-tests were conducted to compare young and older adults on mean accuracy change for AY and BX trials, as well as on the intraindividual variability of PBI measures [13, 21]. A one-way repeated measures ANOVA was used to assess participants' general patterns across of responding all four blocks on the computerized AX-CPT based on their reaction times. Finally, a multiple linear regression was used to assess the relation between intraindividual variability of proactive control and cognitive processes of working memory.

Results

Data Integrity

Preliminary data screening measures were conducted. Cases in which participants scored below the age-normative range on two or more neuropsychological tests were excluded from the analyses. These criteria resulted in the exclusion of three older adults. Additionally, one older adult's MoCA score exceeded the cutoff of +/- 3 standard deviation units and was thus winsorized. For the computerized AX-CPT reaction time analyses, only correct trials were processed, eliminating incorrect trials and trials where participants were too slow to respond within the 1300 ms response window. Two reaction time outliers within the correct responses were not removed, as the original authors suggested that the response window in the AX-CPT paradigm is short enough as is [11]. For error rate exclusions, a chance level of 50% on AX trials in any given block, was used as the threshold level. No participants fell below this threshold.

Computerized AX-CPT reaction time and error rate distributions were assessed for skewness and kurtosis using a z-score value of +/- 1.96. As expected, reaction time distributions were right skewed by young adults. Data normality checks for error distributions also revealed skewness and kurtosis. Both distributions remained skewed after log transformations were applied. Alternative non-parametric tests, such as the independent-samples Mann-Whitney U tests, did not yield different results in the analyses. Therefore, the results from parametric tests are reported in the current study, to be consistent with reporting methods from previous literature [11, 23].

Computerized AX-CPT: Overall Performance

Before testing the hypothesized age difference in cognitive intraindividual variability, basic analyses were carried out to describe the computerized AX-CPT data set more generally. To investigate the general patterns of responding in young adults, a one-way repeated measures ANOVA was conducted using reaction time on all four trial types (see Appendix B for mean reaction times over all four blocks). The assumption of sphericity was violated for trial type according to Mauchly's Test, $\chi^2(5) = 24.02$, $p < .001$. Greenhouse-Geisser estimates were considered to reduce Type I error ($\epsilon = .62$). There was a statistically significant main effect of trial type, $F(1, 39) = 119.03$, $p < .001$, $\eta p^2 = .85$. Bonferroni post-hoc corrections revealed that young adults exhibited significantly slower reaction times on AY trials than on AX trials, MDIFF = 69.68, $p < .001$, 95% CI [93.17, 162.85], $d = -0.86$. However, young adults performed significantly faster on BX trials compared to AX trials, MDIFF = 71.72, $p < .001$, 95% CI [-113.32, -42.04], $d = 1.31$. Therefore, there was evidence of young adults utilizing proactive control in the computerized AX-CPT.

To investigate the general patterns of responding in older adults, a one-way repeated measures ANOVA was conducted, examining reaction time on all four trial types (see Appendix B for mean reaction times over all four blocks). Mauchly's Test revealed that sphericity was violated for trial type, $\chi^2(5) = 14.69$, $p = .012$. Greenhouse-Geisser estimates were applied ($\epsilon = .74$). A statistically significant main effect of trial type was found, $F(2, 55) = 101.30$, $p < .001$, $\eta p^2 = .80$. Bonferroni post-hoc corrections revealed that older adults exhibited significantly slower reaction times on AY trials than on AX trials, MDIFF = 127.71, $p < .001$, 95% CI [164.08, 291.79], $d = -1.44$. However, older adults also performed significantly faster on BX trials compared to AX trials, MDIFF = 134.74, $p < .001$, 95% CI [-349.55, -214.81], $d = 1.79$, therefore, showing evidence that older adults were also engaging in proactive control in the computerized AX-CPT.

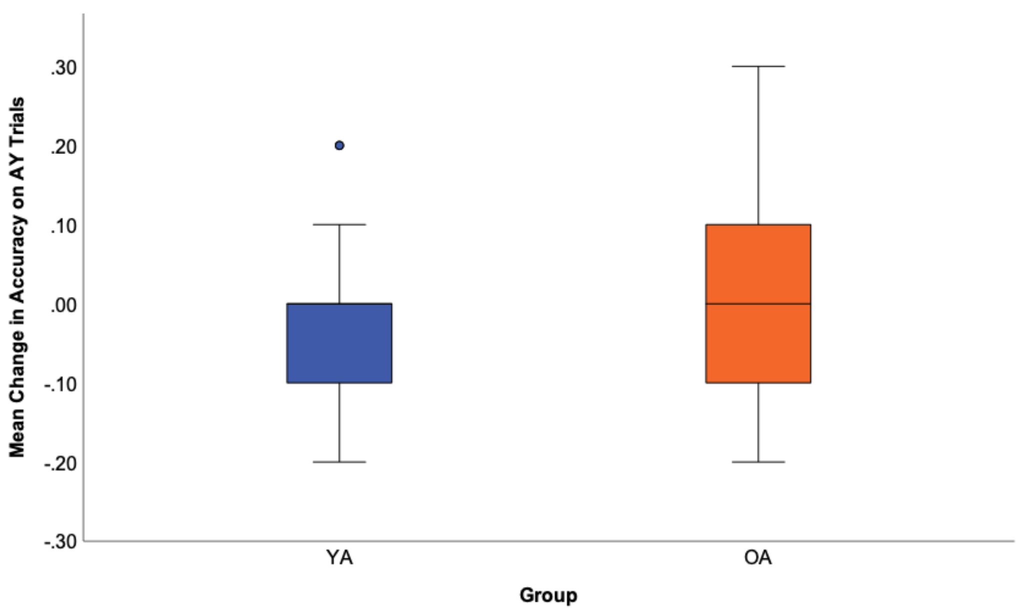
To further compare young and older adults' engagement in proactive control, an independent samples t-test was conducted using the more robust mean PBI scores across all blocks, as a function of reaction time, between young adults (M = 0.197, SD = 0.07) and older adults (M = 0.199, SD = 0.08). No statistically significant difference was revealed, $t(46) = -0.09$, $p = .926$, 95% CI for t [-0.05, 0.04], $d = -0.03$. The same pattern of results was found using PBI scores derived from correct error rates, $t(48) = 0.40$, $p = .695$, 95% CI for t [-0.10, 0.15], $d = 0.11$. Therefore, it was concluded that young and older adults did not significantly differ in their overall use of proactive control.

Hypothesis: Intraindividual Variability in AX-CPT Performance

To test the first hypothesis, that older adults exhibit greater intraindividual variability of proactive control than young adults, Weimers and Redick's [13]proactive shift scores were first considered. An independent samples t-test revealed no statistically significant difference between young adults (M = -0.016, SD = 0.11) and older adults (M = -0.056, SD = 0.22) in their mean accuracy change on AY trials across earlier and later blocks, $t(50) = 0.82$, $p = .418$, 95% CI for t [-0.06, 0.14], $d = 0.23$ (see Figure 1). The same pattern was found in mean accuracy change on BX trials, $t(50) = -1.82$, $p = .075$, 95% CI for t [-0.14, 0.01], $d = -0.51$, between young (M = -0.040, SD = 0.13) and older adults (M = 0.026, SD = 0.14). Therefore, using Weimers and Redick's measure of proactive shift, it was concluded that there were no group differences in variability of proactive control on the computerized AX-CPT.

Figure 1

Mean change in accuracy on AY trials in older and young adults

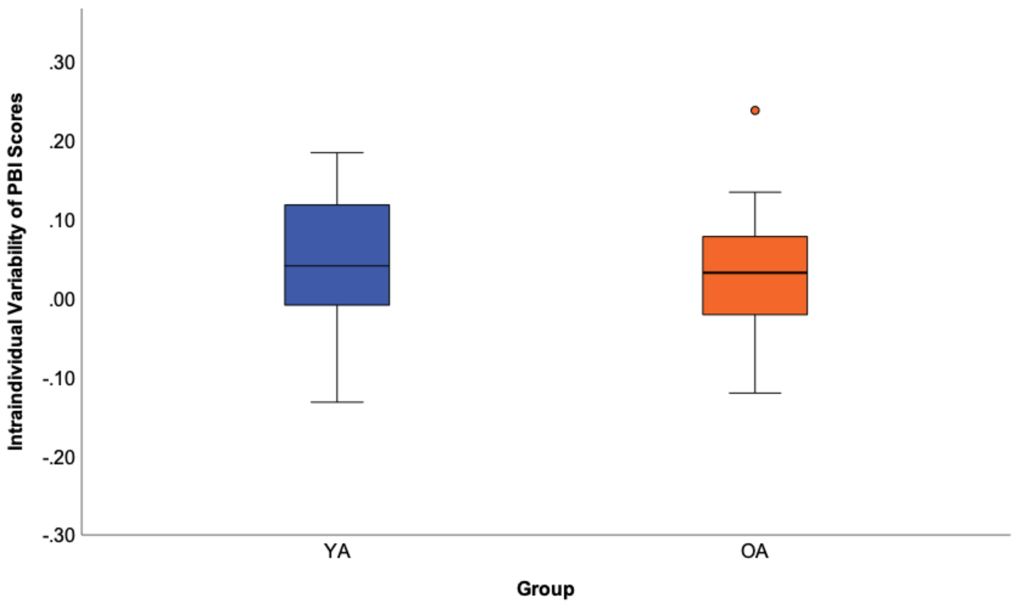


Note. Comparing young adults (YA) and older adults (OA) on the computerized AX-CPT as a function of mean change in accuracy (probability out of 1.00) on AY trials, calculated by subtracting mean accuracy from the first two blocks from mean accuracy of the last two blocks. Error bars represent 95% confidence intervals. Dots falling outside of the intervals represent outliers (less than 50% accuracy on AX trials overall).

A supplementary analysis using Braver's more robust measure of PBI also replicated the findings. There was no statistically significant difference between young adults (M = 0.044, SD = 0.09) and older adults (M = 0.036, SD = 0.08) in their intraindividual variability of PBI scores, based on reaction time, $t(49)$ = .31, p = .759, 95% CI for t [-0.04, 0.05], d = 0.09 (see Figure 2). The same result was found for intraindividual variability of PBI scores, based on corrected error rates, $t(50)$ = -1.43, p = .160, 95% CI for t [-0.42, 0.07], d = -0.39, between young (M = -0.041, SD = 0.28) and older adults (M = 0.132, SD = 0.56). Therefore, the null hypothesis was retained given that there was no statistically significant difference between young and older adults in their intraindividual variability of proactive control based on their reaction times and error rates on the computerized AX-CPT.

Figure 2

Intraindividual Variability of PBI Scores in older and young adults



Note. Comparing young adults (YA) and older adults (OA) on the computerized AX-CPT as a function of intraindividual variability of Proactive Behavioral Index (PBI) scores, calculated using mean reaction times on AY and BX trials with the equation [AY-BX]/[AY+BX]. Error bars represent 95% confidence intervals. Dots falling outside of the intervals represent outliers (+/- 3 standard deviations from the mean).

The previous measures of intraindividual variability did not take into consideration AX trials, which make up 70% of all trials. An independent samples t-test revealed a statistically significant difference between young and older adults in mean reaction times on AX trials overall, $t(48)$ = -4.13, p < .001, 95% CI for t [-159.51, -55.00], d = -1.17. However, an additional independent samples t-test revealed no statistically significant difference between older adults (M = 1.46, SD = 2.27) and young adults (M = 0.84, SD = 2.27) in their mean number of errors on AX trials overall, $t(48)$ = -0.97, p = .336, 95% CI for t [-1.92, 0.67], d = -0.28, indicating that older adults were slower to respond on 70% of trials, but that had no impact on their overall accuracy on AX trials. A lack of differences in error rates on AX trials, further solidifies the similarity in performance between the two groups.

Working Memory and Intraindividual Variability. An exploratory analysis was conducted to determine whether the different measures of intraindividual variability could predict Letter Number Sequencing scores. The reason for this prediction was to investigate the association between working memory processes and cognitive intraindividual variability. A multiple linear regression was conducted with Weimers' and Redick's [13] measures of mean change in accuracy (on AY and BX trials) and measures of intraindividual variability using Braver et al.'s [21] PBI scores. These variables were set as predictors for Letter Number Sequencing total scores (see Appendix C for descriptive statistics). Young and older adults were pooled together, given that they showed no statistically significant difference in performance on the Letter Number Sequencing task (see Table 2). The overall model was not statistically significant, $F(4, 45) = 2.28$, $p = .076$, $R^2 = .17$. However, the following variables were revealed to be statistically significant predictors of Letter Number Sequencing total scores: mean change in accuracy on AY trials ($t = 2.17$, $p = .035$, 95% CI for t [0.44, 11.90], $sr^2 = .087$), mean change in accuracy on BX trials ($t = -3.01$, $p = .004$, 95 % CI for t [-17.49, -3.47], $sr^2 = .167$), and intraindividual variability of PBI based on error rate ($t = 2.38$, $p = .021$, 95% CI for t [.44, 5.17], $sr^2 = .105$). Therefore, intraindividual variability of proactive control within the computerized AX-CPT was associated with working memory capacity, as measured with the Letter Number Sequencing task.

Table 2

Results of Multiple Regression Analysis of Predictors of Letter Number Sequencing Scores

	Unstandardized coefficients						
Predictor	*B*	*95% CI for B*	*SE*	Standardized coefficients	*t* (45)	*p*	s_r^2
AY Change in Accuracy	6.17	[.44, 11.90]	2.85	.525	2.169	.035*	.087
BX Change in Accuracy	-10.48	[-17.49, -3.47]	3.48	-.679	-3.012	.004*	.167
IIV of PBI (reaction time)	-1.95	[-9.15, 5.25]	3.57	-.076	-.546	.588	.000
IIV of PBI (error rate)	2.80	[.435, 5.171]	1.18	.612	2.384	.021*	.105

Note. $N = 50$, $R = .410$, $R^2 = .168$, adjusted $R^2 = .094$. Predictors of Letter Number Sequencing scores were set as the mean change in accuracy on AY trials, the mean change in accuracy on BX trials, the intraindividual variability (IIV) of Proactive Behavioral Index (PBI) as a function of reaction time (ms), and the intraindividual variability (IIV) of Proactive Behavioral Index (PBI) as a function of corrected error rates. *$p < .05$

Discussion

The current study was designed to investigate the role of intraindividual variability of cognitive control in relation to maintaining goal-relevant information in working memory on the computerized AX-CPT paradigm. Age differences in intraindividual variability were examined separately for both older and young adults. The variable nature of proactive control and its association with working memory in older and young adults was the primary focus of the present study. As a function of normative age-related declines in executive functions, it was hypothesized that older adults would exhibit greater intraindividual variability of proactive control in the computerized AX-CPT.

The current findings suggest that both young and older adults engage in proactive control, when goal relevant information is available. Intraindividual variability of proactive control in older adults was comparable to that of young adults, failing to support the hypothesis. In a supplementary analysis, an independent indicator of working memory (the Letter Number Sequencing task) was found to be associated with the measures of intraindividual variability of proactive control, showing partial evidence for a link between working memory processes and individual differences of cognitive strategies.

Computerized AX-CPT

The computerized AX-CPT assessed modes of proactive and reactive control in older and young adults. Measures of reaction time revealed that young adults were slower to respond on AY trials compared to AX trials, indicating a use of proactive control. The trial type distribution in the AX-CPT favors an X stimulus expectancy response following an A cue, as a result of the high occurrence of AX trials (70% of trials). Therefore, slower reaction times on AY trials is indicative of anticipatory modes of cognitive control, as more time is required to resolve the occurrence of an unexpected Y stimulus following an A cue.

Young adults also performed faster on BX trials compared to AX trials, suggesting a lack of reliance on reactive control brought on by the presentation of an X stimulus. Reactive control involves a potential failure to maintain goal relevant information in working memory (the B cue). Therefore, an uncertainty in the preceding cue type would provoke a form of response conflict on BX trials. Reactive control would thus result in slower reaction times and an increased rate of false alarms on BX trials. As a result, the young adult pattern of responding is suggestive of an engagement in proactive control rather than reactive control on the computerized AX-CPT. These findings have been consistently supported in the DMC literature [11, 21].

Inconsistent with the literature, older adults were also found to engage in proactive control on the computerized AX-CPT. Previous studies have reflected age-related differences in modes of proactive and reactive control in older and young adults [11, 21, 23]. Like the young adults, for older adults, slower reaction times were observed on AY trials compared to AX trials, as well as faster reaction times on BX trials compared to AX trials. Further, the Proactive Behavioral Index provides an alternative way to quantify the use of proactive control and revealed statistically comparable levels in young and older adults. A previous study conducted using a smaller subset of the current sample revealed similar findings to the present study; both young and older adults engaged in proactive control in the computerized AX-CPT [18].

Inconsistencies between the present findings and the literature may be attributable to the characteristics of this sample. For example, young and older adults performed similarly on the Letter Number Sequencing task, an indicator of working memory. However, age-related working memory deficits have been reported widely [9, 24, 25], specifically on the Letter Number Sequencing task [26, 27]. Therefore, older adults in this sample may possess a higher level of cognitive functioning. As noted previously, three older adults scored higher on the Letter Number Sequencing task than any of the young adults. The same analyses, with these participants excluded, yielded the same results, suggesting that the overall sample of older adults may be higher functioning than average. Comparing the standardized Letter Number Sequencing scores to the relative age-norms provided further evidence of a high-functioning older adult sample. A total of 10 older adults scored 11 or higher, indicating that they fell in the 69th or higher percentile. Therefore, the sample of older adults would be deemed high functioning in accordance with the published norms [20].

Intraindividual Variability of Proactive Control

Given the high-functioning nature of older adults in this sample, comparable performance was revealed on measures of intraindividual variability of proactive control between the two age groups. Although not statistically significant, the operationalization of intraindividual variability of proactive control by Weimers and Redick [13] using the change in mean accuracy scores on BX trials, produced a moderate effect size (d = -0.51). This pattern was moderately supported by Braver et al.'s [21] more robust Proactive Behavioral Index measures of variability based on corrected error rates (d = -0.39). However, these patterns were not consistent across AX trials or measures of PBI based on reaction time. Previous literature fails to report consistent effect sizes in the field, leaving interpretation to be cautioned. Contextualizing these findings within the literature, the results demonstrate a lack of support for Weimers and Redick's [13] previous findings suggesting individual differences in intraindividual variability of proactive control. However, the work of Weimers and Redick focused on high and low working memory capacity young adult groups and did not examine the effects of aging by including older adults. Additionally, the authors went beyond the scope of proactive control when defining intraindividual variability in the AX-CPT. Weimers and Redick examined AX errors and proactive variability as a function of more time-on-task effects, using two distinct design manipulations, which was not possible for the current study given the archival nature of the data. The current findings are also inconsistent with the overall effect of an age-related increase in intraindividual variability. Specifically, it has been well-documented in the literature that older adults exhibit a greater level of variability in their reaction times compared to young adults [15, 16, 28, 29]. Therefore, the alternative pattern of results in the current study may have been a product of the characteristics of the sample, such as the high-functioning capacity of older adults.

Working Memory and Intraindividual Variability

Letter Number Sequencing was used as an independent indicator of working memory. Performance on this task was found to be predicted by the measures of intraindividual variability of proactive control. Both of Weimers and Redick's [13] measures of proactive shift, using AY and BX trials, were revealed to be statistically significant predictors of working memory performance, uniquely accounting for 8.7% and 16.73% of the variance in intraindividual variability respectively. In addition, Braver et al.'s [21] more robust PBI measure, calculated using error rates, replicated these findings and was also a statistically significant predictor of Letter Number Sequencing scores, uniquely accounting for 10.5% of the variance. The involvement of working memory processes in intraindividual variability of proactive control strengthens the validity of the computerized AX-CPT. This paradigm was designed to capture executive functions involved in cognitive control, such as working memory. The association between working memory and an individuals' preferred mode of cognitive control has been previously studied [30]. Other research using anti-saccade tasks, which require the maintenance of a task rule in working memory, has revealed increased intraindividual variability of cognitive control in individuals with a low working memory capacity [31, 32, 33, 34]. However, the current findings are the first to reveal an association between intraindividual variability of proactive control and working memory in the computerized AX-CPT. The novelty of this finding contributes to solidifying the DMC as a model of executive functions, and the implication of working memory capacity therein.

Implications

Given that young and older adults did not differ in the variability with which they engaged in proactive control in the computerized AX-CPT, it is suggested that they are not reaping the potential adaptive benefits of increased variability, while simultaneously not being affected by any maladaptive effects of increased variability. As proposed by Allaire and Marsiske [17], greater variability in responding offers more opportunities for learning the correct and optimal form of response, thus proving to be adaptive in the long run. Conversely, increased variability is defined by a general inconsistency in responding, resulting in more overall errors on a given task, as opposed to employing the optimal form of response throughout. Therefore, older adults were neither at a loss nor at a gain, as their level of intraindividual variability was comparable to that of young adults on the computerized AX-CPT. An independent index of working memory (the Letter Number Sequencing task) was associated with the measures of intraindividual variability of proactive control. Therefore, the current findings tentatively support the involvement of working memory processes in age-related declines in cognitive control. A greater overall understanding of fall risk can allow for the implementation of prevention measures to minimize such risks.

Limitations and Future Directions

Limitations within the current study also offer potential future avenues for research. Characteristics of the sample may have played a role in the comparable performance of young and older adults. A form of self-selection bias may have been introduced, resulting in a subset of high-functioning older adults choosing to participate in the study. The AX-CPT designs themselves also offered potential limitations to the study. For instance, the number of AY and BX trials was fairly limited throughout the paradigm. These trials are essential to determining the use of proactive control, yet they only occur 10% of the time, amounting to a total of only 20 trials across all four blocks. One error on AY and BX trials can thus have a large impact on a participant's PBI. The current design was similar to Paxton et al.'s study involving the same number of trials [35]. Weimers and Redick [13] improved upon this design by doubling the number of blocks, resulting in double the amount of AY and BX trials. This increase allowed for a greater representation of intraindividual variability within the different blocks. However, given the archival nature of the data, adjustments to the design for the specific hypotheses was not possible.

Future research should consider the role of other executive functions, such as inhibition, task switching, and processing speed. Age differences in processing speed have been previously investigated at length and could offer a new perspective into the DMC model, both in terms of understanding the variability of proactive and reactive control in the computerized AX-CPT [36].

The current study only examined one type of executive function, that is working memory. To the best of my knowledge, different executive functions could be involved in relation to intraindividual variability in cognitive aging. Therefore, it would be interesting to consider the novelty of further examining executive functions through the DMC lens.

Conclusion

The present study investigated the role of intraindividual variability as a function of cognitive aging. A standard computerized AX-CPT was used to measure proactive control in a cued-stimulus presentation paradigm. The focus of the present study was the fluctuation with which older and young adults engaged in different modes of cognitive control and how this variability relates to processes of working memory. Overall, young and older adults performed similarly in their level of intraindividual variability of proactive control in the computerized AX-CPT. However, an independent test of working memory (the Letter Number Sequencing task) revealed to be statistically associated with the measures of intraindividual variability of proactive control. The present findings overall provide preliminary evidence that working memory processes are involved in age-related declines in cognitive control.

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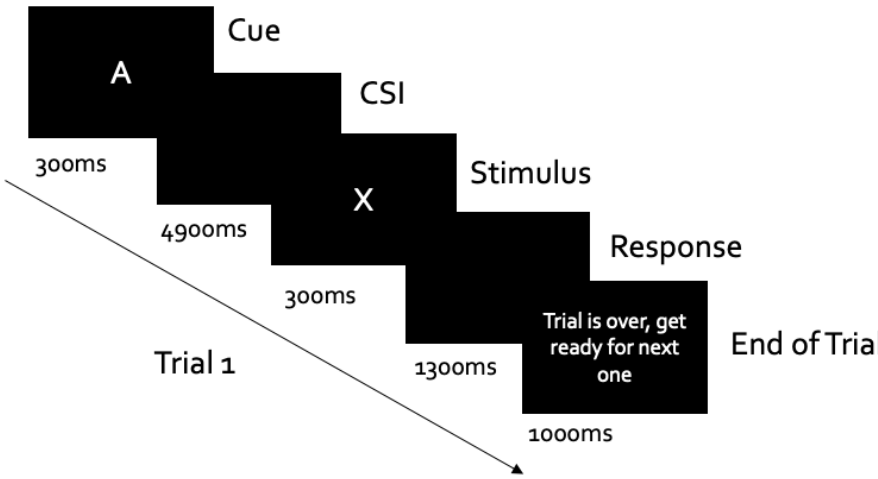
Appendix A

Computerized AX-CPT Paradigm



Note. Experimental paradigm of an AX trial in the computerized AX-CPT design. An "A" cue is presented for 300 ms, followed by a Cue-Stimulus Interval (CSI) of 4900 ms. An "X" stimulus is then presented for 300 ms, and a response window of 1300ms is given to participants. A screen for 1000 ms with the text "Trial is over, get ready for next one" marks the end of the AX trial.

Appendix B

Computerized AX-CPT Mean Reaction Times

Trial Type	AX		AY		BX		BY	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Young Adults	531.00	98.59	646.00	89.46	459.00	129.23	452.00	79.69
Older Adults	638.00	85.22	864.00	113.97	584.00	99.94	581.00	109.80
Overall	589.00	105.52	766.00	150.00	525.00	129.76	523.00	116.26

Average reaction time (ms) across all trial types as a function of age group on the computerized AX-CPT.

Appendix C

Correlations, Means, and Standard Deviations for Working Memory Regression Analyses

Variables	1	2	3	4	5
1. LNS Total Score	—				
2. AX Change in Accuracy	-.018	—			
3. BX Change in Accuracy	-.242	.308	—		
4. IIV of PBI (reaction time)	.007	-.120	-.178	—	
5. IIV of PBI (error rate)	.023	-.563	.427	.042	—
M	19.26	-.04	-.01	.04	.06
SD	2.08	.18	.14	.08	.45

Note. N = 50. Predictors of Letter Number Sequencing (LNS) total scores (out of 30) were set as the mean change in accuracy on AY trials, the mean change in accuracy on BX trials, the intraindividual variability (IIV) of Proactive Behavioral Index (PBI) as a function of reaction time (ms), and the intraindividual variability (IIV) of Proactive Behavioral Index (PBI) as a function of corrected error rates.