Proactive Control Declines While Reactive Control is Preserved Across the Adult Lifespan

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Abstract

We provide a comprehensive investigation of proactive and reactive control during Stroop task performance with younger, middle-aged, and older adults, to test predictions of the Dual Mechanisms of Control (DMC) framework. A novel color-word vocal response paradigm was utilized with separate baseline, proactive, and reactive conditions, which differed in list-level and item-specific proportion congruencies, along with matched and randomly alternating color naming and word reading blocks. When compared to baseline, the proactive condition indexes processes that actively maintain goal-relevant information during contexts in which distraction is expected, while the reactive condition indexes dynamic adjustment processes engaged when items associated with high cognitive control demands are unpredictably encountered. Using a large sample (N = 327) and targeted analyses measuring primary and secondary behavioral markers of proactive and reactive control, the findings strongly indicate that while younger adults demonstrate robust engagement of proactive control mechanisms, proactive control effects were absent in older adults, and diminished in middle-aged adults, suggesting a lifespan related pattern of change. In contrast, the results highlight the selectivity of the proactive pattern, as indices of reactive control did not exhibit age-related change, nor were there any effects of proportion congruency in matched word reading blocks. Together, the findings provide strong confirmation of the DMC framework, in suggesting a tight linkage between proactive control capacity and the dynamic neurocognitive processes that change across the adult lifespan.

Keywords: aging, cognitive control, proactive control, reactive control, dual mechanisms of control

Public Significance Statement

Our study challenges stereotypes about aging and the decline of cognitive control capacity by exploring two distinct modes of control: proactive and reactive control. Proactive control involves sustaining focus in anticipation of conflict, while reactive control responds swiftly to unexpected conflict. In a comprehensive investigation examining proactive and reactive control within the same participants and in a single task, we demonstrated that, while older adults may struggle with proactive control compared to younger adults, they exhibited remarkable resilience in reactive control. Middle-aged adults, an underexplored group, also show evidence of diminished proactive control, indicating a transitional lifespan phase. The results highlight the brain's ability to remain adaptable and responsive as we age, offering a nuanced perspective on aging and cognitive control.

Proactive Control Declines While Reactive Control is Preserved Across the Adult Lifespan

Understanding how cognitive control evolves across different stages of life offers profound insights into human behavior and cognition. Cognitive control encompasses the ability to regulate behavior in alignment with internal goals, by prioritizing relevant information and suppressing irrelevant information. For instance, picture driving a car in a bustling street. Cognitive control provides the capacity to focus on relevant information such as road signs, traffic lights, and pedestrians while filtering out distractions such as roadside advertisements or conversations with passengers, enabling us to achieve the goal of driving safely. Cognitive control is essential for preserving focus, managing disruptions, making well-informed decisions, and adaptively changing behavior to achieve intended goals. As individuals progress through different stages of life, the dynamics of cognitive control undergo notable transformations. While one might assume that cognitive control generally declines with age, it is crucial to recognize that this capacity is not monolithic. Rather, it comprises different subcomponents, some of which may exhibit age-related changes, while others remain preserved. These nuances in cognitive control across the lifespan highlight the complexity of human cognition and underscore the need for a more thorough understanding of how it evolves over time.

The Dual Mechanisms of Control (DMC) framework proposes that cognitive control operates through two dissociable processing modes: proactive control and reactive control (Braver et al., 2007; Braver, 2012).

Proactive control involves maintaining goal-relevant information to guide attention in a preparatory and sustained manner, such as when anticipating expected distractions. Reactive control, on the other hand, comes into play after distraction occurs, and involves the transient activation of goals to regulate behavior. Following ideas originally put forth by Jacoby et al. (1999), Braver et al. (2007) suggested that proactive control may reflect early selection mechanisms, while reactive control instead involves late correction processes (see also Kane & Engle, 2004).

According to the DMC framework, tasks that rely heavily on proactive control, which involve actively maintaining goal representations in the prefrontal cortex, are likely to show more pronounced age-related declines in performance, as the activation of prefrontal regions attenuates (Braver & West, 2008; Dexter & Ossmy, 2023; Grady, 2012). On the other hand, performance on tasks that promote reactive control, where goals are activated transiently, should be more preserved with age (Braver et al., 2007). One of the most frequently utilized tasks to study cognitive control as well as cognitive aging effects is the color-word Stroop task (Stroop, 1935). In the Stroop task, participants are asked to indicate the font color of a word, while ignoring the meaning of the word, which can be congruent (e.g., RED in red font) or incongruent (e.g., RED in green font) with the color. Incongruent stimuli create conflict (distraction), and thus high cognitive control is needed to resolve it. An oft reported finding is that older adults exhibit increased interference on such trials as evidenced by a larger Stroop effect (i.e., the difference in reaction time or accuracy between congruent and incongruent stimuli), suggestive of cognitive control decline (Bugg et al., 2007; Cohn et al., 1984; Comalli et al., 1962; Hartley, 1993; Jackson & Balota, 2013; Logan, 1980; Nicosia & Balota, 2020; but see Rey-Mermet & Gade, 2018; Verhaeghen, 2011, for meta-analytic evidence suggesting no decline in older adulthood).

The overarching goal of the present study was to systematically investigate whether age-related changes in cognitive control as assessed by performance in the Stroop task can be attributed selectively to a change in proactive rather than reactive control. The present study is not the first to address this question, as we will highlight momentarily; however, the study is unique in offering several advances. One, we examine age-related changes in proactive and reactive control by using a within-subjects (and thus within-experiment) comparison of control modes (cf. Ball et al., 2023; Bugg, 2014a; Bugg, 2014b). Two, we include a sample of middle-aged adults, a frequently ignored age category, in addition to younger and older adults, thereby allowing us to characterize for the first time the dynamics of cognitive control changes across the lifespan. Third, extending related prior work (Tang et al., 2022 which employed proactive, reactive, and baseline conditions as the present study, but only in younger adults and without a word reading task), we employ a novel mini-block design that includes blocks in which participants are instructed to respond to the word and ignore the color, as well as more standard color naming blocks, in order to provide a more comprehensive investigation of control-related processes.

In addition to these innovations, the present study leveraged further methodological innovations that have emerged in the last decade or so, providing researchers with tools to more rigorously isolate proactive and reactive control processes within the Stroop task. These tools include theoretically-targeted Stroop task variants that incorporate proportion congruence (PC) manipulations at different levels (for reviews see Braem et al., 2019; Bugg & Crump, 2012; Bugg, 2017). To assess proactive control, researchers employ list-wide proportion congruence (LWPC) manipulations. In the LWPC manipulation, participants engage in the Stroop task across two lists (blocks) and the proportion of congruent (i.e., the color and the word match) and incongruent (i.e., the color and the word conflict) trials is manipulated, creating mostly congruent (MC) and mostly incongruent (MI) lists. Some stimuli serve as inducer items (i.e., PC biased – MC or MI) while the others are diagnostic items (i.e., frequency and PC unbiased – 50% congruent; Bugg et al., 2014a). Diagnostic items provide a pure measure of proactive control since they remain consistent across lists that differ in their list-wide PC. The manifestation of proactive control is evident in the reduced Stroop effect for diagnostic items within the MI list as compared with the MC list (i.e., the LWPC effect). This effect underscores the heightening of cognitive control that occurs in response to the more frequent conflict experienced in the MI lists, which is thought to affect the diagnostic items through utilization of proactive control, as this control mode is hypothesize to be engaged in a sustained manner; that is, prior to the presentation of task stimuli (and thus should impact all item types).

In contrast, item-specific proportion congruence (ISPC) manipulations are employed to assess reactive control (Bugg et al., 2011). ISPC is manipulated by varying the likelihood of conflict at the item level (i.e., typically presenting some stimuli as MC and the others as MI in a random order), while maintaining constant list-wide PC. The ISPC effect, the reduced Stroop effect for the MI items compared with the MC items, provides a measure of reactive control. Control is reactive because participants cannot predict whether the next stimulus will be MC or MI (and thus cannot prepare differentially for the items based on proactive control); rather, cognitive control is adjusted post-stimulus onset, based on features of the encountered items (i.e., the font color) that predict whether an item is MC or MI. As such, the ISPC effect is not expected to transfer to diagnostic items, as the diagnostic items in the theoretically-targeted designs that we employ do not include these predictive features.

Prior Studies Demonstrating Age-Related Dissociations in Control Mechanisms

Consistent with the DMC framework, prior studies have found evidence consistent with a dissociation between proactive and reactive control, with age-related declines being prominent in proactive, but not in reactive control. Bugg (2014a) utilized an LWPC manipulation within a color-word Stroop task designed to isolate proactive control from reactive control. The key finding was younger adults utilized proactive control, while older adults did not (cf. Braver et al., 2005, who observed the same pattern with the AX-CPT task).[1] In contrast, previous studies have shown

[1] It should be noted that an earlier study did not find age-related decline in tasks requiring proactive control (Mutter et al., 2005, Experiment 2). However, this study

that reactive control processes do not exhibit decline with increasing age. Bugg (2014b, Experiment 1) showed intact reactive control in older adults using an ISPC manipulation within a picture-word Stroop task (see Braver et al., 2001, 2005 observing the same pattern with the AX-CPT task).

Importantly, however, most prior studies have investigated only one form of age effect on cognitive control (e.g., either reactive control or proactive control). Consequently, there is a need for a comprehensive study investigating both reactive and proactive control mechanisms within the same task and across all age groups, utilizing a fully within-subjects design. In a recent attempt to comprehensively assess proactive and reactive control in older adults, Ball et al. (2023) compared proactive and reactive control in older adults within the same task and observed intact reactive control manifested with a significant ISPC effect and impaired proactive control manifested with the lack of an LWPC effect, supporting previous results. However, their study was also limited, by not including either a younger adult or middle-aged cohort for direct comparison.

Present Study

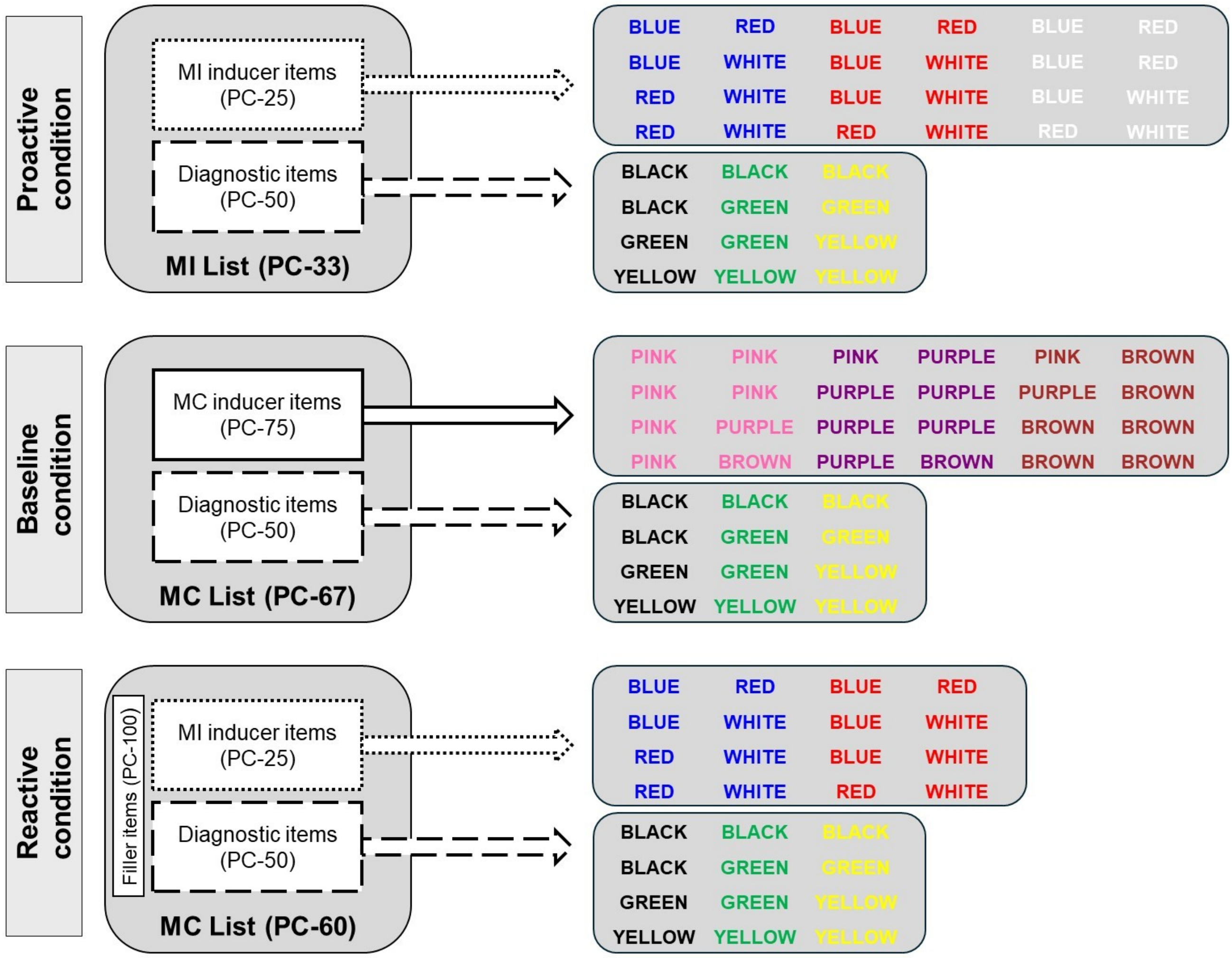
In the present study, we aimed to comprehensively investigate age-related changes in proactive and reactive control processes using an innovative Stroop task design and a lifespan sample (young, middle-aged,

employed a design that confounded LWPC and ISPC manipulations (i.e., inducer items were MC or MI both at the item and list level), rather than utilizing unbiased diagnostic items. Given that this study employed a confounded design, there was no pure measure of proactive control; consequently, it is possible that the observed LWPC effects were instead markers of reactive control.

and older adults). The data were collected on-line, which facilitated the acquisition of large sample-sizes (N > 100) for each age group. All participants performed three conditions: baseline, proactive, and reactive color naming, as well as identically matched word reading blocks, which will be described momentarily (see Table 2 for stimulus frequency in these conditions, and Figure 1 for an illustration of conditions). These conditions allowed us to test four key hypotheses inspired by the DMC framework.

Figure 1

The Illustration of Proactive, Baseline, and Reactive Conditions.



Note. The proactive condition includes MI inducer (PC-25) items and diagnostic (PC-50) items, creating an MI list. The baseline condition includes MC inducer (PC-75) items and diagnostic (PC-50) items, creating an MC list. Finally, the reactive condition includes MI inducer (PC-25) items and diagnostic (PC-50) items, however; due to the inclusion of (PC-100) filler items, it creates an MC list. Note that diagnostic items are matched across conditions. Inducer and diagnostic trials are randomly intermixed for each participant, but they are shown grouped in the figure for simplification.

The first question was whether we could find evidence that engagement of proactive control decreases with aging. To address this question, we contrasted proactive (list-wide MI) and baseline (list-wide

MC) conditions, comparing the identically matched and unbiased (i.e., 50% congruent) diagnostic items across conditions. The key prediction was that while younger adults should show evidence of proactive control, in terms of a reduced Stroop effect in the proactive condition, this effect was predicted to be absent in older adults, indicating a lack of proactive control utilization in this age-group. The inclusion of the middle-aged group allowed a test of whether proactive control diminishes continuously as a function of increasing age.

A second key question of interest was whether we would find evidence that engagement of reactive control would remain intact with aging, using the same design and participants. To address this question, we compared the reactive and baseline conditions, but now focusing on inducer items. Critically, the reactive and baseline conditions have a similarly high LWPC (60% in reactive, 67% in baseline), and so should not differentially engage proactive control. However, the inducer items are *mostly incongruent* in the reactive condition, whereas they are *mostly congruent* in the baseline condition. Thus, evidence of reactive (item-specific) control should be indicated in terms of a reduced Stroop effect for inducer items in the reactive condition. The key prediction is that these reactive effects should be equally present in younger, middle-aged, and older adults, resulting in no significant age effects.

A third question of interest relates to the effects of increasing age on two secondary markers of proactive and reactive control, the congruency cost and transfer cost. In prior work, these markers have been used to directly compare proactive and reactive control, respectively, demonstrating that they are doubly dissociable, and thus reflect semi-independent control processes (Gonthier et al., 2016; Tang et al., 2022). The congruency cost reflects the assumption that with proactive control, cognitive control should be biased towards color and away from word information even prior to stimulus onset (i.e., in a preparatory fashion), which should reduce any (facilitatory) benefit that would otherwise accrue on congruent diagnostic trials.[2] As such, slower responses on congruent diagnostic trials should be present in the proactive condition, relative to both baseline and reactive conditions. In the reactive condition, because cognitive control is modulated post-stimulus onset, and at the item level, it should not impact the processing of congruent diagnostic items (see e.g., Bugg et al., 2011; Bugg & Dey, 2018; Suh & Bugg, 2021, for evidence that item-specific control is almost exclusively operative on incongruent trials). Thus, the congruency cost should show a proactive > reactive pattern. As another indicator of possible age-related differences in proactive control, we asked whether this congruency cost pattern would change, or be eliminated, in older adults.

In contrast, the transfer cost reflects the assumption that for reactive control, the benefit is purely at the item level and should not transfer to diagnostic items, in designs like the present one where the diagnostic items do not share overlapping features (e.g., colors) with inducer items. As such, when reactive control is engaged, a large difference in the magnitude of Stroop effects should be present between

[2] Note that we use congruent diagnostic trials since they are matched across conditions.

inducer and diagnostic items (i.e., diagnostic Stroop > inducer Stroop), indicating a transfer cost. In contrast, when proactive control is engaged, the difference between diagnostic and inducer items should be small, since such control is applicable to all items (i.e., engaged globally across a list). Thus, the transfer cost, a larger Stroop effect for diagnostic items compared to inducer items, is predicted to show a reactive > proactive pattern. As another indicator of how aging may (or may not) affect reactive control, we asked the question of whether the transfer cost would remain intact with increasing age in the reactive condition. We additionally asked whether the transfer cost differed between age groups in the proactive condition (i.e., whether it would increase in the proactive condition for older adults, relative to younger adults).

A fourth question of interest was whether the effects above selectively reflect the cognitive control demands associated with color naming. To address this question, we leveraged an innovative aspect of the task design, in which participants performed matched blocks of word reading randomly inter-mixed with color naming within the proactive, baseline, and reactive conditions. Specifically, the word reading condition can be used to test whether any age-related changes in performance within proactive and reactive conditions, are indeed selectively related to cognitive control processes, as we have assumed, or are instead manifestations of age-related changes that may be less specific to cognitive control. That is, we treated the word reading blocks as a negative control condition. Since word reading is hypothesized to make minimal demands on cognitive control processes – whether proactive or reactive (particularly our design, which utilized vocal responses) – we predicted that none of the key effects tested above would be significant, when examined using the word reading condition. To test this hypothesis, we repeated the analyses performed on the LWPC effect, ISPC effect, congruency cost, and transfer cost, but this time with the word reading data. As an example, for the LWPC effect, the hypothesized age-related changes in proactive control, which are predicted to reduce the LWPC effect in older adults for color naming, would not be expected to impact the LWPC effect when it is computed for word reading. More generally, analyses contrasting color naming with word reading effects provide a strong test of the selectivity of hypotheses regarding proactive and reactive control, and the effects of aging on these control processes.

In summary, we conducted four key analyses[3] to address the questions above, taking advantage of our novel and comprehensive within-subject design to provide a comprehensive investigation of the relationship among proactive and reactive cognitive control effects in the Stroop task, and how these are impacted by increasing age across the adult lifespan. Please see Table 1 for the summary of the measures and the hypotheses related to them.

[3] A fifth exploratory analysis examining color naming costs is also included and fully described, under Results.

Table 1

Predictions and measures for each question of interest

Measure of Interest	Trials Analyzed	Predictions	Predicted Influence of Aging	Confirmation of Predictions
Proactive control (LWPC effect)	Diagnostic	Proactive Stroop Effect < Baseline Stroop Effect	Age-related differences	Confirmed
Reactive control (ISPC effect)	Inducer	Reactive Stroop Effect < Baseline Stroop Effect	No age-related differences	Confirmed
Congruency cost	Congruent Diagnostic	Proactive RT > Reactive RT	Age-related differences	Confirmed
Transfer cost	Diagnostic & Inducer	Reactive Congruency Cost (Diagnostic Stroop Effect- Inducer Stroop Effect) > Proactive Congruency Cost (Diagnostic Stroop Effect- Inducer Stroop Effect)	Age-related differences	Partially Confirmed
Word reading effects	See above for each analysis	Selectivity of proactive and reactive control to color naming (i.e., no significant effects when all above analyses are repeated with word reading data)	No age-related differences	Confirmed
Color naming cost (exploratory)	Congruent Diagnostic	Proactive color naming cost (Color naming RT – Word reading RT) > Baseline color naming cost (Color naming RT – Word reading RT)	Age-related differences	Confirmed
		Proactive color naming cost (Color naming RT – Word reading RT) > Reactive color naming cost (Color naming RT – Word reading RT)	Age-related differences	Confirmed

Method

Transparency and openness. This experiment, including the experimental design, exclusionary criteria, analytic plan, and preliminary results with younger adults, was fully pre-registered on Open Science Framework (https://osf.io/krcn5/ for younger adults and https://osf.io/6b5rm/ for middle-aged and older adults)[4], and study

[4] Please note that we pre-registered data collection for middle-aged and older adults after collecting data for younger adults which was separately pre-registered before data collection.

materials, analysis scripts, and the data are publicly available (https://osf.io/k8tuc/). Data collection was completed in 2023 and data were analyzed using R, Version 4.1.1 (R Core Team, 2021). We describe the methods used to determine our sample size, detail any data exclusions, outline all manipulations, and list all measures included in the study.

Participants. We collected data from a total of 387 participants, ranging from 18-89 years of age, and recruited through the Prolific platform. Participants were compensated for their participation with $10 payment for a ~1-hour experimental session. All participants were native English speakers located in the United States or United Kingdom. One participant who did not have data in one of the conditions and fifty-nine participants having less than 80% accuracy in the experiment were excluded from all analyses as pre-registered, resulting in 327 usable participants.[5] We analyzed data from 114 younger adults (age range = 18-32; 34 females, 80 males, mean age = 26.74, SD = 3.93), 103 middle-aged adults (age range = 33-59; 40 females, 63 males, mean age = 42.79, SD = 7.76), and 110 older adults (age range = 60-89; 60 females, 50 males, mean age = 65.44, SD = 4.42). The study was approved by the Institutional Review Board at Washington University in St. Louis and all participants provided informed consent.

[5] The target sample size was 100 participants per each age group and the stopping rule (i.e., the maximum number of participants we can collect data from unless the total sample size drops below the target sample size) was indicated as 140 participants per each age group in the pre-registration.

Design and stimuli. The study design included the following task factors: Age (Younger Adults, Middle-Aged Adults, Older Adults), Condition (Baseline, Proactive, Reactive), Task (Color Naming, Word Reading), Trial Type (Congruent, Incongruent), and Item Type (Inducer, Diagnostic), along with Condition Order (Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) as a covariate. Age and Condition Order were between-subjects variables, while Condition, Task, Trial Type, and Item Type were within-subject variables. Participants performed the three conditions (Baseline, Proactive, Reactive) in one of two counterbalanced orders (Proactive-Baseline-Reactive or Reactive-Baseline-Proactive). Trials were either congruent (i.e., the color and the word matches) or incongruent (i.e., the color and the word conflicts), and some of the items were used as inducers of PC (i.e., MC or MI) while others were utilized as diagnostic indicators, and thus were equally congruent (i.e., unbiased).

The trial types and stimuli for the design are summarized in Table 2. Participants performed the task in mini-blocks of 36 trials for the baseline and proactive condition, and 45 trials for the reactive condition, responding to 702 task trials in total throughout the experiment. The stimulus structure was identical across color naming and word reading blocks. Thus, the task-relevant stimulus dimension (color or word) was the only thing that distinguished the two block types. Likewise, diagnostic items were matched across all conditions (i.e., 12 trials per block, 50% congruent items, and composed of the words BLACK, GREEN, and

YELLOW and the corresponding colors black, green, and yellow), thus facilitating cross-condition comparisons.

As illustrated in Figure 1, in the baseline condition, trials were list-wide MC (i.e., 67% congruent), with 75% congruent inducer items (composed of the words: PINK, PURPLE and BROWN and the corresponding colors pink, purple and brown). In the proactive condition, trials were list-wide MI (i.e., 33% congruent), with 25% congruent inducer items (composed of the words: BLUE, RED, and WHITE and the corresponding colors blue, red, and white). In the reactive condition, trials were list-wide MC (i.e., 60% congruent), with 25% congruent inducer items (color-words: BLUE, RED, and WHITE), but also included 100% congruent filler items (color-words: ORANGE and GRAY) to maintain the list-wide PC.[6]

[6] The set of colors used with inducer items in the baseline condition differ from those used in the proactive and reactive conditions. This intentional difference was implemented to prevent the carryover effect across conditions featuring different levels of ISPCs.

Table 2

Frequency of Color-Word Pairings in Baseline, Proactive, and Reactive Conditions per Mini-Block

Baseline — PC-75 items (inducer)

Color	Word: Pink	Word: Purple	Word: Brown
Pink	6	1	1
Purple	1	6	1
Brown	1	1	6

Baseline — PC-50 items (diagnostic)

Color	Word: Black	Word: Green	Word: Yellow
Black	2	1	1
Green	1	2	1
Yellow	1	1	2

Proactive — PC-25 items (inducer)

Color	Word: Blue	Word: Red	Word: White
Blue	2	3	3
Red	3	2	3
White	3	3	2

Proactive — PC-50 items (diagnostic)

Color	Word: Black	Word: Green	Word: Yellow
Black	2	1	1
Green	1	2	1
Yellow	1	1	2

Reactive — PC-25 items (inducer)

Color	Word: Blue	Word: Red	Word: White
Blue	2	3	3
Red	3	2	3

Reactive — PC-50 items (diagnostic)

Color	Word: Black	Word: Green	Word: Yellow
Black	2	1	1
Green	1	2	1
Yellow	1	1	2

Reactive — PC-100 items (filler)

Color	Word: Orange	Word: Gray
Orange	9	0
Gray	0	8

Procedure. The experiment was programmed and presented using Inquisit 6 software. Participants performed the task remotely on-line, using their own personal laptop or computer. Participants produced vocal responses, their computer's built-in voice recognition software detected the response, and the Inquisit software recorded the response and accuracy automatically. In color naming blocks, participants received an instruction to respond by naming the font color that the word was presented in, while ignoring the word itself; in the word reading blocks, the instruction indicated they should respond by reading out loud the word while ignoring the word's font color. Trials in which a valid (i.e., one of the possible color-words) but incorrect response was detected were coded as error trials. For trials in which the microphone was triggered by extraneous noise or imperceptible speech, including trials on which no response was detected, the response was coded as scratch / no-response.

Each block began with a visual instruction screen indicating the task (color naming or word reading), followed immediately by a series of trials. All stimuli were presented on a gray background at the center of the screen. Stimuli were presented on the screen for a duration of 2000 ms. After 2000 ms, the stimulus disappeared, and a blank screen (1000 ms) was presented, followed by the next stimulus. At the end of each block, participants were required to indicate what the task rule (color naming or word reading) was in the block they just performed; the blocks in which they chose the wrong rule were excluded from the analyses. Participants were able to take a self-paced rest break after each block. A total of 18 blocks were performed, with 6 blocks of each condition (proactive, baseline, reactive) presented sequentially in a blocked format that included 4 color naming and 2 word reading blocks randomly intermixed. Participants encountered one of the two counter-balanced orders (proactive-baseline-reactive or reactive-baseline-proactive).

Before beginning the experiment, participants completed three practice blocks (i.e., 2 color naming and 1 word reading blocks). The items in the practice blocks mimicked the PCs of the items in the first condition participants performed in the main task (i.e., reactive condition for reactive-baseline-proactive order, and proactive condition for proactive-baseline-reactive order). In addition to familiarizing participants with the tasks, the practice blocks were used to determine if voice detection was adequate to continue to the main experimental session (i.e., at least 75% accuracy). Participants whose voice detection was inadequate were compensated ($3) for the time they spent on the practice blocks and did not continue to perform the main task.

Results

The blocks with incorrectly reported task rule were eliminated from all analyses (eliminated 0.98% of the blocks). Trials faster than 200 ms (eliminated 0.04% of total trials), scratch trials (eliminated 5.85% of total trials) and error trials (eliminated 2.01% of total trials) were excluded from all analyses. Mean RTs are presented in Table 3. To test our hypotheses, we ran separate comparisons for all conditions. We report the critical results that directly test our hypothesis(es) for each research question; a more comprehensive set of analyses and results can be found in Supplementary Materials.

Table 3

Mean RTs (Standard Error in Parenthesis) in the Baseline, Proactive, and Reactive Color-Naming Conditions.

		Baseline		Proactive		Reactive	
Age	Trial Type	Inducer	Diagnostic	Inducer	Diagnostic	Inducer	Diagnostic
Younger	Incongruent	798 (4)	745 (4)	711 (4)	734 (4)	725 (4)	745 (4)
	Congruent	651 (4)	654 (4)	655 (5)	658 (4)	660 (5)	648 (4)
	Stroop Effect	*147 ms*	*91 ms*	*56 ms*	*76 ms*	*65 ms*	*97 ms*
Middle-Aged	Incongruent	823 (4)	751 (4)	710 (5)	735 (5)	727 (5)	752 (5)
	Congruent	673 (4)	667 (4)	655 (5)	659 (4)	689 (4)	657 (4)
	Stroop	*150 ms*	*84 ms*	*55 ms*	*76 ms*	*38 ms*	*95 ms*

	Effect						
Older	Incongruent	836 (4)	764 (4)	727 (4)	757 (4)	755 (4)	763 (4)
	Congruent	689 (4)	679 (4)	664 (4)	668 (4)	688 (5)	673 (4)
	Stroop Effect	*147 ms*	*85 ms*	*63 ms*	*89 ms*	*67 ms*	*90 ms*

Additionally, to test the robustness of the observed findings, as well as to provide more informative parameter estimates for further replication studies, we conducted the same tests with linear mixed effect (LME) models, that included subject-level random effects and age as a continuous variable. The results of these analyses are reported in the Supplementary Materials. Note that all critical effects were consistent across the LME and ANOVA analyses, except where noted. Mean error rates were low, and the error rate analyses did not contradict any conclusions that emerged from the RT analyses. Therefore, we did not report error rate analyses to keep the manuscript and the Supplementary Materials concise, considering the abundance of existing analyses.

Does Proactive Control Decrease with Aging?

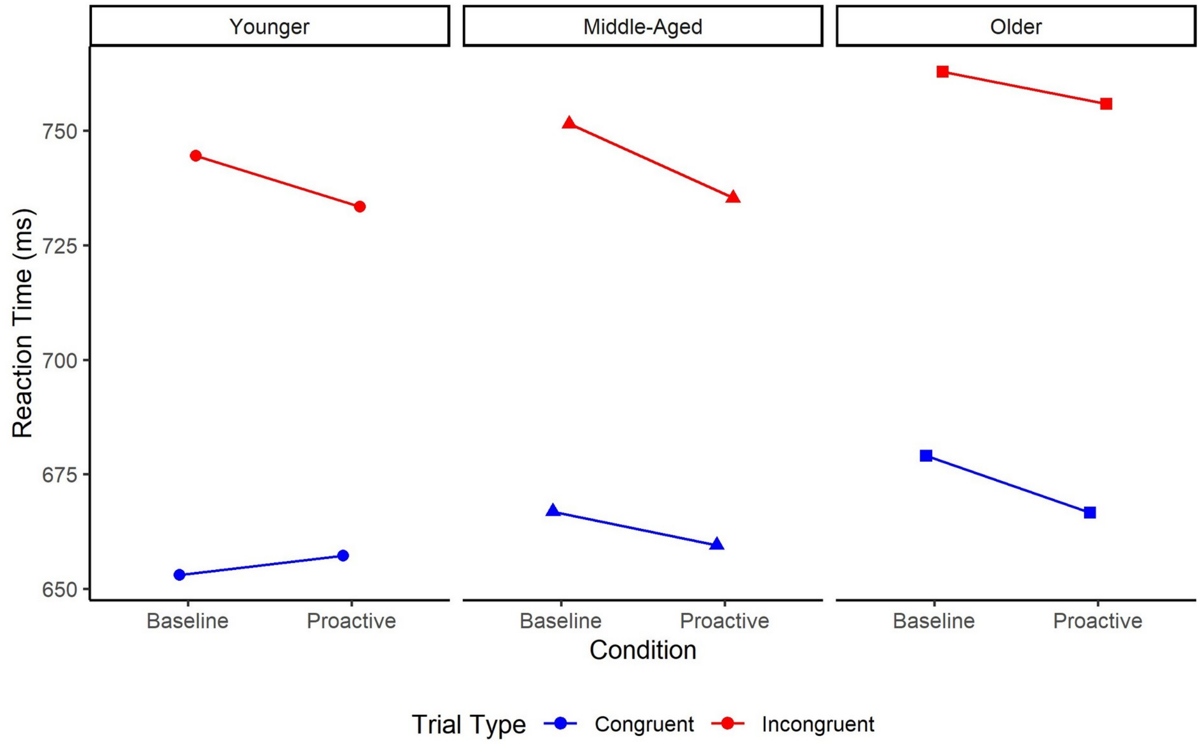
We hypothesized that proactive control would decrease with aging. To assess proactive control, we compared baseline and proactive control color naming blocks with a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Baseline, Proactive) x 2 (Trial Type: Congruent, Incongruent) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA conducted on diagnostic items.[7] Age and condition order were between-subjects variables.

[7] Please note that we used type 3 ANOVA in all analyses.

The overall LWPC (Condition x Trial Type) effect was significant, $F(1, 321) = 7.07$, $p = .008$, = 0.02. The Stroop effect was smaller in the proactive condition ($M = 80$) compared with the baseline condition ($M = 86$). Critically, this effect further interacted with age, $F(2, 321) = 7.11$, $p = .001$, = 0.04, indicating a difference in the engagement of proactive control across age groups (see Figure 2). There was a significant LWPC effect for younger adults ($M = 15$, Baseline = 91, Proactive = 76), $F(1, 112) = 13.72$, $p < .001$, = 0.11, and middle-aged adults ($M = 12$, Baseline = 84, Proactive = 76), $F(1, 101) = 5.65$, $p = .019$, = 0.05; but not for older adults ($M = -4$, Baseline = 85, Proactive = 89), $F(1, 108) = 1.60$, $p = .209$, = 0.02. Post-hoc comparisons corrected with Tukey showed that both younger, $p < .001$, and middle-aged, $p = .021$, adults had a larger LWPC effect compared with older adults. Even though there was a numerical difference between the younger and middle-aged adults, they were not significantly different, $p = .552$. These results indicated that there was an age-related decline in proactive control for older adults as expected, while middle-aged adults showed intact proactive control.

Figure 2

The LWPC Effect with Diagnostic Items for Younger, Middle-Aged, and Older Adults.



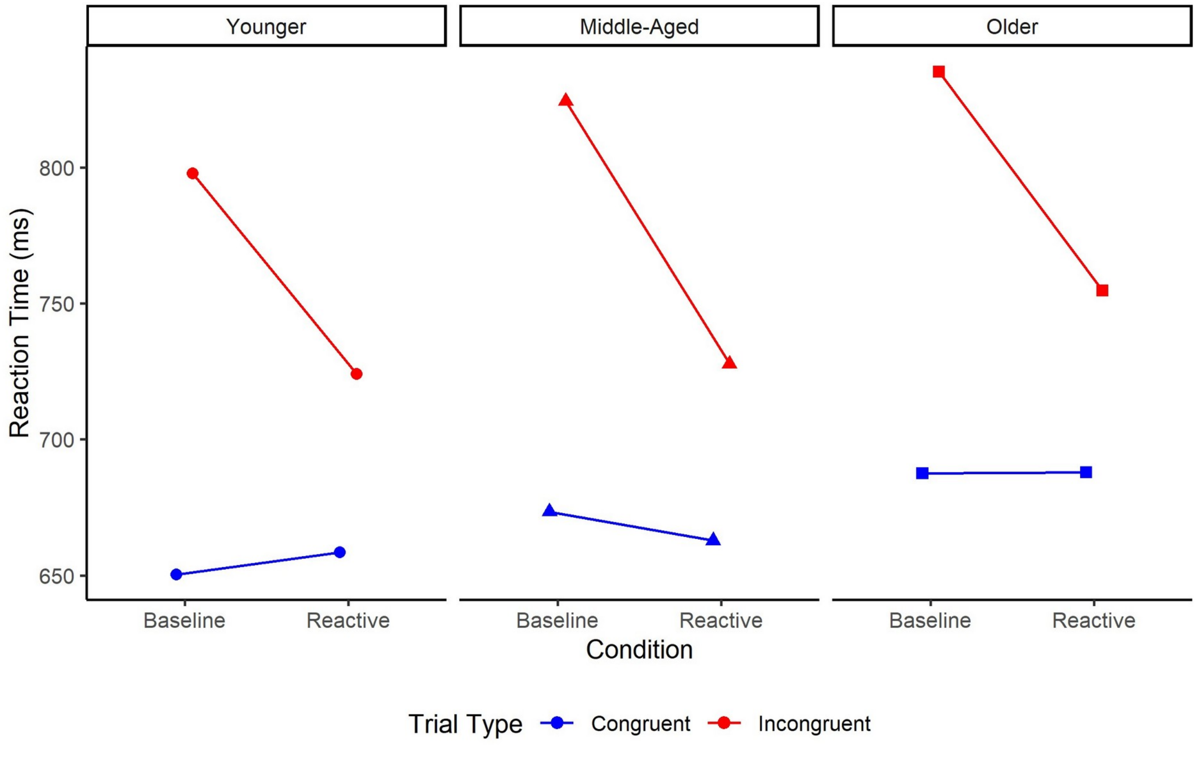
Does Reactive Control Remain Intact with Aging?

We hypothesized that reactive control would remain intact with aging. To assess reactive control, we examined the ISPC effect with a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Baseline, Reactive) x 2 (Trial Type: Congruent, Incongruent) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA conducted on inducer items. Age and condition order were between-subjects variables.

The overall ISPC (Condition x Trial Type) effect was significant, $F(1, 321) = 665.46$, $p < .001$, = 0.68. The Stroop effect was smaller in the reactive condition ($M = 66$) in which the inducer items were mostly incongruent compared with the baseline condition ($M = 148$) in which the inducer items were mostly congruent. Critically, however, this effect *did not interact with age*, $F(2, 321) = 0.14$, $p = .868$, < 0.01, indicating that reactive control was maintained across age groups (see Figure 3). There was a significant ISPC effect for younger adults ($M = 82$, Baseline = 147, Reactive = 65), $F(1, 112) = 237.09$, $p < .001$, $= 0.68$; middle-aged adults ($M = 85$, Baseline = 150, Reactive = 65), $F(1, 101) = 245.10$, $p < .001$, $= 0.71$; and older adults ($M = 80$, Baseline = 147, Reactive = 67), $F(1, 108) = 191.29$, $p < .001$, $= 0.64$.

Figure 3

The ISPC Effect with Inducer Items for Younger, Middle-Aged, and Older Adults.

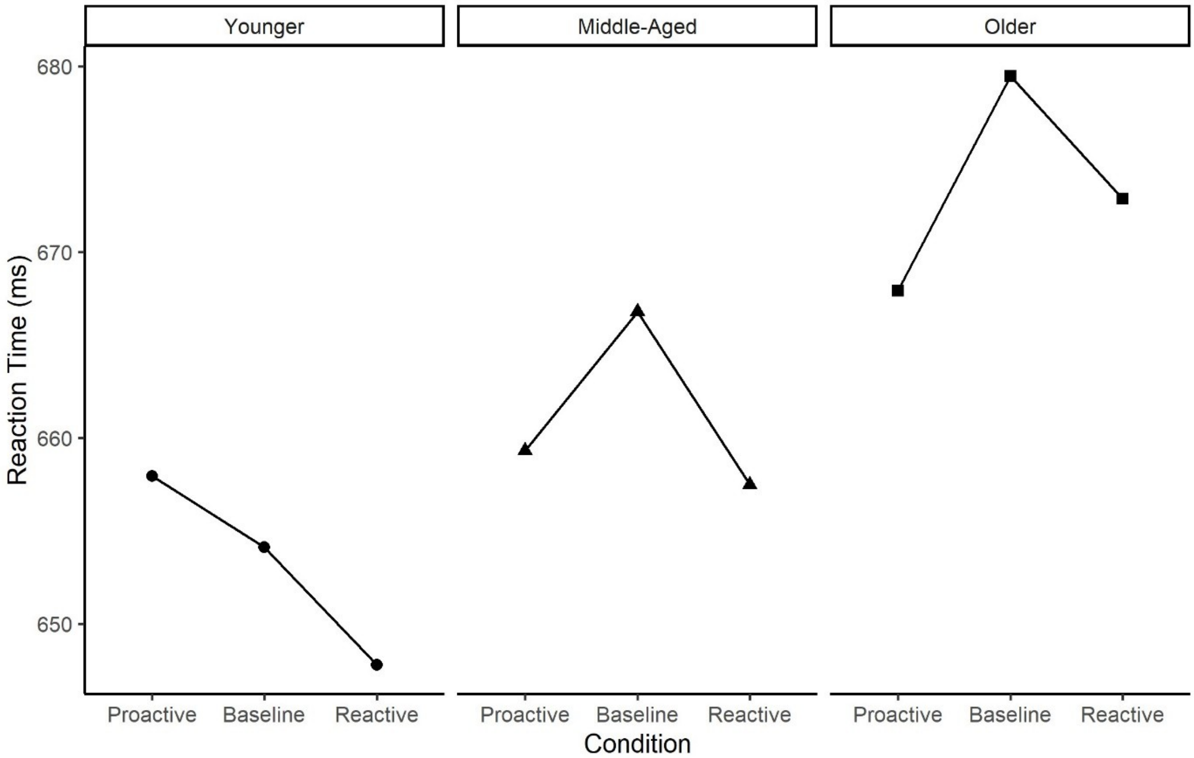


Does the Congruency Cost Decrease with Age?

We hypothesized that congruency cost, as another selective behavioral marker of proactive control, would decrease with age given our expectation that engagement with proactive control should decrease with age. To assess congruency cost, we used diagnostic congruent trials and contrasted them across baseline and proactive conditions. To assess the age differences in congruency cost, we conducted a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Baseline, Proactive) mixed-design ANOVA to isolate proactive control effects (i.e., using the difference between proactive control and baseline conditions). There was a significant interaction between age and condition, $F(2, 324) = 4.12$, $p = .017$, = 0.03, indicating that congruency cost was largest and positive in younger adults ($M = 4$), but smaller and negative in middle-aged ($M = -8$) and older adults ($M = -11$) (see Figure 4). Moreover, we contrasted the proactive and reactive conditions directly. There was a two-way interaction between age and condition, $F(2, 324) = 3.07$, $p = .048$, = 0.02, indicating that the selectivity of congruency cost to condition changed with aging. Congruency cost was largest and significant in younger adults ($M = 10$; $F(1, 113) = 6.13$, $p = .015$), but smaller and not significant in middle-aged ($M = 2$; $F(1, 102) = 0.15$, $p = .697$), and negative and not significant in older adults ($M = -5$; $F(1, 109) = 1.29$, $p = .259$). Overall, the results showed that congruency cost decreased with aging, further supporting that congruency cost is selective to the engagement with proactive control.

Figure 4

The Congruency Cost for Younger, Middle-Aged, and Older Adults.



Does Transfer Cost Change with Aging?

We hypothesized that transfer cost, as another selective marker of reactive control, should remain intact with aging in the reactive condition. First, we examined the transfer cost in the reactive condition, using a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Trial Type: Congruent, Incongruent) x 2 (Item Type: Inducer, Diagnostic) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA. There was a significant interaction between trial type and item type, $F(1, 321) = 115.48$, $p < .001$, = 0.27, indicating a larger Stroop effect with diagnostic items than inducer items (i.e., transfer cost). However, critically, this effect did not interact with age, $F(2, 321) = 1.09$, $p = .336$, < 0.01. The transfer cost was significant and approximately equivalent for younger adults ($M = 32$; Diagnostic =

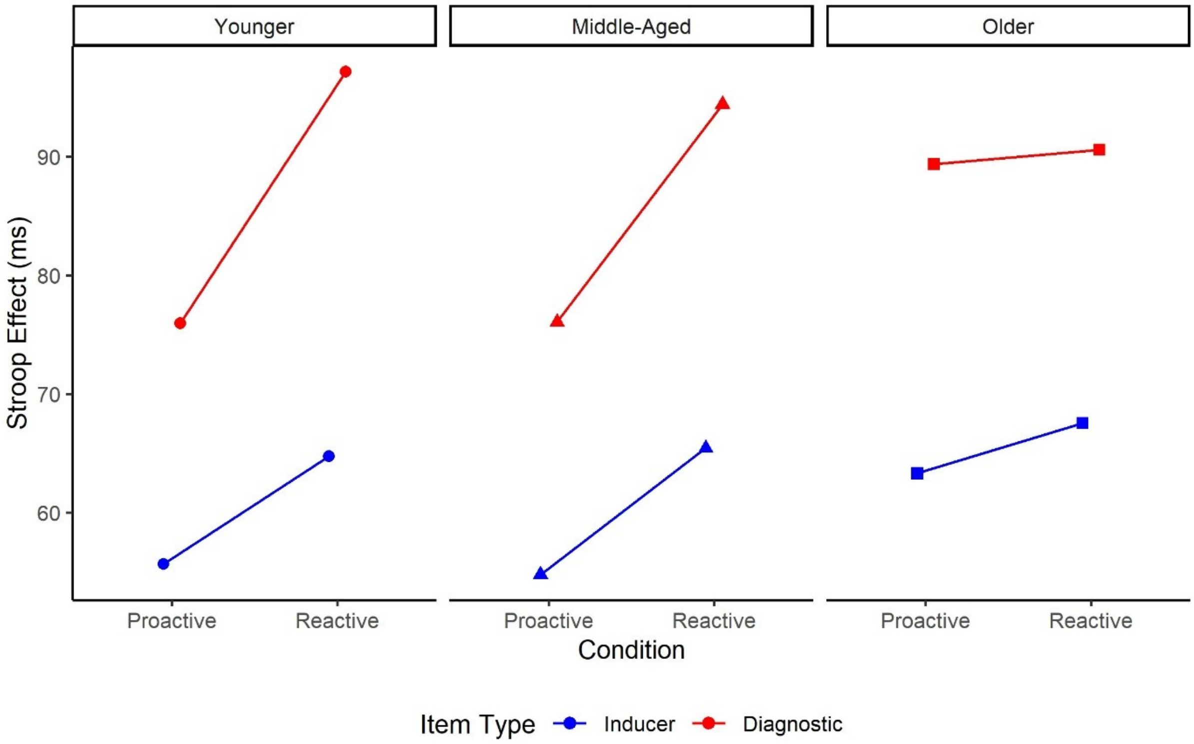
97, Inducer = 65, $F(1, 112) = 47.84$, $p < .001$, = 0.30), middle-aged adults ($M = 30$; Diagnostic = 95, Inducer = 65, $F(1, 101) = 48.12$, $p < .001$, = 0.32) and older adults ($M = 23$; Diagnostic = 90, Inducer = 67, $F(1, 108) = 24.62$, $p < .001$, = 0.19). These findings provide converging evidence for intact reactive control across the lifespan.

We next examined transfer cost in the proactive condition. Again, there was a significant interaction between trial type and item type, $F(1, 321) = 100.11$, $p < .001$, = 0.24, indicating a larger Stroop effect with diagnostic items than inducer items. However, contrary to our prediction, this effect did not interact with age, $F(2, 321) = 0.58$, $p = .560$, < 0.01. The transfer cost was significant and statistically equivalent for younger adults ($M = 20$; Diagnostic = 76, Inducer = 56, $F(1, 112) = 24.44$, $p < .001$, = 0.18), middle-aged adults ($M = 21$; Diagnostic = 76, Inducer = 55, $F(1, 101) = 32.21$, $p < .001$, = 0.24), and older adults ($M = 26$; Diagnostic = 89, Inducer = 63, $F(1, 108) = 47.99$, $p < .001$, = 0.31).

The direct comparison of transfer cost across proactive and reactive conditions tests for the prominence or heightened presence of the cost in the reactive condition. If the transfer cost disproportionately affects reactive control, then it should be larger in this condition relative to the proactive condition. We tested this prediction using a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Reactive, Proactive) x 2 (Trial Type: Congruent, Incongruent) x 2 (Item Type: Inducer, Diagnostic) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA. The three-way interaction between trial type, item type, and condition was not significant, $F(1, 321) = 2.91$, $p = .089$, < 0.01, indicating transfer costs were not clearly different across conditions. Furthermore, the transfer cost difference across conditions (i.e., trial type, item type, and condition interaction) did not interact with age, $F(2, 321) = 1.91$, $p = .150$, $= 0.01$ (see Figure 5). However, we conducted separate analyses for each age group to more precisely examine the specific predictions outlined in our study. Given the potential limitation of statistical power to detect a complex 4-way interaction, this approach allowed us to focus our analyses on testing the theoretical hypotheses pertinent to each age group individually. For younger adults, the transfer cost was significantly larger in the reactive relative to proactive condition ($M = 11$, $F(1, 112) = 4.46$, $p = .037$, $= 0.04$), suggesting selective utilization of reactive control in this condition. However, the transfer cost was not significantly greater in the reactive condition for middle-aged adults ($M = 9$, $F(1, 101) = 2.29$, $p = .133$, $= 0.02$) and older adults ($M = -3$, $F(1, 108) = 0.26$, $p = .612$, < 0.01). These results partially support the hypothesis that older adults were not engaging reactive control selectively, but were in fact equivalently engaging this form of control even within the proactive condition.

Figure 5

The Transfer Cost in Proactive and Reactive Conditions for Younger, Middle-Aged, and Older Adults.



Note. To simplify the figure, the Stroop effect was plotted for proactive and reactive conditions. Transfer cost represents the larger Stroop effect with diagnostic items compared with inducer items. Transfer cost was significantly larger in the reactive relative to proactive condition for younger adults, but not for middle-aged or older adults.

Are Proactive, Reactive, and Aging Effects Selective to the Color Naming Task?

We next examined performance in the matched word reading task as a negative control condition, to test whether the proactive and reactive effects we observed in color naming (i.e., LWPC and ISPC effects, transfer cost, and congruency cost) as well as the age-related changes we observed, would also be present or absent in the word reading conditions. Mean RTs are presented in Table 4.

Table 4

Mean RTs (Standard Error in Parenthesis) in the Baseline, Proactive, and Reactive Word-Reading Conditions.

		Baseline		Proactive		Reactive	
Age	Trial Type	Inducer	Diagnostic	Inducer	Diagnostic	Inducer	Diagnostic
Younger	Incongruent	581 (5)	590 (5)	574 (5)	577 (5)	577 (5)	582 (5)
	Congruent	564 (4)	573 (5)	561 (5)	557 (4)	561 (5)	562 (5)
	Stroop Effect	*17 ms*	*17 ms*	*13 ms*	*20 ms*	*16 ms*	*20 ms*
Middle-Aged	Incongruent	592 (5)	593 (5)	573 (5)	575 (5)	576 (5)	585 (5)
	Congruent	572 (5)	570 (5)	565 (5)	564 (5)	565 (5)	569 (5)
	Stroop Effect	*20 ms*	*23 ms*	*12 ms*	*11 ms*	*11 ms*	*16 ms*
Older	Incongruent	571 (4)	573 (5)	568 (4)	568 (4)	577 (5)	582 (5)
	Congruent	561 (4)	559 (4)	559 (4)	553 (4)	555 (4)	552 (4)
	Stroop Effect	*10 ms*	*14 ms*	*9 ms*	*15 ms*	*22 ms*	*30 ms*

Word Reading LWPC Effect

We compared the baseline and proactive word reading blocks using diagnostic items, with a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Baseline, Proactive Control) x 2 (Trial Type: Congruent, Incongruent) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA. First, although the overall trial type effect was significant (F(1, 321) = 111.47, p < .001, = 0.26), indicating a word reading Stroop effect, it was quite small (M = 17), relative to that observed in color naming (M = 84). Second, the word reading LWPC effect was not significant (Baseline Stroop Effect = 18 ms, Proactive Stroop effect = 15 ms, F(1, 321) = 0.90, p = .344, < 0.01). Moreover, there was not a significant interaction with age, F(2, 321) = 2.52, p = .082, = 0.02, indicating there was no impact of age on the word reading LWPC effect.

Word Reading ISPC Effect

We compared the baseline and reactive word reading blocks using inducer items, with a 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Condition: Baseline, Reactive Control) x 2 (Trial Type: Congruent, Incongruent) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVA. Again, the overall trial-type effect was significant (F(1, 321) = 84.04, $p < .001$, = 0.21) but quite small (M = 14). However, the ISPC effect was not significant (Baseline Stroop Effect M = 16, Reactive Stroop Effect M = 12, F(1, 321) = 1.95, p = .164, < 0.01), nor was it different across age groups, F(2, 321) = 1.10, p = .335, < 0.01.

Word Reading Congruency Cost

We examined the congruency cost within the word reading condition, testing for age differences on congruent diagnostic items with a two-way ANOVA, following the analyses with color naming, to isolate potential proactive control effects (i.e., contrasting proactive and baseline conditions), though these were not expected. There was not a significant interaction between age and condition, F(2, 324) = 1.46, p = .234, = 0.01. Congruency cost was negative and similar for younger (M = -16), middle-aged (M = -6), and older adults (M = -6). Similar patterns were observed when comparing proactive and reactive conditions directly, F(2, 324) = 0.42, p = .659, < 0.01.

Word Reading Transfer Cost

To test the selectivity of the transfer cost, we tested for the presence of this effect in word reading blocks, separately for both reactive and proactive conditions, with 3 (Age: Younger Adults, Middle-Aged Adults, Older Adults) x 2 (Trial Type: Congruent, Incongruent) x 2 (Item Type: Inducer, Diagnostic) x 2 (Condition Order: Proactive-Baseline-Reactive, Reactive-Baseline-Proactive) mixed-design ANOVAs. For the reactive condition, there was a significant interaction between trial type and item type, $F(1, 321) = 4.44$, $p = .036$, = 0.04, indicating a larger Stroop effect with diagnostic items (M = 18) than inducer items (M = 12). This transfer cost effect did not interact with age, $F(2, 321) = 0.20$, $p =$ .817, < 0.01. Further, when age groups were analyzed separately, the transfer cost was not significant for any of them. For the proactive condition, again, there was a significant interaction between trial type and item type, $F(1, 321) = 4.66$, $p = .032$, = 0.05, indicating a larger Stroop effect with diagnostic items (M = 15) than inducer items (M = 10), while it did not interact with age, $F(2, 321) = 0.58$, $p = .560$, < 0.01. Similarly, in the proactive condition, the transfer cost was not significant for any of the age groups when analyzed separately. Note that these small transfer cost effects with word reading may not be reliable, as they were not significant in the LME analyses (see Supplementary Materials)[8].

Additionally, to assess if there is any selectivity of reactive control indexed by the transfer cost in word reading blocks, we directly compared the transfer cost across proactive and reactive conditions. The three-way interaction between trial type, item type, and condition was not significant, $F(1, 321) = 0.03$, $p = .860$, < 0.01, indicating transfer costs

[8] In the LME models, the proactive transfer cost effect was estimated as $\beta = 4.17$ ms, CI = [-10.97, 19.31], $t = .54$, $p = .589$); the reactive transfer cost was estimated as $\beta = 1.85$ ms, CI = [-15.44, 19.14], $t = .21$, $p = .834$.

were similar across conditions. Furthermore, the transfer cost difference across conditions (i.e., trial type, item type, and condition interaction) did not interact with age, $F(2, 321) = 0.23$, $p = .795$, < 0.01. When age groups were analyzed separately, transfer cost was not different across proactive and reactive conditions for any groups, Fs < 1, indicating that there was no selective utilization of reactive control in the word reading task in contrast to the color naming task.

Thus, across all four analyses, the effects observed in color naming were not observed when analyzing word reading blocks. These results provide strong evidence that the measures of proactive and reactive control and the associated aging effects observed with color naming selectively reflect the cognitive control demands associated with the Stroop task.

Can the Color Naming Cost Be Used as an Alternative Index of Proactive Control?

As a final exploratory analysis, we explored whether the word reading condition could be used to identify an alternative and not yet explored form of proactive control, namely the color naming cost. The color naming cost can be computed by contrasting response speed on color naming relative to word reading blocks, focusing on congruent diagnostic items. For such items, the word reading task provides an alternative, and potentially ideal, within-condition baseline from which to isolate the costs associated with directing cognitive control towards the color dimension and away from the word dimension. Importantly, for congruent diagnostic items, the exact same stimulus and response are generated in both color naming and word reading blocks, so that there is no response conflict (competition from a conflicting word and color response), and any remaining conflict (i.e., task conflict between color naming and word reading) should be present across baseline, proactive, and reactive blocks. Nevertheless, given that color naming is a less automatic and slower process than word reading, response time costs in the color naming condition should reflect the degree to which cognitive control is directed away from the word. On baseline and reactive conditions, because of the high LWPC, modulation of cognitive control likely occurs on a post-stimulus basis, after some initial processing of the word occurs, which may facilitate quicker responses. In contrast, under proactive control, cognitive control should be directed toward the color and away from the word in an anticipatory manner, and thus be present even prior to stimulus onset, causing a greater degree of slowing on congruent trials relative to these other conditions. Conversely, if proactive control is not engaged, then there should be no additional slowing in this condition, relative to reactive and baseline. Thus, a key prediction is that for younger adults, there should be a significantly greater color naming cost in the proactive condition, relative to baseline or reactive; however, no additional color naming cost should be present for older adults if engagement with proactive control declines with age.

We computed the color naming cost as the RT difference between color naming and word reading blocks for all three conditions separately (e.g., proactive word reading RT subtracted from proactive color naming RT) using congruent diagnostic trials. After calculating these differences, we compared them across conditions with separate ANOVAs. When comparing proactive and baseline conditions, the effect of condition was not significant, $F(1, 324) = 1.65$, $p = .200$, = 0.01[9], but it did interact with age, $F(2, 324) = 6.36$, $p = .002$, = 0.04 (see Figure 6). In younger adults, the color naming cost was significantly larger in proactive than baseline (M = 19, Proactive = 101, Baseline = 82), $F(1, 113) = 9.92$, $p = .002$, = 0.08. However, such differences were not observed in either middle-aged adults (M = -1, Proactive = 96, Baseline = 97, $F(1, 102) = 0.09$, $p = .765$, < 0.01) or older adults (M = -6, Proactive = 115, Baseline = 121, $F(1, 109) = 1.49$, $p = .225$, = 0.01). A similar pattern was observed when comparing proactive and reactive conditions, in that the effect of condition was not significant, $F(1, 324) = 2.75$, $p = .098$, = 0.01[10], but it did interact with age, $F(2, 324) = 3.50$, $p = .031$, = 0.02. In younger adults, the color naming cost was larger in proactive ($M = 15$, Reactive = 86, $F(1, 113) = 6.02$, $p = .016$, = 0.05), but no differences were observed for either middle-aged adults ($M = 8$, Reactive = 88, $F(1, 102) = 1.39$, $p = .241$, = 0.01) or older adults ($M = -6$, Reactive = 121, $F(1, 109) = 1.44$, $p = .233$, = 0.01). When comparing reactive and baseline conditions, no differences in color naming cost were observed (Fs < 1.56).

Finally, it is worth noting that these age differences were observed even in the presence of a larger overall color naming cost for older adults

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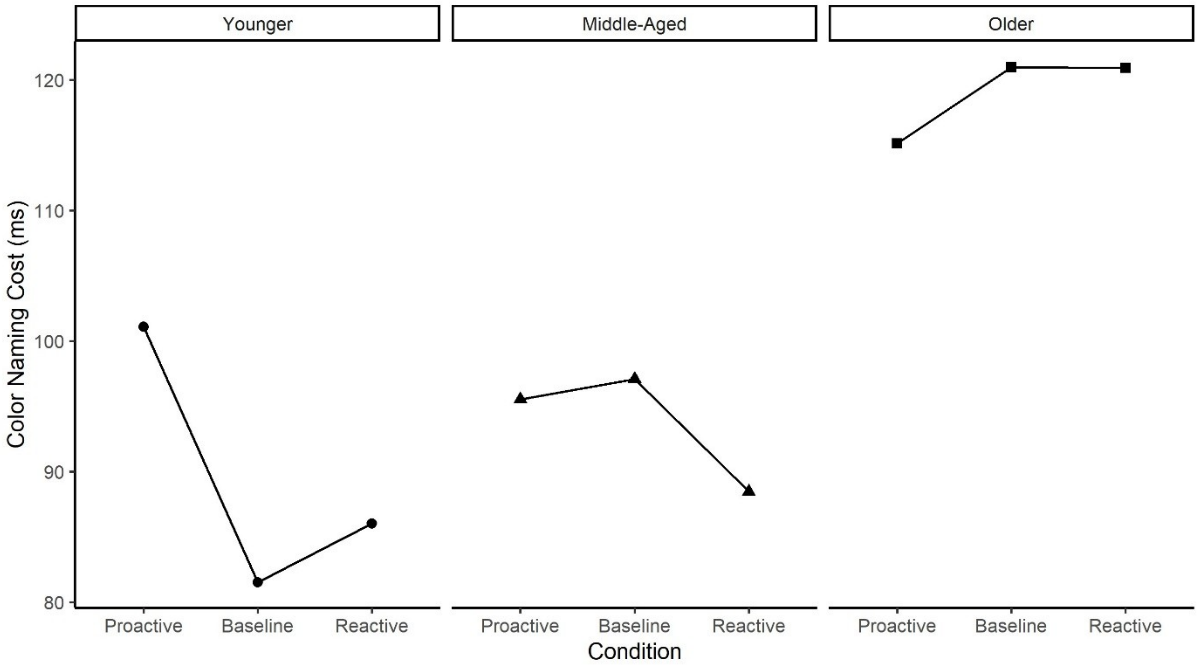
[9] Note that the condition effect on color naming cost was significant when comparing proactive and baseline conditions with LME models (β = 27.08 ms, CI = [9.73, 44.43], $t = 3.06$, $p = .002$).

[10] Note that the condition effect on color naming cost was significant when comparing proactive and reactive conditions with LME models (β = 28.71 ms, CI = [10.79, 46.64], $t = 3.14$, $p = .002$).

(M = 119) than younger adults (M = 90), Tukey corrected $p < .001$; and middle-aged adults (M = 94), Tukey corrected $p < .001$. This result suggests that even though older adults may face greater difficulty (i.e., slowing) when shifting attention towards the color and away from the word, they do not modulate cognitive control settings across conditions in the way that younger adults do, suggesting less willingness (or ability) to engage proactive control even when appropriate (i.e., in list-wide MI color naming blocks).

Figure 6

The Color Naming Cost in Proactive, Baseline, and Reactive Conditions for Younger, Middle-Aged, and Older Adults.



Note. To simplify the figure, the color naming cost was plotted for proactive, baseline, and reactive conditions. Color naming cost represents the RT difference between color naming and word reading blocks.

Discussion

In a comprehensive investigation examining proactive and reactive control within the same participants in a single task, we tested how well younger, middle-aged, and older adults prepare for expected distraction ahead of time (i.e., proactive control) as well as how they deal with distractions when they arise unpredictably, but are systematically linked to stimulus features (i.e., reactive control). Our findings revealed that older adults struggle to proactively prepare for expected distractions by biasing attention away from the distracting information, indicating a decline in proactive control. However, amidst this decline, they exhibited preservation of reactive control, effectively managing distractions after they occur. These findings align with the predictions of the DMC framework, illustrating that proactive and reactive control are two qualitatively distinct processes, with age-related change primarily reflecting a decline in proactive, rather than reactive control. Our study supports the notion that aging does not uniformly impact all cognitive control processes (Andrés et al., 2008; Ball et al., 2023; Kramer et al., 1994; Rey-Mermet & Gade, 2018). Instead, the findings suggest a nuanced interplay, in which certain control capacities may wane while others persist. More directly, the present findings are strongly compatible with previous studies observing differential age-related effects on proactive and reactive control (Ball et al., 2023; Bugg, 2014a, 2014b; Braver et al., 2001, 2005). Yet they extend beyond this prior work, using a fully within-subjects design that permitted direct comparison of aging effects across the adult lifespan on distinct proactive and reactive conditions that were manipulated within the same individuals, task paradigm, and experimental session. Our study revealed a rich set of findings by testing both primary and secondary markers of proactive and reactive control and utilizing word reading data to introduce novel measurements.

Our hypotheses were first confirmed with primary behavioral markers of proactive and reactive control, the LWPC and ISPC effects, which have been well-established in the prior literature. Younger and middle-aged adults showed a smaller Stroop effect in the proactive compared to baseline condition with the unbiased diagnostic items (i.e., the LWPC effect). Conversely, this LWPC effect was notably absent among older adults. Our findings also highlighted a noteworthy observation: the presence of the LWPC effect among middle-aged adults suggests that the decline in proactive control may not emerge until later stages of life, underscoring the nuanced trajectory of cognitive control across the lifespan. In contrast, a consistent reduction in Stroop effects was observed in reactive compared to baseline condition for the inducer items, indicating an ISPC effect present for all age groups, demonstrating the persistence of reactive control with aging.

Moreover, we also observed age-related changes with more novel secondary behavioral markers that were designed to doubly dissociate proactive and reactive control (Gonthier et al, 2016; Tang et al, 2022). The first of these, the congruency cost, is an indicator of proactive control. Proactive control entails pre-setting attentional biases towards color over word information prior to stimulus presentation, thereby diminishing the benefit derived from congruent trials. As expected, congruency cost showed an age-related decline as the engagement with proactive control decreases. RTs with congruent diagnostic items were larger in proactive condition compared to baseline, and significantly greater than the reactive condition in younger adults, indicating that the engagement with proactive control attenuated the benefit of congruency. However, congruency cost disappeared not only for older adults but also among middle-aged adults.

The second behavioral marker of interest was the transfer cost, indicative of reactive control. Grounded in the premise that reactive control benefits are restricted to the item level and do not extend to unbiased diagnostic items, the transfer cost is expected to be large in the reactive condition, and significantly greater than the proactive condition. In other words, under conditions where reactive control is active, a substantial difference should be observed between the Stroop effect for the unbiased diagnostic items and that observed in the mostly incongruent inducer items. Conversely, when proactive control dominates, the transfer cost is expected to diminish, owing to the sustained / global influence of proactive control. As expected, the transfer cost was larger in the reactive compared to proactive condition for younger adults, but not for middle-aged or older adults (although the interaction with age did not reach statistical significance).

The inclusion of middle-aged adults, an underexplored age category, revealed novel and intriguing findings. With the primary markers of proactive and reactive control (i.e., the LWPC and ISPC effects), middle-aged adults resembled younger adults, demonstrating robust proactive control. However, secondary behavioral markers (i.e., congruency and transfer costs) suggested some decrements in proactive control may begin in middle-aged adulthood. Bridging the gap between younger and older adults, results with middle-aged adults represent a transitional phase and suggest that proactive control operates on a continuum. Interestingly, supplementary LME analyses that included age as a continuous variable partially supported this interpretation. These analyses enabled us to estimate when the LWPC effect would be reduced to 0 ms and suggested that would occur by age 58; the congruency cost was estimated to decline to 0 ms at even earlier age (by age 51). Though the numbers differ somewhat, overall, the analyses suggest similar rates of age-related change, converging on the idea that proactive control declines by late middle-age.

These findings highlight the importance of including middle-aged adults in research to better understand how cognitive control mechanisms change or remain stable across the adult lifespan. Likewise, they also highlight the benefits of supplementing traditional ANOVA models with continuous LME models. The supplementary analyses provided the means to not only confirm the robustness and reliability of the observed effects, when more precisely modeling the full structure of the dataset, including age, but also revealed its impact on proactive control indices even during the middle-age period. Moreover, although the findings of the two types of analyses were mostly consistent, we did observe some differences with the LME models (i.e., confirming expected null effects in word reading transfer cost, and predicted main effect of color naming cost effects in the proactive condition), which support the increased sensitivity and specificity of this modeling approach.

One striking and predicted aspect of our findings is the differential impact of PC manipulations on color naming compared to word reading. The novel Stroop design we used in the present study provided the means to conduct negative control analyses, by evaluating participants' performance in word reading blocks. These control analyses allowed us to test whether the primary and secondary behavioral markers of interest were indeed specific to conditions necessitating cognitive control rather than reflecting age-related variations in other constructs (e.g., general task performance). Indeed, when we conducted LWPC, ISPC, congruency cost, and transfer cost analyses using the word reading data, none of the effects observed in our primary analyses manifested within the word reading data, underscoring the specificity of our findings to conditions requiring cognitive control. The qualitatively distinct patterns across color naming and word reading highlight the task-specific nature of cognitive control processes, and suggest that control exerts a more substantial influence when there is a need to override automatic responses, as in color naming. In particular, the absence of age-related differences in the word reading data provide further support for the validity and task-specificity of our key interpretation regarding age-related changes in cognitive control.

Finally, we assessed the color naming cost in exploratory analyses, as a potentially new marker of proactive control engagement that utilized the word reading data. Under the assumption that the proactive condition would prompt a stronger and tonic redirection of attention away from the irrelevant word dimension, we expected a selective slowing of responses on congruent trials in the color naming condition, when compared to the matched trials in the word reading condition. That is, we hypothesized that the color naming cost would be stronger in the proactive than baseline or reactive conditions. Moreover, if there is diminishing engagement with proactive control associated with aging, then the color naming cost difference between conditions would be predicted to be reduced or eliminated in older adults. Once more, the findings confirmed predictions: among younger adults, color naming cost exhibited a substantial increase in the proactive condition compared to both baseline and reactive conditions. This observation aligns with the notion that younger adults proactively shift their focus away from the word dimension in the proactive condition, thereby incurring a higher cost associated with color naming. However, neither middle-aged nor older adults demonstrated a significant increase in color naming cost in the proactive condition relative to baseline or reactive conditions. The distinct patterns across the age groups underscore the idea that middle-aged and older adults may not engage with proactive control to the same extent as younger adults, thereby eluding the heightened color naming cost associated with proactive control engagement. Finally, this pattern was also supported by the supplemental continuous age analyses, which estimated the color naming cost difference between proactive and reactive conditions to reduce to 0 ms by age 55, quite similar to the age at which the LWPC and congruency cost were estimated to disappear.

Our assessment of color naming cost yielded significant effects of both proactive control and aging, marking a novel contribution to the existing literature. This new finding and behavioral index opens up intriguing questions regarding the precise underlying mechanisms at play. One relevant theoretical consideration to consider is whether the observed color naming cost reflects task-conflict. Task conflict, first suggested by MacLeod and MacDonald (2000), arises in a color-word Stroop task because the task set for color identification, which is intentionally activated by the participant, competes with the task set for word reading, which is automatically activated by the presence of the word (Entel & Tzelgov, 2018; Kalanthroff et al., 2018; Littman et al., 2019, Parris et al., 2022). This conflict occurs because the two task sets are activated simultaneously, even before the participant processes the specific details of the color and the word. This competition for cognitive resources leads to interference, manifesting as slower responses in the task. During color naming, congruent trials may evoke both color naming and word reading tasks, producing interference. However, there may be no task conflict during word reading as it is a more automatic and over-learned task. Therefore, the comparison of congruent trials across color naming and word reading blocks (i.e., color naming cost) might be used as a measure of task conflict. The finding that the PC manipulations differentially affected color naming and word reading tasks as well as the age-related changes in the color naming cost suggest that the impact of task conflict on color naming, most purely assessed on congruent trials, is less prominent during word reading.

Kalanthroff et al. (2018) introduced a proactive control/task conflict (PC-TC) model, emphasizing the role of proactive control in regulating task conflict. Their model suggests that strong proactive control weakens bottom-up activation of word reading and enables rapid top-down resolution of task competition, reducing task conflict. Conversely, weak proactive control allows greater bottom-up activation, leading to increased task conflict and slower responses. However, our data suggest that color naming cost increases with proactive control and decreases with age, which appears contradictory to Kalanthroff et al.'s predictions. Nevertheless, it should be noted that task conflict is typically assessed by comparing congruent trials relative to non-word neutral trials, while our work utilizes a novel contrast, by comparing congruent trials across word reading and color naming tasks. Likewise, an important difference in our design is that we used vocal responding, whereas most prior Stroop studies, including those examining task conflict, typically employ manual responses. It is quite well-established that the locus of Stroop interference changes as a function of response mode and tends to be stronger for vocal responding (Augustinova et al., 2019; Parris et al., 2022). Therefore, we cannot conclusively state whether our color naming cost measure reflects task conflict. Moreover, these discrepancies highlight the need for further research to understand the mechanisms and triggers of task conflict and how these may interact with varying factors.

Why Reactive Control but not Proactive Control is Spared with Aging?

With the wealth of evidence from our findings, it becomes apparent that aging exerts differential effects on cognitive control processes. An individual’s ability to react swiftly and adaptively to external stimuli, known as reactive control, appears to be resistant to age-related decline. This enduring capacity may stem from the preservation of the ability to quickly adapt to unforeseen challenges in addition to employing compensatory strategies, such as heightened attention to environmental cues or reliance on automatic responses (Bugg, 2014a). However, the pattern observed with reactive control contrasts strongly to that present for proactive control; this control process, which involves anticipatory planning and preparation, appears to show a consistent linear decline with age. Older individuals may struggle to maintain task-relevant information, update goal representations, and plan over time, due to impairments in executive functions such as working memory and cognitive flexibility.

These contrasting patterns suggest a puzzle, since at a surface level they both appear to involve similar forms of cognitive control related to top-down attentional biases that reduce distraction. Possibly the solution to this puzzle lies in the brain activity patterns associated with each mode of control. An intuitive assumption is that the dissociation of two control modes would be related to the engagement of distinct brain regions. However, an alternative explanation could be that the same brain region, rather than different regions, is utilized in qualitatively distinct ways across proactive and reactive control. Braver et al. (2009) investigated this possibility, focusing on differential temporal dynamics. Specifically, they hypothesized that the signature of proactive control would be an anticipatory/sustained mode of lateral PFC activity while the signature of reactive control would be transient and interference-sensitive activity in this same brain region (alongside with anterior cingulate cortex [ACC] for conflict detection or posterior cortical regions via associative connections). They also tested if the activity would be modulated depending on task demands and changing goals, using the AX-CPT task as the experimental paradigm (see DePisapia & Braver, 2006 for a similar theoretical account of the Stroop task).

In the AX-CPT, participants are presented with a series of cue-probe pairs and are required to respond based on specific rules, in which the context provide by the cue specifies, for some trial types, how to respond to the probe. Proactive and reactive control are assessed by examining participants' responses on these trial types. A proactive control strategy is predicted to show performance patterns reflective of strong cue-based response preparation, whereas a reactive strategy will be more sensitive to the characteristic features of the probe. Supporting the predictions of DMC, younger adults showed a more cue-based performance (indicative of proactive control) while older adults showed a more probe-based performance (indicative of reactive control).

In an additional session, Braver et al. (2009) aimed to shift control settings for participants by promoting reactive control through a reward/penalty manipulation for younger adults and, for older adults, promoting proactive control through focused cognitive training to attend and utilize the cue. Using fMRI to monitor brain activity during task performance, shifts in the activity dynamics of lateral PFC activity were observed in the predicted directions: from cue-based to probe-based for younger adults and from probe-based to cue-based for older adults. The results support the notion that proactive and reactive control are associated with different temporal dynamics, but within the same regions of lateral PFC, indicating that activity can be flexibly shifted within this region depending on the task demands and goals. The results also signal that proactive control might not be entirely absent in older adults; rather, there appears to be a shift towards favoring reactive control with aging. In other words, while proactive control remains a possibility, there is a notable tendency for older adults to rely more heavily on reactive control mechanisms. This interpretation suggests the possibility that older adults could also be induced to utilize proactive control within the Stroop, such as with training or manipulations of incentive motivation. The novel Stroop color-word paradigm, and the rich set of behavioral indices of proactive control (LWPC, congruency cost, color naming cost) associated with it, provide a useful target from which to evaluate such experimental manipulations. We currently lack evidence showing shifts in lateral PFC activity at the middle age stage of life. Consequently, it would also be valuable to investigate whether middle-aged adults exhibit more flexibility in shifting away from a bias towards proactive control than older adults. Studying this possibility might reveal that middle-aged individuals are able to maintain or enhance their ability to employ proactive control strategies more effectively than those in older adulthood.

An important difference between the Stroop and AX-CPT paradigms, however, is that the Stroop does not have a cue-probe structure, so anticipatory goal-related processes are more challenging to detect. In the current paradigm, which used a task-switching format across blocks, the signature of proactive control might be present in terms of active goal maintenance process that are sustained across color naming blocks to a greater degree than in word reading, but are further amplified under conditions of high interference expectancy. Thus, the task-switching characteristics of the current design may also make it particularly attractive for use in neuroimaging contexts, to reveal the presence of task-goal representations which may be activated in a sustained fashion during proactive color naming blocks, but switch to being transiently activated, in a post-stimulus manner, on incongruent color naming trials during reactive color naming blocks. The key prediction regarding age-related change is that task-goal representations may be present and transiently activated to the same degree in both groups during reactive conditions, but that older adults might fail to show the switch to sustained activation during proactive conditions.

Limitations and Future Directions

While our study offers valuable insights into the dynamics of proactive and reactive control across the lifespan, some limitations warrant consideration. A notable limitation is our reliance on online data collection. Online data collection provides broad access to diverse participant samples, yet it also introduces variability in participant environments and potential technical issues, such as variations in microphone quality for vocal responses or timing sensitivity of participants’ computers. These factors can introduce noise into the data and potentially affect the reliability of vocal response measurements. Although it is tricky to collect vocal responses online, we aimed to collect vocal responses rather than manual keypress responses since the Stroop effect is expected to be larger with vocal responses compared to manual responses (Augustinova, 2019), and because our designs included 11 different colors, which would be difficult to implement and train participants to use in a manual Stroop task, perhaps especially for older age groups. To mitigate these concerns, we tested microphone quality during the practice phase to ensure it was sufficient before participants continued with the experiment. Future studies could further address these issues by running experiments in more controlled laboratory settings or incorporating additional quality control measures for online data collection.

As the present study primarily used task-related behavioral markers of proactive and reactive control, it is limited regarding the inferences that can be drawn regarding the mechanisms that give rise to such behavioral effects, and the causes of age-related changes in them. As discussed above, a natural direction for future work is to utilize this paradigm in neuroimaging contexts, such as fMRI and EEG, to further elucidate neural mechanisms. Again, the key methodological innovations here are critical, including within-subject and independent manipulations of reactive and proactive control, via LWPC and ISPC conditions, reducing confounds through the use of diagnostic trials that are matched across conditions, and finally, the use of inter-mixed word reading blocks from which to examine the specificity of these manipulations to conditions of high cognitive control demand.

In addition to enabling analyses regarding the temporal dynamics of neural activity that may distinguish proactive and reactive control, the condition-rich design of the paradigm makes it very well-suited for use with Representational Similarity Analysis (RSA) approaches (Kriegeskorte & Kievit, 2013; Haxby et al., 2014). In particular, RSA may provide a powerful means by which to go beyond activation dynamics and instead generate precise predictions regarding the neural coding patterns associated with proactive and reactive control (Freund et al., 2021). For example, RSA models could differentiate between task coding (discriminating color naming from word reading trials), color and word feature coding (discriminating between different colors or words), and conflict coding (discriminating between incongruent and congruent trials) (Freund et al., 2021). The DMC framework would predict an increase in task coding under proactive conditions, but an increase in color feature and conflict coding (specifically for mostly incongruent items) under reactive conditions. Furthermore, by examining these coding patterns across different age groups, it would be possible to test hypotheses regarding which neural mechanisms are impacted by aging.

A final noteworthy aspect of the current study is that we initiated a more robust and rigorous analysis of the behavioral data through supplemental LME analyses. These models offer significant advantages, particularly in handling continuous age-related variation which permit more precise inferences to be drawn, such as estimating the age at which proactive control is reduced to be undetectable. Although we provide a tentative inference that in the current dataset this happened within the late middle-age period, these conclusions could be limited by the use of linear models. Estimating age effects more carefully, and with non-linear models, might further increase precision and accuracy of inferences related to age-related change in proactive control.

To further increase the flexibility and precision of estimating age-related changes in cognitive control, hierarchical Bayesian modeling (HBM) approaches could be employed. Although beyond the scope of the current study, we have begun utilizing such approaches in other work to examine proactive and reactive control effects (Lin et al., 2024; Snijder et al., 2024). A particular benefit of these approaches is the enhanced flexibility in modeling the shape of RT distributions, to more precisely account for the fact that such distributions are well established to be non-Gaussian. For example, using HBM it is possible to systematically investigate various potential distributions that have been suggested in the literature (e.g., ex-Gaussian, inverse Gaussian, shifted log-normal) to see which fit the data better, and to provide greater sensitivity and power to detect age effects. A second key advantage of HBM approaches is that they permit a cumulative approach to science, shifting away from frequentist assumptions and null hypothesis statistical testing, and towards true parameter estimation, whereby the accuracy and precision of these estimates can be incrementally updated across studies, by treating estimates derived from a prior study (such as the estimates for the LWPC effect, the ISPC effect, congruency cost, transfer cost, and color naming cost in the present study), as informed priors for a subsequent one. This goal is an important one that we plan to employ for future research in this domain; we encourage other investigators to do so as well.

Conclusion

Our comprehensive investigation into proactive and reactive control has yielded valuable insights into the nuanced trajectory of cognitive control across the lifespan. Using a large sample from the adult lifespan and a series of targeted analyses of primary and secondary behavioral markers of proactive and reactive control, we observed that younger adults demonstrated a robust engagement of proactive control mechanisms, while this pattern was absent in older adults; middle-aged adults appeared to represent a transitional phase. Conversely, and critically, the present study underscores the selective preservation of reactive control across age groups. Furthermore, the absence of age-related differences in word reading data and the specificity of observed effects to conditions requiring cognitive control further validate our findings and interpretations. Overall, our research underscores the nuanced age-related dynamics related to proactive and reactive control mechanisms, and paves the way for future investigations aimed at elucidating, and – in the case of proactive control – potentially restoring the underlying mechanisms that give rise to this form of age-related cognitive change.

References

Andrés, P., Guerrini, C., Phillips, L. H., & Perfect, T. J. (2008). Differential effects of aging on executive and automatic inhibition. *Developmental Neuropsychology*, *33*(2), 101-123. https://doi.org/10.1080/87565640701884212

Augustinova, M., Parris, B. A., & Ferrand, L. (2019). The loci of Stroop interference and facilitation effects with manual and vocal responses. *Frontiers in Psychology*, *10*, 474934. https://doi.org/10.3389/fpsyg.2019.01786

Ball, B. H., Peper, P., & Bugg, J. M. (2023). Dissociating proactive and reactive control in older adults. *Psychology and Aging, 38*(4), 323–332. https://doi.org/10.1037/pag0000748

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. Trends in Cognitive Sciences, 16(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., Janowsky, J. S., Taylor, S. F., Yesavage, J. A., Mumenthaler, M. S., Jagust, W. J., & Reed, B. R. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General, 130*(4), 746–763. https://doi.org/10.1037/0096-3445.130.4.746

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In C. Jarrold (Ed.), Variation in working memory (pp. 76–106). Oxford University Press.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. Proceedings of the National Academy of Sciences, 106(18), 7351–7356. https://doi.org/10.1073/pnas.0808187106

Braver, T. S., Satpute, A. B., Rush, B. K., Racine, C. A., & Barch, D. M. (2005). Context Processing and Context Maintenance in Healthy Aging and Early Stage Dementia of the Alzheimer's Type. *Psychology and Aging, 20*(1), 33–46. https://doi.org/10.1037/0882-7974.20.1.33

Braver, T. S., & West, R. (2008). Working memory, executive control, and aging. In F. I. M. Craik & T. A. Salthouse (Eds.), The handbook of aging and cognition (3rd ed., pp. 311–372). Psychology Press.

Bugg, J. M. (2014a). Conflict-triggered top-down control: Default mode, last resort, or no such thing? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(2), 567–587. https://doi.org/10.1037/a0035032

Bugg, J. M. (2014b). Evidence for the sparing of reactive cognitive control with age. *Psychology and Aging, 29*(1), 115–127. https://doi.org/10.1037/a0035270

Bugg, J. M. (2017). Context, Conflict, and Control. In T. Egner (Ed.), The Wiley handbook of cognitive control (pp. 79–96). Wiley-Blackwell. https://doi.org/10.1002/9781118920497.ch5

Bugg, J. M., & Crump, M. J. C. (2012). In support of a distinction between voluntary and stimulus-driven control: A review of the literature on proportion congruent effects. *Frontiers in Psychology, 3,* 367. https://doi.org/10.3389/fpsyg.2012.00367

Bugg, J. M., & Dey, A. (2018). When stimulus-driven control settings compete: On the dominance of categories as cues for control. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(12), 1905-1932. https://doi.org/10.1037/xhp0000580

Bugg, J. M., DeLosh, E. L., Davalos, D. B., & Davis, H. P. (2007). Age differences in Stroop interference: Contributions of general slowing and task-specific deficits. *Aging, Neuropsychology, and Cognition*, *14*(2), 155-167. https://doi.org/10.1080/138255891007065

Bugg, J. M., Jacoby, L. L., & Chanani, S. (2011). Why it is too early to lose control in accounts of item-specific proportion congruency effects. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(3), 844-859. https://doi.org/10.1037/a0019957

Cohn, N. B., Dustman, R. E., & Bradford, D. C. (1984). Age-related decrements in stroop color test performance. *Journal of Clinical Psychology*, *40*(5), 1244-1250. https://doi.org/10.1002/1097-4679(198409)40:5%3C1244::AID-JCLP2270400521%3E3.0.CO;2-D

Comalli Jr, P. E., Wapner, S., & Werner, H. (1962). Interference effects of Stroop color-word test in childhood, adulthood, and aging. *The*

Journal of Genetic Psychology, *100*(1), 47-53. https://doi.org/10.1080/00221325.1962.10533572

De Pisapia, N., & Braver, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing*, *69*(10-12), 1322-1326. https://doi.org/10.1016/j.neucom.2005.12.100

Dexter, M., & Ossmy, O. (2023). The effects of typical ageing on cognitive control: recent advances and future directions. *Frontiers in Aging Neuroscience*, *15*. https://doi.org/10.3389/fnagi.2023.1231410

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *Psychology of Learning and Motivation*, *44*, 145-200.

Freund, M. C., Bugg, J. M., & Braver, T. S. (2021). A representational similarity analysis of cognitive control during color-word Stroop. *Journal of Neuroscience*, *41*(35), 7388-7402. https://doi.org/10.1523/JNEUROSCI.2956-20.2021

Freund, M. C., Etzel, J. A., & Braver, T. S. (2021). Neural coding of cognitive control: the representational similarity analysis approach. *Trends in Cognitive Sciences*, *25*(7), 622-638. https://doi.org/10.1016/j.tics.2021.03.011

Gonthier, C., Braver, T. S., & Bugg, J. M. (2016). Dissociating proactive and reactive control in the Stroop task. *Memory & Cognition*, *44*, 778-788. https://doi.org/10.3758/s13421-016-0591-1

Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience*, *13*, 491-505. https://doi.org/10.1038/nrn3256

Hartley, A. A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychology and Aging, 8*(3), 371–379. https://doi.org/10.1037/0882-7974.8.3.371

Haxby, J. V., Connolly, A. C., & Guntupalli, J. S. (2014). Decoding neural representational spaces using multivariate pattern analysis. *Annual Review of Neuroscience*, *37*, 435-456. https://doi.org/10.1146/annurev-neuro-062012-170325

Ileri-Tayar, M., Bugg, J., & Braver, T. S. (2024, April 18). Cognitive Control and Aging. Retrieved from osf.io/krcn5

Ileri-Tayar, M., Bugg, J., & Braver, T. S. (2024, April 18). Cognitive Control and Aging - Follow-up. Retrieved from osf.io/6b5rm

Ileri-Tayar, M., Bugg, J., & Braver, T. S. (2024, June 30). Proactive Control Declines While Reactive Control is Preserved Across the Lifespan. Retrieved from osf.io/k8tuc

Jackson, J. D., & Balota, D. A. (2013). Age-related changes in attentional selection: Quality of task set or degradation of task set across time? *Psychology and Aging, 28*(3), 744–753. https://doi.org/10.1037/a0033159

Jacoby, L. L., Kelley, C. M., & McElree, B. D. (1999). The role of cognitive control: Early selection versus late correction. In S. Chaiken & E. Trope (Eds.), Dual Process Theories in Social Psychology (pp. 383-400). NY: Guildford.

Kalanthroff, E., Davelaar, E. J., Henik, A., Goldfarb, L., & Usher, M. (2018). Task conflict and proactive control: A computational theory of the Stroop task. *Psychological Review*, *125*(1), 59–82. https://doi.org/10.1037/rev0000083

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention and general fluid intelligence: An individual differences perspective. Psychonomic Bulletin and Review, 9, 637-671. https://doi.org/10.3758/BF03196323

Kramer, A.F., Humphrey, D.G., Larish, J.F., & Logan, G.D. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging*, *9*(4), 491-512. https://doi.org/10.1037/0882-7974.9.4.491

Kriegeskorte, N., & Kievit, R. A. (2013). Representational geometry: integrating cognition, computation, and the brain. *Trends in Cognitive Sciences*, *17*(8), 401-412. https://doi.org/10.1016/j.tics.2013.06.007

Lin, Y., Brough, R. E., Tay, A., Jackson, J. J., & Braver, T. S. (2024). Working memory capacity preferentially enhances implementation of proactive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 50*(2), 287–305. https://doi.org/10.1037/xlm0001195

Littman, R., Keha, E., & Kalanthroff, E. (2019). Task conflict and task control: A mini-review. *Frontiers in Psychology*, *10*, 472476. https://doi.org/10.3389/fpsyg.2019.01598

Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, *12*(4), 523-553. https://doi.org/10.1016/0010-0285(80)90019-5

MacLeod, C. M., & MacDonald, P. A. (2000). Interdimensional interference in the Stroop effect: Uncovering the cognitive and neural anatomy of attention. *Trends in Cognitive Sciences*, *4*(10), 383-391. https://doi.org/10.1016/S1364-6613(00)01530-8

Mutter, S. A., Naylor, J. C., & Patterson, E. R. (2005). The effects of age and task context on Stroop task performance. *Memory & Cognition*, *33*, 514-530. https://doi.org/10.3758/BF03193068

Nicosia, J., & Balota, D. (2020). The consequences of processing goal-irrelevant information during the Stroop task. *Psychology and Aging, 35*(5), 663–675. https://doi.org/10.1037/pag0000371

Parris, B. A., Hasshim, N., Wadsley, M., Augustinova, M., & Ferrand, L. (2022). The loci of Stroop effects: A critical review of methods and evidence for levels of processing contributing to color-word Stroop effects and the implications for the loci of attentional selection. *Psychological Research*, *86*, 1029-1053. https://doi.org/10.1007/s00426-021-01554-x

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin*

& Review, *25*, 1695-1716. https://doi.org/10.3758/s13423-017-1384-7

Snijder, J. P., Tang, R., Bugg, J. M., Conway, A. R., & Braver, T. S. (2024). On the psychometric evaluation of cognitive control tasks: An Investigation with the Dual Mechanisms of Cognitive Control (DMCC) battery. *Behavior Research Methods*, *56*, 1604-1639. https://doi.org/10.3758/s13428-023-02111-7

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. https://doi.org/10.1037/h0054651

Suh, J., & Bugg, J. M. (2021). On the automaticity of reactive item-specific control as evidenced by its efficiency under load. *Journal of Experimental Psychology: Human Perception and Performance*, *47*(7), 908-933. https://doi.org/10.1037/xhp0000914

Tang, R., Bugg, J. M., Snijder, J. P., Conway, A. R., & Braver, T. S. (2023). The Dual Mechanisms of Cognitive Control (DMCC) project: Validation of an online behavioural task battery. *Quarterly Journal of Experimental Psychology*, *76*(7), 1457-1480. https://doi.org/10.1177/17470218221114769

Verhaeghen, P. (2011). Aging and executive control: Reports of a demise greatly exaggerated. *Current Directions in Psychological Science*, *20*(3), 174-180. https://doi.org/10.1177/096372141140877