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BRIEF REPORT

Dissociating Proactive and Reactive Control in Older Adults

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The Dual Mechanisms of Control framework predicts that age-related declines should be most prominent for tasks that require proactive control, while tasks requiring reactive control should show minimal age differences in performance. However, results from traditional paradigms are inconclusive as to whether these two processes are independent, making it difficult to understand how these processes change with age. The present study manipulated the proportion congruency in a list-wide (Experiments 1 and 2) or item-specific (Experiment 1) fashion to independently assess proactive and reactive control, respectively. In the list-wide task, older adults were unable to proactively bias attention away from word processing based on list-level expectancies. Proactive control deficits replicated across multiple task paradigms, with different Stroop stimuli (picture-word, integrated color-word, separated color-word), and different behavioral indices (Stroop interference, secondary prospective memory). In contrast, older adults were successfully able to reactively filter the word dimension based on item-specific expectancies. These findings provide unambiguous support that aging is associated with declines in proactive, but not reactive, control.

Public Significance Statement

Completion of task goals (e.g., going to grocery store) often requires overcoming automatic tendencies (e.g., taking normal route home). Goal completion can be improved by activating the goal and preparing attention before anticipated distraction occurs (proactive control) or by quickly retrieving the task goal and focusing attention after distraction occurs (reactive control). The present study demonstrates that although aging is associated with declines in proactive control, successful goal completion by use of reactive control remains intact with advanced age. These findings are important for theories of cognitive aging, as they indicate that not all control processes decline with age.

Keywords: attention, cognitive control, inhibition, prospective memory

Supplemental materials: https://doi.org/10.1037/pag0000748.supp

The Dual Mechanisms of Control framework suggests that cognitive control can operate via two independent processing modes (Braver, 2012). Proactive control refers to the top-down maintenance of goal representations to bias attention prior to stimulus onset, whereas reactive control refers to the bottom-up reactivation of goals following stimulus onset. Critically, this framework predicts that age-related declines should be most prominent for tasks that require proactive control, while tasks requiring reactive control should show minimal age differences in performance (Braver et al., 2007). Contrary to these predictions, some research has shown comparable performance between younger and older adults on tasks that purportedly rely on proactive control (Mutter et al., 2005; West & Baylis, 1998). However, these studies have important task confounds that preclude making strong inferences about age-related changes in cognitive control. The present study addresses this issue by examining older adult performance across tasks that place dissociable demands on proactive versus reactive control to provide unambiguous support for age-related predictions from the Dual Mechanisms of Control framework.

The Stroop effect refers to the robust finding that naming the ink color of color words is slower and less accurate for incongruent trials (e.g., the word "red" in blue font) than congruent trials (e.g., the word "red" in red font). Central to the aims of the present study, the Stroop effect can be modulated by manipulating proportion congruency between lists (that is, list-wide proportion congruence [LWPC]

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The data from this article were not disseminated prior to submission and can be accessed on Open Science Framework at https://osf.io/ycba4/?view_only=44fd2512b86c417f9cd4f98a0b5d8e70.

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manipulation) or between items within the same list (that is, item-specific proportion congruence [ISPC] manipulation), with the resulting changes in performance thought to reflect different underlying processes (Bugg & Crump, 2012). The LWPC effect refers to the finding that the Stroop effect is larger in lists with mostly congruent (MC) items (e.g., 75% congruent) compared to lists with mostly incongruent (MI) items (e.g., 25% congruent; e.g., Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979). The reduction in the Stroop effect in MI lists has been attributed to proactive control. That is, the high probability of conflict in the MI list encourages participants to proactively filter the word dimension in a global fashion (across the entire list) to minimize interference (Braver, 2012; Bugg, 2012; Gonthier et al., 2016). In contrast, the ISPC effect refers to the finding that the Stroop effect is reduced for MI items (e.g., green, purple) compared to MC items (e.g., red, blue) *within* a list that is 50% congruent. The reduction in the Stroop effect for MI items has been attributed to reactive control. In this case, certain colors become associated with a high (e.g., "green") or low (e.g., "red") probability of conflict and thereby more or less focused attentional control, respectively. Participants reactively (poststimulus onset) retrieve the associated attentional control setting, producing rapid filtering of the word dimension for MI items and thereby less interference (Bugg, Jacoby, & Chanani, 2011; Bugg & Hutchison, 2013). Proactive control cannot explain the ISPC effect because the presentation of a given item is unpredictable (items are randomly intermixed and occur equally often as do congruent and incongruent trials) meaning one cannot prepare for a given item in advance.

Contrary to predictions that the list-wide paradigm should produce difficulties for older adults given demands on proactive control within the MI list (Braver et al., 2007; Hasher & Zacks, 1988), several studies have found that younger and older adults showed comparable reductions in Stroop effect in MI lists relative to MC lists (e.g., Mutter et al., 2005; West & Baylis, 1998). Critically, however, the proportion congruency manipulations in these studies confounded LWPC and ISPC and thereby list-level (proactive) and item-level (reactive) control processes. This is because *all* the items within a list were either MC or MI, meaning that participants could respond based on list-level expectancies (i.e., a high global probability of conflict within the list) or based on item-specific features (e.g., specific items within the list like "red" that were MI) that trigger retrieval of a control setting. This means that the reduction in the Stroop effect for MI lists could occur via proactive *or* reactive control mechanisms.

To control for the contribution of item-specific mechanisms including reactive control, Bugg et al. (2008) developed a novel variant of the LWPC paradigm whereby a subset of the items within each list were 50% congruent. These are referred to as diagnostic[1] items and importantly, isolate proactive from reactive control. Assuming that proactive control is operating globally across all trials in the MI list, the Stroop effect should be reduced even for the diagnostic items compared with the MC list. While younger adults showed a reduction in the Stroop effect for diagnostic items in the MI relative to the MC list, older adults did not (Bugg, 2014a). This suggests proactive control may be compromised in older adults, and furthermore supports the possibility that the LWPC effect observed for older adults in prior studies (Mutter et al., 2005; West & Baylis, 1998) may be attributable to reactive control of Stroop interference.

In line with this possibility, older adults show clear reductions in the Stroop effect for MI *items* compared with MC items in the ISPC paradigm (Bugg, 2014b), suggesting reactive control processes remain intact with increased age. Direct comparisons across studies are, however, limited in two ways. The contrasting patterns of impaired proactive control (Bugg, 2014a) and intact reactive control (Bugg, 2014b) for older adults in the Stroop task were observed in different samples and using different tasks. The impairment in proactive control was found in a color-word Stroop task, whereas the evidence for intact reactive control was found in a picture-word Stroop task, leaving open the possibility that the differences may reflect task differences and not differences in control. In the present study, we address these limitations and thereby seek clearer evidence for a selective decline in proactive control in older adults by comparing control processes within the same group of participants within the same task (Experiment 1). Furthermore, we seek converging evidence by examining performance in multiple tasks using multiple behavioral indicators of proactive control (Experiment 2).

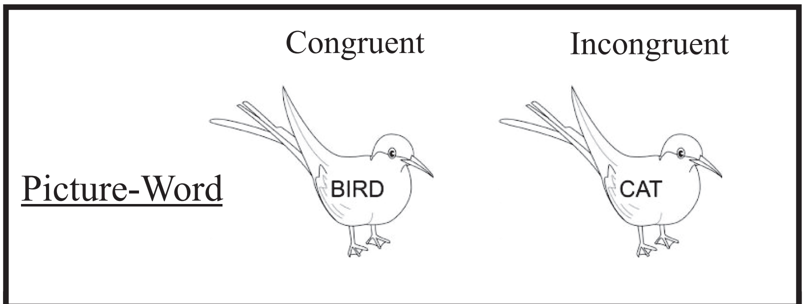
Experiment 1

In Experiment 1, older adults performed a list-wide version (with diagnostic items) and an item-specific version of the picture-word Stroop task with the goal of using select behavioral indices to isolate proactive and reactive control, respectively. Participants were instructed to ignore an animal word (e.g., "bird," "fish") that was superimposed on a drawing of a to-be-named animal (e.g., bird, cat; see Figure 1). The list-wide task included an MC block with inducer items that were 75% congruent (e.g., *bird, fish*; referred to as LW PC-75) and an MI block with inducer items that were 25% congruent (e.g., *bird, fish*; referred to as LW PC-25). Critically, within each block there were also diagnostic items with a proportion congruency of 50% (e.g., *cow, frog*; referred to as LW PC-50). Examining the LWPC effect for diagnostic items allowed us to isolate proactive control without item-specific confounds. In the item-specific task, the block was 50% congruent but half of the items had a proportion congruency of 75% (referred to as IS PC-75) and the other half had a proportion congruency of 25% (referred to as IS PC25). The ISPC effect served as the indicator of reactive control without list-specific confounds.

Gonthier et al. (2016) adopted this design in a study involving younger adults and found that the LWPC manipulation successfully modulated the Stroop effect, with a reduced Stroop effect in MI blocks compared to MC blocks. Importantly, this pattern was observed for both inducer and diagnostic items, with the diagnostic effect unambiguously supporting a proactive control account of the LWPC effect. The ISPC manipulation resulted in reduced interference for MI items compared to MC items, evidence for reactive control. Importantly, the LWPC and ISPC effects were uncorrelated, suggesting independent processes. In the present study, based on the dual mechanisms of control account, we anticipated that older adults would not show a LWPC effect for diagnostic items but would show an ISPC effect, which would indicate deficits in proactive control but spared reactive control, respectively.

[1] Prior studies have referred to these items as unbiased (Gonthier et al., 2016) or transfer items (Bugg, 2014a).

Figure 1
Example Stimuli (Top Half) and Presentation Frequency (Bottom Half) Across Blocks in Experiment 1



Task Block	Item Type	Picture	Word			
			CAT	DOG	FISH	BIRD
LW-MC	PC-75	Cat	54	6	6	6
		Dog	6	54	6	6
		Fish	6	6	54	6
		Bird	6	6	6	54
			COW	FROG	PIG	SEAL
	PC-50	Cow	12	4	4	4
		Frog	4	12	4	4
		Pig	4	4	12	4
		Seal	4	4	4	12
			CAT	DOG	FISH	BIRD
LW-MI	PC-25	Cat	18	18	18	18
		Dog	18	18	18	18
		Fish	18	18	18	18
		Bird	18	18	18	18
			COW	FROG	PIG	SEAL
	PC-50	Cow	12	4	4	4
		Frog	4	12	4	4
		Pig	4	4	12	4
		Seal	4	4	4	12
			CAT	DOG	FISH	BIRD
IS	PC-75	Cat	72	8	8	8
		Dog	8	72	8	8
	PC-25	Fish	24	24	24	24
		Bird	24	24	24	24
			COW	FROG	PIG	SEAL
	PC-50	Cow	6	2	2	2
		Frog	2	6	2	2
		Pig	2	2	6	2
		Seal	2	2	2	6

Note. LW-MC = list-wide mostly congruent; LW-MI = list-wide mostly incongruent; IS = item-specific; PC = proportion congruency. Adapted from "Dissociating proactive and reactive control in the Stroop task," by C. Gonthier, T. S. Braver, and J. M. Bugg, 2016, *Memory & Cognition*, *44*, p. 782. (https://doi.org/10.3758/s13421-016-0591-1). CC BY-NC.

Method

Transparency and Openness in Data, Analysis, and Materials

All research was conducted using appropriate ethical guidelines approved by the institutional review board at Washington University in St. Louis (International Review Board protocol No. 201208135, *Controlling Attention and Memory*). Although not preregistered, all hypotheses in Experiments 1 and 2 were made a priori based on prior research (Bugg, McDaniel, et al., 2011; Gonthier et al., 2016). All manipulations and measures are reported. Deidentified data, analytic code, programs, and stimuli for each experiment is available on Open Science Framework at https://osf.io/ycba4/?view_only=44fd2512b86c417f9cd4f98a0b5d8e70.

Participants

Sixty community-dwelling older adults (aged 60 and above) received monetary compensation for participation in sessions that lasted approximately 2 hr.[2] Prescreening requirements included having English as one's native language, normal or corrected-to-normal vision, and normal color vision. No participants reported in the demographics questionnaire that they were taking any medication

[2] Seventy-two participants initially began the study. Data from twelve participants were excluded: Seven participants had incomplete data (computer freeze, microphone error, falling asleep, left early), one participant failed to follow task instructions (would not stay in front of microphone), one participant had error trials scored incorrectly by the experimenter, and three participants had Stroop effects greater than 3 *SD* from the group mean (Gonthier et al., 2016).

for stroke, mild cognitive impairment, or Alzheimer's disease and related dementias. The sample size was chosen to approximate the younger adult sample from Gonthier et al. (2016). The mean age in years, years of education, and Shipley's vocabulary score was 74.05 (SD = 7.62), 15.52 (SD = 2.63), and 28.91 (SD = 4.78), respectively. Participants were predominately female (Male = 32%, Female = 68%) and White (White = 98%, Black/African American = 2%).

Materials and Procedure

The materials and procedure were a direct replication of Gonthier et al. (2016). All participants performed three picture-word Stroop blocks (list-wide MC, list-wide MI, and item-specific). Stimuli consisted of eight black-and-white drawings of animals that were divided into two sets (see top half of Figure 1). One set of four animals (frog, cow, pig, seal) was used for the diagnostic (PC-50) items and a second set (cat, dog, bird, fish) was used for the inducer items (PC-75 or PC-25). A superimposed animal word (e.g., "cat") matched the drawing (e.g., cat picture) on congruent trials. On incongruent trials, the word (e.g., "dog") conflicted with the drawing (e.g., cat picture). In each of the three blocks, the diagnostic item set was always 50% congruent (PC-50).[3] The inducer items were 75% congruent in the MC block (PC-75) and 25% congruent in the MI block (PC-25). In the item-specific block, two of the items from the inducer set were 75% congruent (PC-75) and two of the items were 25% congruent (PC-25), which was counterbalanced across participants.

Participants were instructed to name aloud the animals shown in the pictures as quickly and as accurately as possible. Responses were timed with a voice key (E-prime serial response box device; Schneider et al., 2002) and an experimenter manually coded the participant's answers on a keyboard. A "scratch" trial was coded when the participant provided an unclear answer or if the voice key did not recognize the audible response. Trials were separated by a 1,000 ms interstimulus interval following the experimenter's coding of the response. Pictured in the bottom half of Figure 1, participants performed 384 trials in the list-wide MC block (96 PC-50 trials and 288 PC -75 trials), 384 trials in the list-wide MI block (96 PC-50 trials and 288 PC-25 trials), and 432 trials in the item-specific block (192 PC-25 trials, 192 PC-75 trials, and 48 PC-50 trials). Participants performed 22 practice trials before each block with the same proportion congruencies as the subsequent experimental block. Each experimental block lasted approximately 20 min with a short break halfway through each block. Participants were given as much time as needed to rest between blocks and during each break. Similar to Gonthier et al. (2016), participants always performed either the list-wide MC or MI block first, and the order of the other list-wide block and the item-specific block was counterbalanced across participants (i.e., MC, MI, ISPC; or MC, ISPC, MI; or MI, MC, ISPC; or MI, ISPC, MC).

Results

Response time (RT) analyses were conducted on accurate trials only. RTs less than 200 ms and greater than 3,000 ms were excluded from the RT analyses (Gonthier et al., 2016), resulting in removal of 1% of the trials in each block type. Table 1 presents descriptive statistics. Accuracy and RT analyses are reported for the Stroop effect (incongruent–congruent) for each contrast of interest. As many results produce theoretically anticipated null effects, we also provide Bayes factor estimates. The Bayes factor in favor the alternative hypothesis (BF_{10}) relative to the null hypothesis (BF_{01}) was computed as $1/BF_{01}$. We considered a BF_{10} less than .33 as moderate evidence in favor of the null hypothesis (i.e., that the two conditions do not differ) and a BF_{10} greater than 3.0 as moderate evidence in favor of the alternative hypothesis (i.e., that the two conditions do differ).

LWPC (Inducer; PC-75, PC-25)

List-wide proportion congruency modulated the Stroop effect, with a reduced Stroop effect in the MI block compared to the MC block for accuracy, $F(1, 59) = 8.12$, $p = .006$, $\eta_p^2 = .121$; $BF_{10} = 4.31$, and RTs, $F(1, 59) = 55.79$, $p < .001$, $\eta_p^2 = .586$; $BF_{10} > 100$. This pattern does not unambiguously indicate use of proactive versus reactive control, as either process could produce this result.

LWPC (Diagnostic; PC-50)

List-wide proportion congruency did *not* modulate the Stroop effect, with no differences in the Stroop effect between the MI and MC block for accuracy ($F < 1$; $BF_{10} = 0.10$) or RTs, $F(1, 59) = 3.68$, $p = .06$, $\eta_p^2 = .059$; $BF_{10} = 0.59$. This pattern of results can be unambiguously linked to the lack of use of proactive control. However, it should be noted that the Bayes factor for the RT analysis provides only weak evidence in favor of the null.

ISPC (PC-75, PC-25)

Item-specific proportion congruency modulated the Stroop effect, with a reduced Stroop effect for PC-25 items compared to PC-75 items for accuracy, $F(1, 59) = 11.27$, $p < .001$, $\eta_p^2 = .160$; $BF_{10} = 16.67$, and RTs, $F(1, 59) = 21.67$, $p < .001$, $\eta_p^2 = .269$; $BF_{10} > 100$. This unambiguously indicates the use of reactive control.

Discussion

Experiment 1 demonstrated that older adults did not show clear evidence for proactive control but did effectively utilize reactive control. Older adults were unable to reduce the Stroop effect on diagnostic items that require proactive engagement of control across the entire block to reduce interference in the MI block compared with the MC block. However, they did show a reduction in the Stroop effect for MI items compared with MC items in the ISPC block, which demonstrates reactive engagement of control based on specific items being associated with high conflict. Moreover, they showed a reduced Stroop effect for inducer items in the MI block compared with the MC block, a pattern that can also result from reactive mechanisms (Bugg et al., 2008). The findings corroborate previous findings of age-related declines in proactive control in a color-word Stroop task (Bugg, 2014a), but spared reactive control in a picture-word Stroop task (Bugg, 2014b). Taken together, these findings highlight that proactive and reactive control

[3] The diagnostic items were also included in the item-specific block to match the number of possible responses across blocks and for a separate question not directly relevant to the present study. Thus, performance on diagnostic items in the item-specific blocks will not be discussed further.

Table 1
Descriptive Statistics for Accuracy and Response Times as a Function of Task Block, Item-Specific Proportion Congruency, and Type of Trial in Experiment 1

Block	DV	Proportion congruency	Congruent	Incongruent	Stroop
LW-MC	Acc	PC-75	.994 (.001)	.970 (.004)	.024 (.003)
		PC-50	.987 (.002)	.963 (.005)	.024 (.005)
	RT	PC-75	732 (12)	872 (17)	140 (9)
		PC-50	791 (14)	965 (19)	173 (11)
LW-MI	Acc	PC-25	.994 (.001)	.979 (.002)	.015 (.002)
		PC-50	.993 (.001)	.969 (.005)	.024 (.004)
	RT	PC-25	740 (15)	830 (16)	90 (6)
		PC-50	783 (14)	939 (20)	156 (10)
IS	Acc	PC-75	.992 (.001)	.959 (.006)	.034 (.006)
		PC-25	.995 (.001)	.978 (.003)	.017 (.003)
	RT	PC-75	730 (13)	850 (18)	120 (9)
		PC-25	739 (14)	829 (16)	89 (7)

Note. Average values with standard errors in parentheses. DV = dependent variable; LW-MC = list-wide mostly congruent; LW-MI = list-wide mostly incongruent; IS = item-specific; PC = proportion congruency; Acc = accuracy; RT = response time; Congruent = congruent trials; Incongruent = incongruent trials; Stroop = magnitude of the Stroop effect computed as incongruent–congruent.

can be dissociated within the same individuals in the same task and across studies with different tasks.

Experiment 2

In Experiment 1, older adults did not produce a LWPC effect for diagnostic items, the key indicator of proactive control. However, the Bayes factor evidence in favor of the null RT effect was weak, and thus Experiment 2 aimed in part to seek converging evidence of impaired proactive control for older adults using a behavioral indicator that was distinct from that used in Experiment 1 (Bugg, McDaniel, et al., 2011). As in Experiment 1, participants performed a list-wide version of the picture-word Stroop task. The proportion congruency was 70% in the MC block (PC-70) and 15% in the MI block (PC-15). In contrast to Experiment 1, the diagnostic items were neutral trials comprising neutral words (e.g., "table") superimposed on the animal images. These occurred on 15% of the trials within each block. If participants proactively filter the irrelevant words in the MI block, then reaction times for the diagnostic items should be faster in the MI block compared with the MC block.

The inclusion of neutral trials also allowed for a second measure of proactive control. In a second phase of the Stroop task also comprising MC and MI blocks, participants were given a secondary prospective memory intention (i.e., remembering to complete a planned action in the future) in which they were asked to make a different (non-Stroop) response any time they encountered a target word (e.g., "lamp") during the Stroop task. Assuming participants filter the word dimension to a greater degree in MI blocks, they should be less likely to notice the prospective memory target words and thus less likely to respond to these words. Using this design in a sample of younger adults, Bugg McDaniel, et al. (2011) found this exact pattern of results—participants were faster on neutral trials and were less likely to detect the prospective memory target in the MI blocks compared to MC blocks. Thus, while proactive control can be used to reduce the Stroop effect, it can also lead to failures of prospective memory when word processing is required. In the present study, we anticipated that older adults would show no differences between blocks in performance on diagnostic (neutral) trials or in prospective memory target detection, consistent with age-related declines in proactive control.

A second goal of Experiment 2 was to investigate older adults' ability to use proactive control across multiple tasks to determine whether performance might vary based on task characteristics. We used three different tasks (see Figure 2), including the aforementioned picture-word Stroop task (as in Experiment 1), a standard integrated color-word Stroop task (Bugg & Hutchison, 2013), and a separated color-word Stroop task in which the color-word was presented in black font but was surrounded by a colored border (Hiatt et al., 2004). Some have argued that these tasks may rely on different underlying processes (Dell'Acqua et al., 2007; but see Starreveld & La Heij, 2017), meaning that it could be possible to find evidence of proactive control in one task but not another. For example, the perceptual overlap between (i.e., integration of) the relevant (e.g., the color) and irrelevant (e.g., the word) dimensions is greater for the standard color-word Stroop task compared to the picture-word Stroop task (and the separated color-word Stroop used herein), which may influence the Stroop effect (West & Bell, 1997) as well as older adults' ability to use or benefit from a proactive word filter. Showing comparable findings across multiple task metrics and task types would provide strong evidence to suggest that aging is associated with deficits in proactive control.

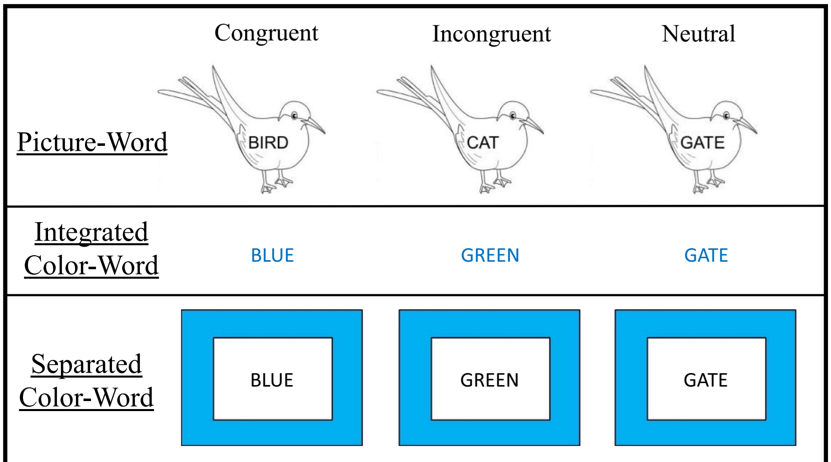
Participants

Participants included 30 (picture-word), 25 (integrated color-word), and 26 (separated color-word) community-dwelling older adults (aged 60 and above) who received monetary compensation for participation in sessions that lasted approximately 1 hr.[4] Prescreening requirements included having English as one's native language, normal or corrected-to-normal vision, and normal color

[4] The separated color-word Stroop condition initially included 31 participants. Data were excluded from three participants because one of the lists was not randomized and from two participants that did not complete all blocks.

Figure 2

Example Stimuli (Top Half) and Presentation Frequency (Bottom Half) Across Task Types and Blocks in Experiment 2



Task Block	Item Type	Picture	Word					
			CAT	DOG	FISH	BIRD	SEAL	PIG
LW-MC	PC-70	Cat	28	2	1	1	1	1
		Dog	1	28	2	1	1	1
		Fish	1	1	28	2	1	1
		Bird	1	1	1	28	2	1
		Seal	1	1	1	1	28	2
		Pig	2	1	1	1	1	28
			HILL	KNEE	MAP	RAY	TAR	WINE
	Neutral	Cat	1	1	1	1	1	1
		Dog	1	1	1	1	1	1
		Fish	1	1	1	1	1	1
		Bird	1	1	1	1	1	1
		Seal	1	1	1	1	1	1
		Pig	1	1	1	1	1	1
			CAT	DOG	FISH	BIRD	SEAL	PIG
LW-MI	PC-15	Cat	6	4	6	6	6	6
		Dog	6	6	4	6	6	6
		Fish	6	6	6	4	6	6
		Bird	6	6	6	6	4	6
		Seal	6	6	6	6	6	4
		Pig	4	6	6	6	6	6
			GATE	HOOK	JAM	MUD	REED	VAN
	Neutral	Cat	1	1	1	1	1	1
		Dog	1	1	1	1	1	1
		Fish	1	1	1	1	1	1
		Bird	1	1	1	1	1	1
		Seal	1	1	1	1	1	1
		Pig	1	1	1	1	1	1

Note. Note that the task arrangement does not include neutral buffer trials or control trials. LW-MC = list-wide mostly congruent; LW-MI = list-wide mostly incongruent; PC = proportion congruency. Adapted from "Dissociating proactive and reactive control in the Stroop task," by C. Gonthier, T. S. Braver, and J. M. Bugg, 2016, *Memory & Cognition*, *44*, p. 782. (https://doi.org/10.3758/s13421-016-0591-1). CC BY-NC. See the online article for the color version of this figure.

vision. No participants reported in the demographics questionnaire that any medication was being taken for stroke, mild cognitive impairment, or other Alzheimer's disease and related dementias. The sample size for each condition was chosen to approximate the younger adult sample from Bugg, McDaniel, et al. (2011). The overall mean age, years of education, and Shipley's vocabulary score were 68.44 (SD = 5.32), 16.49 (SD = 2.88), and 34.97 (SD = 3.38), respectively, with no significant differences across the three task conditions ($ps > .05$). Participants were predominately female (Male = 37%, Female = 63%) and White (White = 90%, Black/African American = 7%, Asian = 1%, American Indian/Native Alaskan = 1%).

Materials and Procedure

The materials and procedure for the integrated color-word condition were a direct replication of Bugg, McDaniel, et al. (2011). The picture-word and separated color-word conditions used an identical procedure, but different stimuli (see top half of Figure 2). We first describe the picture-word procedure and then detail how the color-word conditions differed. Participants performed two phases of the Stroop task, one without the secondary task (control phase) and one with the secondary task (prospective memory phase). Participants completed an MC and MI block within each phase in one of the following two orders: Phase 1 MC/MI and Phase 2 MC/MI, or Phase 1 MI/MC and Phase 2 MI/MC. The order of the control (e.g., Phase 1) and prospective memory (e.g., Phase 2) blocks was counterbalanced across participants. The percentage of neutral trials was held constant in each block (15%). The remaining trials were 70% congruent and 15% incongruent in the MC blocks (PC-70), and 15% congruent and 70% incongruent in the MI blocks (PC-15).

Six animals (fish, bird, seal, dog, cat, and pig) from Experiment 1 were used as stimuli in the picture-word task. Neutral stimuli were three- and four-letter concrete nouns that matched the length of the animal word stimuli. Two sets of 18 unique neutral words appeared in each block, with 12 items serving as buffer trials (six at beginning and six at end of the block) and the remaining six appearing with each animal. The different trial types are displayed in the bottom half of Figure 2. The word "lamp" served as the prospective memory target in the prospective memory phase and required a special response, whereas the word "lake" served as the control-matched target (same length and syllables) in the control phase and required no response. Within both the control and prospective memory phases, participants performed 262 trials in the MC block (12 buffer trials, 36 neutral trials, 204 PC-70 trials, and four target trials) and 262 trials in the MI block (12 buffer trials, 36 neutral trials, 204 PC-15 trials, and four target trials). Participants performed 18 practice trials before each block. Prior to performing the prospective memory phase, participants were instructed to press a button box if they ever saw the word "lamp" during the experimental trials. The prospective memory (prospective memory phase) or control (control phase) words occurred on trials 61, 122, 183, and 243 in the MC and MI blocks. Each experimental phase lasted approximately 30 min with a short break halfway through, after which the LWPC was switched.

The integrated and separated color-word Stroop versions included six colors (red, black, green, white, purple, and yellow). The neutral stimuli were three- to six-letter concrete nouns. The prospective memory target was "horse" and the control-matched target (in terms of length and frequency) was "plane" (Bugg, McDaniel, et al., 2011). In all other manners, the materials and procedure were identical to the picture-word version. The difference between the two color-word versions was that in the integrated version the words were presented in a to-be-named colored font (as is standard), whereas in the separated version the words were presented in black font surrounded by a to-be-named colored border.

Results

Table 2 presents descriptive statistics. Analyses are reported from the control phase for the Stroop effect (incongruent—congruent) on the inducer items (PC-70 and PC-15) and for mean performance on the diagnostic items (neutral). Prospective memory target detection is reported for the mean proportion of targets responded to during the prospective memory phase. Because an identical pattern of results was found for each of the three task conditions (picture-word, integrated color-word, separated color-word), analyses are collapsed across the condition factor.[5] As with Experiment 1, RT analyses were conducted on accurate trials only. RTs less than 200 ms and greater than 3,000 ms were excluded from the RT analyses, resulting in removal of 2% of the trials in the MC block and 1% of trials in the MI block.

LWPC (Inducer; PC-70 and PC-15)

Proportion congruency modulated the Stroop effect, with a reduced Stroop effect in the MI block compared to the MC block for accuracy, $F(1,80) = 27.09$, $p < .001$, $\eta_p^2 = .253$; $BF_{10} > 100$, and RTs, $F(1,80) = 87.99$, $p < .001$, $\eta_p^2 = .524$; $BF_{10} > 100$. This ambiguously indicates use of proactive or reactive control.

LWPC (Diagnostic; Neutral)

Proportion congruency did *not* modulate performance, with no differences in mean performance between the MI and MC blocks for accuracy ($F < 1$; $BF_{10} = 0.13$) or RTs ($F < 1$; $BF_{10} = 0.12$). This unambiguously indicates the absence of proactive control.

Prospective Memory

The proportion congruency manipulation did *not* modulate target detection, with no differences in accuracy between the MI and MC blocks ($F < 1$; $BF_{10} = 0.09$). This unambiguously indicates the absence of proactive control.

Discussion

Experiment 2 provided clear and consistent evidence across multiple Stroop paradigms showing that older adults exhibit no evidence of proactive control. While older adults were able to reduce the Stroop effect on the theoretically ambiguous inducer items (which as discussed earlier can be explained by intact reactive control), they were not able to do so for the diagnostic items that necessitate engagement of proactive control across the block to reduce interference. Moreover, if older adults were able to proactively filter word reading in MI lists, they should have been less likely to detect the prospective memory target words in that list, which was not the case (Bugg, McDaniel, et al., 2011). Consistent findings across the three paradigms and two indices of proactive control provide strong support for the idea that aging is associated with difficulties implementing proactive control.

General Discussion

The current results are consistent with the Dual Mechanisms of Control framework in showing that older adults produced patterns of performance indicative of impaired proactive control, but spared reactive control (Braver et al., 2007). When controlling potential item-specific confounds by using diagnostic (PC-50 or neutral) items in the list-wide paradigm, there was no evidence that older adults were able to reduce the Stroop effect in MI compared to MC blocks. Moreover, there was no difference in prospective memory target detection across blocks (Bugg, McDaniel, et al., 2011). This pattern replicated across multiple task paradigms, with different Stroop stimuli (picture-word, integrated color-word, separated color-word), and different behavioral indices (Stroop effect and prospective memory performance). Given that younger adults in previous research show reduced Stroop effects for diagnostic items, faster reaction times on neutral trials, and reduced prospective memory performance in MI blocks compared with MC blocks using the same designs in color-word and picture-word Stroop tasks (Bugg, McDaniel, et al., 2011; Gonthier et al., 2016), these results provide strong support for the idea that older adults have difficulty proactively biasing attention away from word processing based on list-level expectancies. In contrast, when specific items were

[5] The only difference across experiments was for LWPC inducer items, such that the reduction in the Stroop effect was greater in the integrated color-word task relative to the other tasks (see Table 2). There were no other interactions including task type ($ps > .05$). See the Supplemental Material for analyses including task type as a factor and each task analyzed separately.

Table 2

Descriptive Statistics for Accuracy and Response Times in the Control Phase as a Function of Task Block, Proportion Congruency, and Type of Trial for the Three Conditions in Experiment 2

Condition	DV	Proportion congruency	Congruent	Incongruent	Stroop	Neutral	Prospective memory
Picture-word	Acc	PC-70	.990 (.002)	.914 (.017)	.075 (.017)	.987 (.004)	.858 (.031)
		PC-15	.995 (.002)	.971 (.003)	.024 (.004)	.988 (.004)	.850 (.044)
	RT	PC-70	698 (19)	853 (31)	155 (20)	790 (24)	
		PC-15	733 (21)	828 (26)	94 (11)	783 (22)	
Color-word (integrated)	Acc	PC-70	.996 (.001)	.926 (.016)	.070 (.016)	.991 (.004)	.930 (.034)
		PC-15	.997 (.002)	.966 (.004)	.031 (.005)	.992 (.003)	.960 (.024)
	RT	PC-70	729 (24)	998 (38)	269 (18)	847 (24)	
		PC-15	788 (27)	939 (36)	151 (15)	840 (31)	
Color-word (separated)	Acc	PC-70	.995 (.001)	.955 (.009)	.040 (.009)	.989 (.003)	.856 (.044)
		PC-15	.996 (.002)	.982 (.003)	.013 (.003)	.995 (.003)	.856 (.050)
	RT	PC-70	666 (22)	829 (34)	162 (20)	751 (26)	
		PC-15	694 (22)	806 (29)	112 (11)	748 (25)	

Note. Average values with standard errors in parentheses. DV = dependent variable; PC = proportion congruency; Acc = accuracy; RT = response time; Congruent = congruent trials; Incongruent = incongruent trials; Stroop = magnitude of the Stroop effect computed as incongruent–congruent; Neutral = neutral trials; Prospective Memory = proportion of specific words detected in prospective memory block. The response time and accuracy data are presented for the control block only (no secondary prospective memory intention), whereas the prospective memory data is only from the prospective memory block.

indicative of response conflict (inducer items in list-wide manipulations or items in item-specific manipulation), older adults were successfully able to reduce the Stroop effect (Bugg, 2014b; West & Baylis, 1998). This suggests that older adults can reactively engage control to minimize word processing for MI items based on item-level expectancies. These findings are critical for theories of cognitive aging, as they indicate that not all control processes decline with age (Andrés et al., 2008; Kramer et al., 1994; Rey-Mermet & Gade, 2018).

The pattern of results is consistent with prior observations from two separate studies showing that older adults do not show evidence of proactive control in the color-word Stroop task (Bugg, 2014a) but do show spared reactive control in a picture-word Stroop task (Bugg, 2014b). It has been argued that these tasks may rely on different underlying processes (Dell'Acqua et al., 2007; but see Starreveld & La Heij, 2017), meaning that these patterns could be task-specific rather than indicating selective impairment of proactive control in older adults. However, Experiment 1 revealed a similar pattern of performance for older adults using a single task (picture-word Stroop) that allowed the two types of control to be dissociated within the same individuals. Furthermore, Experiment 2 found consistent evidence showing the lack of proactive control in older adults across multiple task paradigms. If different underlying processes do indeed operate across different task paradigms, we can confidently say, at least in older adults, that proactive control as defined in the current set of studies is not one of those processes. Together these findings highlight that proactive and reactive control can be dissociated within the same individuals in the same task (Experiment 1) and across studies with different tasks (Experiment 2; Bugg, 2014a, 2014b).

The current results are consistent with previous findings showing age-related declines in proactive control, but relative sparing of reactive control, in the AX continuous performance task (AX-CPT). In this task, participants are instructed to make a target response any time the cue "A" precedes the probe "X" and a nontarget response for any other cue-probe combination (e.g., A-Y, B-X, or B-Y). Because most trials (70%) are AX trials, participants can proactively prepare a target response for the probe trial following an A cue or a nontarget response following a B cue. However, this expectancy can lead to errors on AY trials. Research has shown that older adults have impaired BX performance but preserved AY performance, suggesting that they are not proactively utilizing the cue information to prepare responding (Braver et al., 2005). Neuroimaging studies have also found that older adults show less cue-related and more probe-related activation, indicating a reliance on more reactive processes (Paxton et al., 2008). Importantly, however, standard versions of the AX-CPT are unable to dissociate proactive and reactive control processes within the same participant, which calls into question whether they are truly independent processes. The list-wide and item-specific manipulations used in the present study can dissociate proactive and reactive control. Similar versions of the AX-CPT and other cognitive control tasks have also been recently developed to provide evidence for dissociable processes (Braver et al., 2021; Etzel et al., 2022) that will be fruitful for understanding age-related changes in cognitive control.

Although considerable research has supported the idea of age-related declines in inhibitory processing, age effects are not always seen. Rey-Mermet and Gade (2018) suggest that these discrepancies could reflect that older adults with better preserved executive functioning are the ones who do not show age effects, studies use different tasks to measure inhibition and use different methodologies within the same tasks, and/or studies differ in how they calculate speed differences between age groups (e.g., proportional scores, *z*-score transformations, etc.). Another possibility is that there may be different subsets of inhibitory processes (e.g., Chuderski et al., 2012; Friedman & Miyake, 2004; Nigg, 2000) that may differ with age, such as the ability to reduce response interference (e.g., Stroop), ignore distracting information (e.g., flanker), and/or suppress dominant responses (e.g., go/no go). Lastly, it has been suggested that some tasks may rely on more controlled inhibitory processes (e.g., Stroop), while others may require more automatic inhibitory processes (e.g., negative priming;

Andrés et al., 2008; Kramer et al., 1994). The advantages of the procedures used in the present study are that we had confound-minimized measures that mitigate many of these concerns. Both the LWPC and ISPC effects are measured within the same type of Stroop task that only differ in the relative frequencies of conflict for different items using the same dependent variables (i.e., RTs and accuracy). This suggests that the different patterns of control do not reflect different inhibitory processes or task-specific features that may be more or less affected by aging. Furthermore, showing different patterns of control within the same individuals accounts for various individual differences factors (e.g., executive functioning, processing speed).

One limitation of the present study is that there is no direct comparison between younger and older adult participants. While prior research clearly shows evidence of intact proactive control in younger adults (Braver et al., 2021; Bugg, McDaniel, et al., 2011; Etzel et al., 2022; Gonthier et al., 2016) that was not seen in the present study with older adults, directly comparing the two would allow for stronger inferences on whether the efficacy of employing proactive control significantly differs between the two.[6] Future work also examining whether the efficacy of reactive control differs across age groups may also prove useful. Despite these concerns, we believe that the results are particularly informative regarding the nature of age-related declines in cognitive control, which appear to be localized to proactive control.

Finally, it is worth noting that failing to find behavioral signatures of proactive control does not necessarily mean that older adults are *unable* to engage demanding top-down control processes to support performance. Rather, older adults may opt to rely on environmental support when possible (Bugg, 2014a). In the present study, most trials (inducer PC-25 items) in the MI block still contained item-specific information that could be used to reduce interference. Indeed, older adults consistently showed reductions in the Stroop effect for inducer items. This environmental support may make older adults less likely to adopt a proactive control strategy that would otherwise facilitate performance on diagnostic (PC-50 or neutral) items. Indeed, prior research has shown that older adults show performance comparable to that of younger adults on the AX-CPT following sufficient training on how to engage proactive control (Paxton et al., 2006). Future work disentangling whether capacity limitations, strategic effort avoidance, or both underlie declines in proactive control in older adults may have important implications for understanding why certain aspects of cognitive control decline with age and how to effectively intervene to reduce these declines.

[6] Supplemental Table S1 reports the effect sizes reported from the younger adult data collected in Gonthier et al. (2016) and Bugg, McDaniel, et al. (2011) relative to older adult data in the present study. Interestingly, the effect sizes for trial types in which reactive control could be implemented (LWPC inducer items, ISPC items) were generally comparable between younger and older adults. In contrast, the effect sizes were considerably larger for younger adults than older adults for trial types in which proactive control is required (LWMC diagnostic items, prospective memory).

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