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The Flexibility of Cognitive Control: Age Equivalence With Experience Guiding the Way

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Prior research has shown that aging is accompanied by changes in cognitive control. Older adults are less effective in maintaining an attentional bias in favor of goal-relevant information and are less flexible in shifting control relative to younger adults. Using a novel variant of the Stroop color-naming task, we tested the hypothesis that age-related differences in the flexible shifting of control may be small or absent when control is guided by experience (i.e., environmental input guiding attention). Younger and older adults named the color of color words in abbreviated lists of trials. In Experiment 1, experience within the early segment of the list was manipulated to encourage adoption of more (mostly congruent condition) or less (mostly incongruent condition) attention toward the word. More important, the middle and late portions were 50% congruent in both conditions. Older adults, like younger adults, demonstrated flexible acquisition and shifting of control settings (i.e., relative attention to word vs. color information). In Experiment 2 we replicated this finding. Additionally, we found that both age groups flexibly acquired and shifted control settings for "transfer" items (i.e., items that were 50% congruent in all lists and list segments), pointing to a generalizable (i.e., global) form of control rather than an item-specific mechanism. Discussion focuses on the role of experience-guided control in enabling flexible performance in older adults.

Keywords: cognitive control, Stroop, proportion congruent, experience-guided control, statistical learning

Cognitive control encompasses the selection and processing of task-relevant over task-irrelevant information, thereby enabling goal-directed behavior even in the face of habitual but incorrect response tendencies (Braver, Gray, & Burgess, 2007). Cognitive control also enables individuals to flexibly adjust attention in response to changing contextual demands (e.g., increasing focus on task-relevant information or strongly filtering irrelevant information when likelihood of distraction is high but relaxing control when it is low). Although there is considerable evidence that normal aging is accompanied by deficits in cognitive control (e.g., Zacks & Hasher, 1994; but see Verhaeghen, 2011), novel theorizing suggests the relationship between aging and cognitive control may be more nuanced than thought (Braver et al., 2007; Bugg, 2014a, 2014b; Bugg, 2015). In accordance with this theorizing, the purpose of the current study was to examine age-related differences in the flexibility of cognitive control through a new lens—one that views older adults as being as flexible as younger adults when flexibility can be achieved via experience (i.e., environmental input guiding shifts in control). We first review evidence supporting the view that aging is associated with declines in cognitive control. We then introduce prior literature that provides support for the prediction that older adults may show intact, experience-guided flexibility of cognitive control, including findings demonstrating intact implicit/incidental learning and increased reliance on environmental context with age.

Age-Related Declines in Cognitive Control

Older adults have difficulty flexibly switching between rules, task sets, or goals. On the Wisconsin card-sorting task, after being told that their responses based on a repeatedly applied sorting rule are no longer correct, older adults struggle to switch to a new rule (i.e., perseverate; Fisk & Sharp, 2004; Fristoe, Salthouse, & Woodard, 1997; Rhodes, 2004). Deficits in flexibility are also apparent on other neuropsychological tasks, presenting as disproportionate age-related differences on switch versions relative to nonswitch versions (e.g., Trails B vs. Trails A, Tombaugh, 2004; but see Salthouse, 2011). A similar deficit appears in experimental paradigms such as task-switching in which participants switch (often unpredictably) between task sets (e.g., making parity vs. vowel/consonant judgments) when cued. Older adults show impaired performance relative to younger adults on switch trials (Kray & Lindenberger, 2000; Mayr, 2001; but see Verhaeghen,

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2011; Wasylyshyn, Verhaeghen, & Sliwinski, 2011, for counter-evidence suggesting small or absent switch costs with age).

A common feature of studies demonstrating age-related decrements in flexibility is that participants are informed (e.g., via instructions, a cue, or feedback) of the demand to switch between rules, task sets, or goals. This observation raises the question of whether such decrements may be related to deficits in effortful control processes that are needed to initiate a shift in attention to support flexible performance. In other words, age-related decrements in flexibility may be weaker or absent if the shifts in control could be mediated externally, that is, via changes in task experience that may occur outside of participants' awareness. This idea converges with two present themes in the aging literature. One is that implicit or incidental learning largely remains intact in older adulthood (e.g., Campbell, Zimerman, Healey, Lee, & Hasher, 2012; Schwab et al., 2016; see Howard & Howard, 2013, for exceptions). Most relevant to the current study, this implicit learning includes learned attentional biases (Jiang, Koutstaal, & Twedell, 2016). The second theme is that older adults appear to be more reliant on the environment than younger adults. This is evidenced by the increased tendency for older adults to attend to irrelevant environmental features (e.g., Hamm & Hasher, 1992; Lustig, Hasher, & Tonev, 2006; Spieler, Mayr, & LaGrone, 2006) and rely on external task cues even when those cues are no longer imperative (Mayr, Spieler, & Hutcheon, 2015; Spieler et al., 2006). Critically, for present purposes, older adults' sensitivity to and reliance upon the environment also yields benefits (e.g., Biss, Ngo, Hasher, Campbell, & Rowe, 2013; Campbell et al., 2012; for review, see Amer, Campbell, & Hasher, 2016), possibly because these tendencies reduce demands on active, self-initiated processing, and allow older adults to offload processing (see Lindenberger & Mayr, 2014, for a review). Drawing on these two themes, we hypothesize that older adults may show intact flexibility under task conditions that afford reliance on the environment to modulate flexible shifts in control. In the introduction to Experiment 1 below, we discuss predictions generated by these findings.

Current Approach

In the current study, we harness the Stroop color-naming task to test the above hypothesis. In this task, participants are slower on incongruent (the word "blue" displayed in red) than congruent (the word "red" in red) trials (i.e., the Stroop effect), a difference that is exacerbated by aging (even after accounting for generalized slowing; Bugg, DeLosh, Davalos, & Davis, 2007; Jackson & Balota, 2013; Spieler, Balota, & Faust, 1996, cf. Verhaeghen, 2011). This task is ideally suited for testing the hypothesis because both younger and older adults are sensitive to experience-based manipulations that affect control of attention, thereby producing modulations in the magnitude of the Stroop effect. These experience-based manipulations are known as *proportion congruence* (PC) manipulations. PC refers to the percentage of trials within a context that are congruent (as opposed to incongruent), that is, the percentage of trials on which the irrelevant word corresponds to the to-be-named color. In a classic variant called the list-wide PC manipulation (e.g., Kane & Engle, 2003; Lindsay & Jacoby, 1994; Logan, 1980; Logan & Zbrodoff, 1979; Logan, Zbrodoff, & Williamson, 1984; Lowe & Mitterer, 1982), mostly congruent (MC) or mostly incongruent (MI) lists of around 100 trials are presented. Younger and older adults show larger Stroop effects in MC than MI lists (Bugg, Jacoby, & Toth, 2008; Mutter, Naylor, & Patterson, 2005; West & Baylis, 1998). Critically, this *list-wide proportion congruence effect* (i.e., PC effect) demonstrates that older, in addition to younger, adults are sensitive to experience (here, frequency of congruent relative to incongruent trials) and loosen (MC list) or tighten (MI list) control over word reading (Lindsay & Jacoby, 1994) and/or color-naming accordingly (cf. Egner & Hirsch, 2005; Melara & Algom, 2003). The evidence to date suggests this PC effect is dependent on the *implicit* learning of PC and not an intentional strategy (Blais, Harris, Guerrero, & Bunge, 2012; Bugg & Diede, 2017; Bugg, Diede, Cohen-Shikora, & Selmeczy, 2015).

In the current study, we modify the typical list-wide PC paradigm to investigate whether younger and older adults are sensitive to dynamic changes in experience (PC) from one segment of a list to another (as evidenced by changes in the magnitude of the Stroop effect), thereby providing a window into age-related differences in the experience-guided shifting of control settings. Given that it is the experience with PC that is assumed to stimulate adoption of an initial control setting within a list and be responsible for any shifts in control that occur when PC changes during the list, the prediction is that older adults will flexibly shift control as well as younger adults.

Experiment 1

We used an abbreviated lists paradigm comprising many short lists of Stroop color-naming trials with participant-paced breaks between lists (cf. precued lists paradigm; Bugg & Diede, 2017; Bugg et al., 2015). This paradigm affords many more observations per condition than if the PC manipulation was administered within a single, lengthy list of trials (that results in one estimate of performance per participant for each PC level). In Experiment 1, each list comprised 18 trials. Critically, PC was manipulated selectively during the first six trials (*early segment* of the list). As illustrated in Figure 1, these six trials were 83% congruent (MC), 17% congruent (MI), or 50% congruent (PC50). Then, regardless of the composition of the early segment of the list, the middle segment (next six trials) and later segment (final six trials) were both 50% congruent. MC, MI, and PC50 lists were randomly intermixed throughout the experiment.[1]

[1] This paradigm assumes that control settings reset or refresh between lists. The fact that prior studies (Bugg & Diede, 2017; Bugg et al., 2015) have found list-wide PC effects when comparing MC, MI, and PC50 lists in this paradigm supports this assumption. That is, because lists are randomly intermixed, for any given list, the overall PC averaged across all preceding lists is ~50%. Thus, if attention was not reset and was instead based on experience across prior lists, there should be approximately equivalent Stroop effects for all list types (i.e., no list-wide PC effect). To foreshadow the current results, we again found that the PC of the current list (here, manipulated only within first six trials) affected performance such that the Stroop effect varied as a function of PC, supporting this assumption. We sought converging evidence for this assumption by examining potential effects of the PC of just the immediately preceding list on performance of the earliest segment of the current list, conditions that would presumably produce the most robust effects of previous list PC if such effects exist. We did not find any meaningful effects involving previous list PC (most importantly, no Previous List PC × Current List PC interaction, and no Previous List PC × Current List PC × Age interaction). Collectively, these analyses support our assumption.

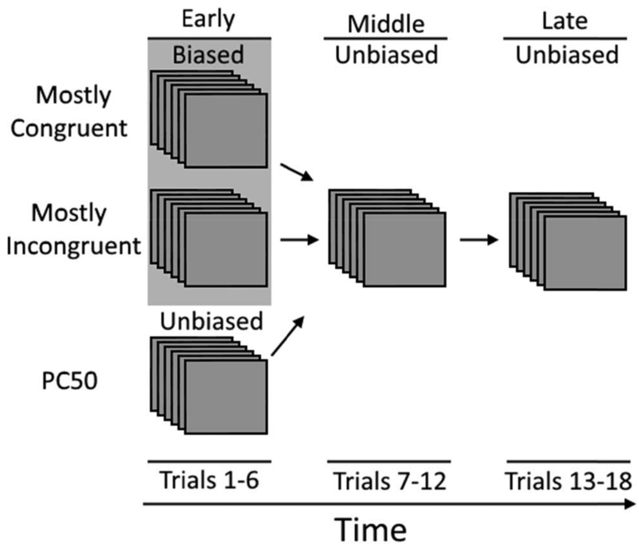

Figure 1. Schematic representation of the method for each 18-trial list in Experiment 1. The early (biased) portion of the list comprised six mostly congruent (MC), mostly incongruent (MI), or 50% congruent (PC50) trials. The middle and late portions were both unbiased, comprising six PC50 trials each.

There were two questions of interest. First, are younger and older adults equally able to establish an initial control setting based on the experience within the early segment of the list? If they are, then both age groups should show a PC effect in the early segment with the magnitude of the Stroop effect being largest for the MC condition (looser control setting resulting in greater word processing) and smallest for the MI condition (tighter control setting resulting in reduced word processing), with the 50% condition (intermediate) falling in the middle. Given that younger and older adults are sensitive to PC manipulations (Bugg, 2014a, 2014b; Mutter et al., 2005; West & Baylis, 1998), we predicted that both groups would establish PC-consistent control settings. However, this prediction was uncertain given that no prior study has examined whether either age group can establish control settings within just six trials. Prior evidence for congruency sequence effects in both age groups appears consistent with this prediction. A congruency sequence effect is the pattern whereby congruency effects are smaller after incongruent trials than after congruent trials (Gratton, Coles, & Donchin, 1992). There is evidence that this effect (under select conditions) reflects the tuning of cognitive control in response to conflict on a *single* trial (Botvinick, Braver, Barch, Carter, & Cohen, 2001; see Egner, 2017, for a review), and additionally there is evidence of age-invariance in congruency sequence effects in the Stroop task (Puccioni & Vallesi, 2012; West & Moore, 2005) or stronger congruency sequence effects for older adults (Aschenbrenner & Balota, 2015). Accordingly, one might anticipate that both age groups can tune control in response to accumulated conflict (PC) across six trials. However, this rests on the assumption that the PC effect is simply an extension of congruency sequence effects, and there is evidence dissociating these two effects (Funes, Lupiáñez, & Humphreys, 2010; Meier & Kane, 2013; Torres-Quesada, Funes, & Lupiáñez, 2013).

The primary question of interest concerned the effects of changing experience within the list, that is, the onset of PC50 trials across the middle to late portions of the MC and MI lists. If younger and older adults flexibly shift control settings based on changes in experience (e.g., statistical input from the environment, here, in the form of the PC change), this should manifest as a reduction in the Stroop effect from the early to the middle segment for MC lists, and an increase in the Stroop effect from the early to the middle segment for MI lists. In other words, there should be differing patterns of Stroop effects across the course of the list depending on the initial PC. Inclusion of the late PC50 segment of the list will enable us to address the question of whether younger and older adults are able to shift control equally rapidly. The hypothesized age-equivalence in these processes is supported by prior literature demonstrating potential benefits of attending to and implicitly learning from nominally *irrelevant* information (e.g., Amer et al., 2016; Campbell et al., 2012). Perhaps most relevant is the evidence for age-equivalence in "habitual attention." Younger and older adults learned which nominally *irrelevant* quadrant of a screen had a higher probability of target occurrence in a search task, thereby facilitating attention to targets (Jiang et al., 2016). In the current paradigm, the learning and updating of PC as a list unfolds is similarly dependent on attention to an *irrelevant* feature, here the to-be-ignored word that is probabilistically related to congruency. For example, in the early segment of an MC list, the words are highly predictive of congruent colors, but in the middle and late (50% congruent) portions the words become less predictive of congruency. If attention does not at least partially bleed over into the processing of the irrelevant word, then learning/updating of PC cannot occur and control settings will not shift from the early to late segment. Finding that older adults are able to shift control similarly to younger adults with experience as the guide may suggest that the concept of habitual attention extends to attention control and shifting in a conflict task, and additionally support prior observations demonstrating older adults' tendency to offload cognitive control to the environment (e.g., Mayr et al., 2015; Spieler et al., 2006).

The alternative prediction is that relative to younger adults, older adults may show a decreased ability to shift cognitive control settings once biased by early list experience, even though the PC manipulation minimizes any need for internally-mediated shifting of control. This would manifest as an initial modulation of Stroop effects within the early segment of the list, but then strong persistence of those control settings into the middle and later list. This would converge with prior findings in showing an age-related deficit in flexibility (e.g., increased perseverative tendencies), and counter the view that flexibility may be intact for older adults when it is driven by experience.

Method

Participants. The participants were 31 younger adults and 31 older adults. Younger adults (ages 18–25) were recruited from the Washington University undergraduate participant pool and offered course credit or $10 per hour.[2] Older adults (ages 66–94, M_{age} = 74.70; M_{health} = 3.82, on a 5-point scale ranging from 1 = *poor* to 5 = *excellent*; $M_{\text{education}}$ = 14.83 years; $M_{\text{vocabulary}}$ = 27.72 on the

[2] Unfortunately, we did not collect demographic information for the younger adults in Experiment 1. The participants were drawn from the same pool as Experiment 2, and likely have the same characteristics.

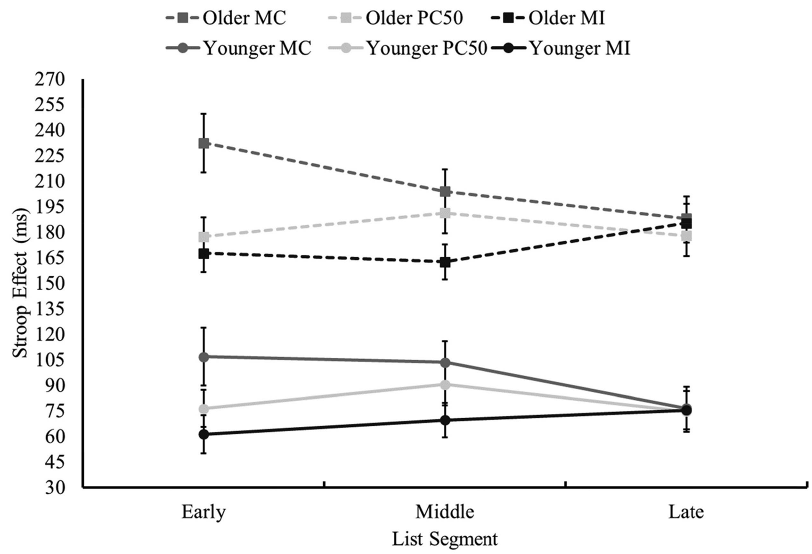

Figure 2. Change in the Stroop effect across list segments in Experiment 1. The early list segment was mostly congruent (MC), unbiased (PC50), or mostly incongruent (MI) whereas the middle and late list segments were always PC50. Error bars represent *SEM*s.

Shipley vocabulary scale, Shipley, 1946)[3] were community-dwelling volunteers from the Aging and Development participant pool and paid $10 per hour. All participants were native English speakers with normal or corrected vision and color vision. One younger adult was excluded from analyses for having an error rate above 50% on incongruent trials, and two older adults were excluded, one for failing to complete the experiment and one for having a mean response time (RT) of more than 3 SDs from the overall sample mean. Therefore, 30 younger and 29 older adults were included in final analyses.

Design and materials. A 2 (congruency: congruent vs. incongruent) × 3 (list segment: early [Trials 1–6], middle [Trials 7–12], or late [Trials 13–18]) × 3 (PC [bias in the first 6 trials]: PC50, MC, or MI) × 2 (age group [younger vs. older]) mixed design was used. Age was the only between-subjects factor. Each participant received 30 lists: 10 of each of the possible early list segment biases (MC, MI, or PC50).

Within each list, congruent trials consisted of the colors red, blue, green, and yellow displayed in colors corresponding to their identity. Incongruent trials consisted of the same colors presented in one of the incongruent options. As shown in Figure 1, in the early list segment, the MC condition was 83% congruent (i.e., 5 out of 6 trials were congruent), the MI condition was 17% congruent, and the PC50 condition was 50% congruent. Regardless of the PC of the early list segment, the middle and late list segments in each list were 50% congruent. This resulted in ~61% PC overall for MC lists and ~39% PC overall for MI lists. The computer program selected trials randomly without replacement in accordance with the PC of each segment of the list. The three list types were randomly intermixed, and RT and error rate were recorded. The methods and all materials were approved by the Washington University Institutional Review Board.

Procedure. Participants were given color-naming task instructions (name aloud the color as quickly as possible while maintaining a high level of accuracy) and performed eight practice trials. In the experimental phase, each list of trials was preceded by a 3-s screen indicating the next list was about to begin, and another screen indicating they could hit a key when they were ready to move on. Each trial began with a 1,000-ms gray screen, followed by the stimulus on a gray background until the voice key detected a response. The experimenter coded the response, and the next trial began. Trials on which the voice key was triggered by irrelevant speech (e.g., "um") or extraneous noise (e.g., cough), or on which the speech was imperceptible or unintelligible, were coded as scratch trials and excluded.

Results

Trials <200 ms or >3,000 ms were trimmed, excluding 1.0% of trials (as in Bugg et al., 2015). Scratch trials were also removed from analysis, eliminating 2.8% of trials. Overall, error rates were low ($M = 1.6\%$, $SD = 2.6$) and analyses of error rate did not contradict the RT results. We also examined *z* scored RT to control for spurious age-related differences because of general slowing (see Faust, Balota, Spieler, & Ferraro, 1999), and all critical analyses were consistent with raw RT. Therefore, for brevity, error rate and *z* score analyses are not reported (see Tables 1 and 2 for mean RTs and error rates). The mean *Stroop effect* (incongruent RT–congruent RT) was calculated for each list segment in each PC condition. We use the term "PC effect" to refer to the difference in the Stroop effect between conditions (e.g., MC vs. MI). In both Experiments 1 and 2, a *p* value of .05 was used for all inferences. Because of the complex nature of the design and analyses, only theoretically relevant analysis of variance (ANOVA) results are reported below; for full analyses see Table 3.

For theoretically critical effects that did not reach significance, Bayes factors were calculated (using JASP Version 0.8.2.0; see

[3] There was some missing data for participants in both experiments because of incomplete forms or illegible writing.

Table 1
Experiment 1 Reaction Times Across List Segments for Each PC and Congruency in Younger and Older Adults

PC	Age group	Early[a]		Middle[b]		Late[b]	
		Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
MC							
	Younger	573 (50)	680 (90)	578 (64)	681 (85)	591 (62)	668 (70)
	Older	663 (85)	896 (143)	677 (101)	881 (133)	693 (109)	881 (138)
PC50							
	Younger	582 (49)	658 (77)	582 (54)	673 (77)	594 (66)	668 (77)
	Older	685 (102)	862 (123)	690 (107)	881 (139)	694 (104)	872 (141)
MI							
	Younger	597 (67)	658 (68)	588 (60)	658 (63)	586 (57)	661 (66)
	Older	697 (117)	865 (129)	705 (111)	867 (140)	697 (113)	882 (157)

Note. PC = proportion congruency; MC = mostly congruent; MI = mostly incongruent. Mean outside parentheses, *SD*s within.
[a] All trials were biased, except during PC50 lists. [b] All trials were unbiased.

Wagenmakers, Morey, & Lee, 2016, for more detail on Bayesian statistics) to assess the amount of evidence in favor of a prior null distribution with an r scale for fixed effects set to 0.5. Bayes factor inclusion ($BF_{\text{inclusion}}$) was then used for interpretation. The $BF_{\text{inclusion}}$ measures the change from the summed prior probability of including a factor across all possible models to the posterior probability of including the factor across all possible models. A $BF_{\text{inclusion}} > 1$ indicates stronger evidence in favor of including the factor in an explanatory model, while a $BF_{\text{inclusion}} <$ 1 indicates stronger evidence in favor of excluding the factor. For example, a $BF_{\text{inclusion}}$ of 2 would indicate that the given factor predicted the data two times better than predicted by the prior. Inversely, a $BF_{\text{inclusion}}$ of 0.5 would indicate that the prior model predicted the data two times better than the given factor. A $BF_{\text{inclusion}}$ of 1 would indicate equivocal evidence for both models.

Early list acquisition. A 3 (PC: MC, PC50, MI) × 2 (age group: younger, older) mixed-design ANOVA was conducted on the Stroop effects from the early list segment. This analysis showed that differential control settings were acquired within just six trials. Furthermore, this early acquisition did not differ by age group (see Figure 2). Supporting these conclusions, there was a significant main effect of PC, $F(2, 114) = 15.88$, $MSE = 3109$, $p < .001$, $\eta_p^2 = .218$; the Stroop effect was larger during the early MC segment ($M = 170$ ms) than the early PC50 segment ($M =$ 127 ms), $t(58) = 3.99$, $p < .001$, $d = .519$, 95% confidence interval (CI) of the difference between MC and MI [21.19, 63.86], or early MI segment ($M = 114$ ms), $t(58) = 4.76$, $p < .001$, $d =$ .619, 95% CI [31.85, 78.13]. The Stroop effect during the early PC50 segment had an intermediate size, being nonsignificantly larger than when the early list segment was MI, $t(58) = 1.51$, $p =$ .14, $d = .197$, 95% CI [−4.03, 28.95]. Critically, the PC effect did not differ between younger and older adults, $F < 1$, $BF_{\text{inclusion}} =$ 0.603. These patterns indicate that the predicted control settings were acquired by younger and older adults.

Converging with the above patterns demonstrating age-equivalence, the number of participants demonstrating a positive PC effect in the early segment (larger Stroop effect in the early MC list than early MI list) did not differ between age groups, $\chi^2(1, N = 59) = 1.33$, $p = .249$, Cramer's $V = .150$. Twenty-one (70%) younger adults and 24 (83%) older adults showed a positive PC effect.

Experience-guided shifting of control. Trend analyses were conducted to track the Stroop effect across each list segment using a 3 (PC: MC, PC50, MI) × 3 (list segment: early, middle, late) × 2 (age group: younger, older) mixed-design ANOVA. The Stroop effect had the potential to either increase or decrease (linear trends) across the list segments (indicative of experience-guided shifting of control settings), or to hold constant (the lack of a linear trend; indicative of the maintenance [perseveration] of a control setting) as the PC changed from the early segment of the list to the middle and late list segments.

These analyses suggested that shifting of control settings occurred rapidly and was age-invariant, as can be seen by the different linear trends for each PC in Figure 2, $F(1, 57) = 14.84$, $MSE = 2804$, $p < .001$, $\eta_p^2 = .207$, a pattern that was similar across age groups, $F < 1$, $BF_{\text{inclusion}} = 0.002$. Following an early MC segment, the Stroop effect decreased linearly, $F(1, 57) =$ 10.48, $MSE = 3913$, $p = .002$, $\eta_p^2 = .155$, from 170 to 154 ms during the middle list segment to 132 ms during the late list segment, suggesting control was heightened as participants began to experience more incongruent trials. The opposite pattern was observed following an early MI segment. A linear *increase* in the Stroop effect was found, $F(1, 57) = 1.23$, $MSE = 1568$, $p = .034$, $\eta_p^2 = .077$, as it climbed from 114 ms to 116 ms during the middle list segment, ending at 130 ms during the late list segment, suggesting control was relaxed as participants began to experience more congruent trials (cf., Schlaghecken & Martini, 2012). Not surprisingly, the Stroop effect held constant following an early PC50 segment, $F < 1$, $BF_{\text{inclusion}} = 0.207$, while a quadratic trend was marginally significant, $F(1, 57) = 3.75$, $MSE = 2044$, $p =$ .058, $\eta_p^2 = .062$.[4] The Stroop effects for MC, PC50, and MI lists were equivalent by the late segment of the list, $F < 1$, $BF_{\text{inclusion}} =$ 0.048, with no PC by Age interaction, $F < 1$, $BF_{\text{inclusion}} = 0.025$.

Discussion

In Experiment 1, Stroop effects for the early list segment were significantly larger in MC than in MI lists with PC50 lists falling

[4] This reflected a small increase in the Stroop effect during the middle list segment; it changed from 127 ms (early) to 141 ms (middle) to 126 ms (late).

Table 2
Experiment 1 Error Rates Across List Segments for Each PC and Congruency in Younger and Older Adults

		Early[a]		Middle[b]		Late[b]	
PC	Age group	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
MC							
	Younger	.001 (.004)	.024 (.054)	.001 (.006)	.035 (.049)	.003 (.010)	.032 (.048)
	Older	.000 (.000)	.031 (.066)	.000 (.000)	.039 (.048)	.000 (.000)	.015 (.028)
PC50							
	Younger	.002 (.009)	.023 (.026)	.004 (.011)	.018 (.025)	.005 (.012)	.028 (.035)
	Older	.001 (.006)	.018 (.031)	.003 (.011)	.026 (.037)	.000 (.000)	.021 (.033)
MI							
	Younger	.000 (.000)	.017 (.022)	.002 (.009)	.017 (.019)	.003 (.010)	.021 (.034)
	Older	.003 (.019)	.017 (.025)	.002 (.009)	.022 (.033)	.001 (.006)	.044 (.056)

Note. PC = proportion congruency; MC = mostly congruent; MI = mostly incongruent. Means outside parentheses, *SD*s within.
[a] All trials were biased, except during PC50 lists. [b] All trials were unbiased.

in the middle. This demonstrates that younger and older adults initially acquired control settings corresponding to the PC of the list (e.g., looser [MC] or tighter [MI] control over word reading) based on just six trials of experience. Such rapid acquisition of experience-guided control settings (i.e., based on the learning of PC) has not been shown previously in either age group, and the current data suggest this ability is intact across the life span.

Most critically, younger and older adults showed flexible and equally rapid shifting of control settings, as indexed by changes in the Stroop effect from one segment of the list to another. Both age groups shifted from a setting that corresponded to the initial PC in the early segment to a more neutral setting in the middle and late segments, consistent with the PC50 in these segments. This was evidenced by decreasing linear trends in the Stroop effect in early MC lists and increasing linear trends in the early MI lists. In fact, the Stroop effect, which we interpret as a signature of control settings, was indistinguishable for all three list types by the late segment. The fact that Stroop effects did not differ by the late list segment suggests that participants shifted control settings based on more local experience within the list (e.g., the last 6 to 12 trials; cf. Aben, Verguts, & Van den Bussche, 2017; Jiménez & Méndez, 2013) rather than the overall PC of the entire list because the overall PC still differed at the end of the list (e.g., 39 vs. 61 vs. 50% congruent). Again, there was no evidence for age-related differences in these patterns; this suggests older adults can flexibly shift control settings as rapidly as younger adults when shifting is based on experience with varying trial types (frequencies of conflict) as the task dynamically unfolds.

Experiment 2

There were two primary aims in Experiment 2. First, given the significance of Experiment 1 in demonstrating novel evidence for experience-guided control with age, we sought to replicate the primary findings. Second, we aimed to examine how generalizable such experience-guided control may be for younger as compared with older adults. Before describing the theoretical significance of this question, we first describe the design changes.

Experiment 2 adopted the design of Experiment 1 with one major change in addition to eliminating the early PC 50 lists (see Figure 3). As in Experiment 1, a 4-item set of color-word stimuli established the PC of the early (MC or MI), middle (PC50), and late (PC50) list segments. In Experiment 2, we refer to these stimuli as "inducer items" to differentiate them from "transfer items," which represent the novel and critical component of Experiment 2. Transfer items appeared in each segment of the list and were comprised from a separate 2-item set of color-word stimuli (i.e., different colors/words so that these stimuli did not share features with the inducer items). The key defining characteristic of

Table 3
ANOVA Table for Experiment 1

Analysis	Effect	*F*	*df*	*MSE*	*p*	η_p^2
Early list acquisition						
	PC	15.88	(2, 114)	3109	<.001	.218
	Age group	50.74	(1, 57)	10735	<.001	.471
	PC × Age group	.79	(2, 114)	3109	.46	.014
Shifting of control						
	PC	21.46	(2, 114)	2121	<.001	.274
	Segment	1.51	(1, 57)	3150	.23	.026
	Age group	59.86	(1, 57)	24796	<.001	.512
	PC × Segment	14.84	(1, 57)	2804	<.001	.207
	PC × Age group	.73	(2, 114)	2121	.48	.013
	Segment × Age group	.06	(1, 57)	3150	.82	.001
	PC × Segment × Age group	.41	(1, 57)	2804	.53	.007

Note. PC = proportion congruence; ANOVA = analysis of variance.

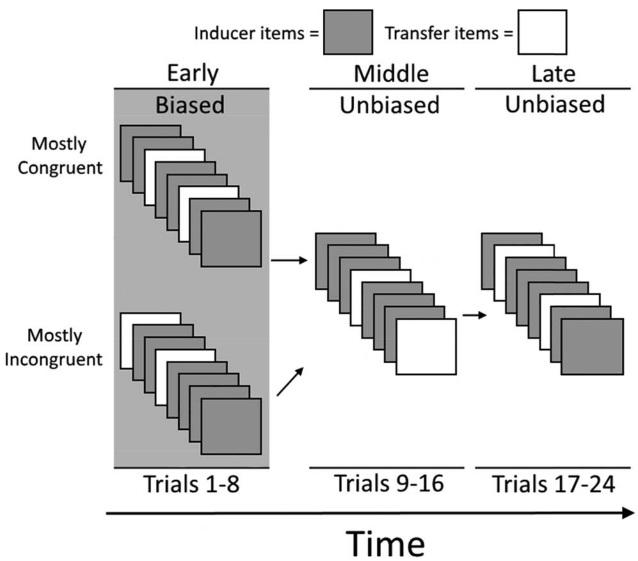

Figure 3. Schematic representation of the method for each 24-trial list in Experiment 2. The first eight trials included six mostly congruent (MC) or mostly incongruent (MI) inducer items and two 50% congruent (PC50) transfer items. The middle and late portions of the list included six PC50 inducer items and two PC50 transfer items. Transfer items could appear randomly during any trial within each list segment, with the limitation that only two transfer items could appear during any given list segment.

transfer items is that, unlike inducer items, they were always PC50 (i.e., unbiased) regardless of the segment.

Transfer items enabled us to evaluate the theoretical question of whether age-equivalence in the acquisition and shifting of control settings may be accomplished by a generalizable control mechanism (referred to hereafter as "global," meaning that it is operating based on the PC of the overall segment and not the PC of specific items), or, if such age-equivalence is limited to the operation of an item-specific mechanism (e.g., learning of stimulus-control or stimulus–response associations; cf. Blais & Bunge, 2010; Bugg, 2014a, 2014b; Bugg & Chanani, 2011; Bugg & Hutchison, 2013; Bugg, Jacoby, & Chanani, 2011; Bugg et al., 2008; Chiu, Jiang, & Egner, 2017). For instance, Experiment 1 findings may reflect age-equivalence in the rapid acquisition and updating of control settings associated with particular items based on how likely conflict is for a given item (e.g., learning stimulus-control associations for individual items such as the colors red, green, blue, and yellow and updating these associations as the item-specific input changes across the list; Bugg & Crump, 2012; Chiu et al., 2017; Crump & Milliken, 2009; cf. Bugg, 2014a). Or, the age-equivalence could reflect the learning of high contingency responses (e.g., saying "blue" to the word blue; Schmidt & Besner, 2008) and age-invariance in the updating of these item-specific contingencies as the list unfolds (cf. Bugg et al., 2008; Jiang et al., 2016). The age-equivalence is striking regardless, but it is theoretically important to disentangle the mechanisms, which Experiment 1 could not do (see also West & Baylis, 1998).

To the extent that shifts in control are global and generalize from biased, inducer items to unbiased, transfer items in the same segment, the prediction is that the signatures of control and flexibility observed in Experiment 1 (early acquisition of control settings followed by subsequent shifting) should be observed for inducer *and* transfer items in Experiment 2. For example, if the Stroop effect in the early segment is exaggerated when inducer items are MC compared with MI, then the Stroop effect in that segment should also be exaggerated for transfer items in MC compared with MI lists even though these transfer items are PC50 in each list. In contrast, to the extent that acquisition of control settings and shifts in control are mediated by an item-specific mechanism, signatures of control and flexibility should be evident for inducer items *but not* transfer items because the PC of transfer items is always 50% and never changes.

Method

Participants. A larger sample of 63 younger adults and 60 older adults participated as the effect on transfer items was expected to be smaller than inducer items (see Bugg, 2014b, for detection of a related but distinct transfer effect with $N = 36$). Participants were recruited using the same sources and met the same inclusion criteria as Experiment 1. Four older adults were excluded from analyses, 2 for having Stroop effects greater than 3 *SD* above the mean, 1 for having an error rate 3 *SD* above the mean, and 1 for not completing the task. Therefore, 63 younger adults (ages 18 to 23; $M_{\text{age}} = 19.75$, $M_{\text{health}} = 3.9$, $M_{\text{education}} = 14.50$, $M_{\text{vocabulary}} = 25.91$) and 56 older adults (ages 64 to 92; $M_{\text{age}} = 74.59$, $M_{\text{health}} = 3.8$, $M_{\text{education}} = 14.33$, $M_{\text{vocabulary}} = 28.67$) were included in final analyses.

Design and materials. Experiment 2 included only early list MC or MI conditions to maximize the number of observations in these conditions. We used a 2 (congruency: congruent vs. incongruent) × 3 (list segment: early [Trials 1–8], middle [Trials 9–16], and late [Trials 17–24]) × 2 (PC [bias in the early list segment]: MC vs. MI) × 2 (age group: younger vs. older) mixed design for the inducer items. The same design was used for the transfer items except PC refers to the global (segment) bias created by the early inducer trials, not the actual bias of the transfer items (that were always unbiased [PC50] regardless of segment). Each participant received 30 lists of 24 trials: 15 early MC lists and 15 early MI lists.

The 4-item set of inducer items consisted of the words and colors red, blue, white, and purple, and the 2-item set of transfer items consisted of the words and colors yellow and green. The computer program randomly selected without replacement six inducer items (according to the PCs specified above) and two transfer items (one congruent, one incongruent) for each early, middle, and late segment of the list.

In the early list segment, five out of six (MC lists) or one out of six (MI lists) inducer trials were congruent, respectively, resulting in 83% and 17% congruency for inducer items in the early list segment, as in Experiment 1 (see Figure 3). However, when considering both inducer and transfer items, the early list segment was 75% (MC) and 25% congruent (MI). Middle and late segments of each list (i.e., both inducer and transfer items in these segments) were 50% congruent. The overall list PCs (considering both inducer and transfer items in all segments) were ~58% congruent for MC and ~42% congruent for MI lists. The list types were randomly intermixed, and RT and accuracy were recorded for all trials.

Procedure. The procedure was identical to Experiment 1.

Results

As in Experiment 1, trials <200 and >3,000 ms were trimmed from analysis, excluding <1.0% of trials. Scratch trials were then removed from analysis, eliminating 2.4% of trials. Error rates were again low (M = 5.0%, SD = 3.4%) and neither error rate nor z score analyses contradicted RT results; for brevity, raw RT and error rate are reported in tables (see Tables 4 and 5 for mean RTs and error rates in all conditions). Again, only theoretically relevant ANOVA results are reported; for complete ANOVA results, see Table 6.

Early list acquisition.

Inducer items. First, Stroop effects for inducer items from the early list segment were analyzed using a 2 (PC: MC, MI) × 2 (age group: younger, older) mixed-design ANOVA. This analysis, like Experiment 1, showed that differential control settings were acquired with experience on just six inducer trials and this pattern did not differ by age group. Replicating Experiment 1, we found a significant main effect of PC, $F(1, 117) = 19.27$, $MSE = 2600$, $p < .001$, $\eta_p^2 = .141$. Shown in Panel A of Figure 4 on the left side, the Stroop effect was larger during early MC lists (M = 145, SD = 90) compared with early MI lists (M = 117, SD = 89), $t(118) = 4.44$, $p < .001$, $d = .386$, 95% CI [16.20, 42.29]. This PC effect did not differ between younger and older adults, $F < 1$, $BF_{\text{inclusion}} = 0.225$. Additionally, the number of participants demonstrating a positive PC effect (larger Stroop effect in the MC list than MI list) did not differ between age groups, $\chi^2(1, N = 118) = 2.34$, $p = .126$, Cramer's $V = .141$. Forty-three (68%) younger adults and 30 (55%) older adults showed a positive PC effect. Notably, however, these percentages were much lower than in Experiment 1, an issue which we revisit later in the Results section.

Transfer items.[5] Stroop effects for transfer items from the early list segment were analyzed using a 2 (PC) × 2 (age group) mixed-design ANOVA. This analysis demonstrated that even unbiased transfer items showed PC effects depending on the early inducer condition they appeared in. This observation was supported by the following statistics: the main effect of PC was again significant, $F(1, 117) = 11.67$, $MSE = 2751$, $p < .001$, $\eta_p^2 = .091$. As seen in Panel B of Figure 4, the Stroop effect was larger for transfer items in the early segment of MC lists (M = 142, SD = 111) compared with the early segment of MI lists (M = 119, SD = 106), $t(118) = 3.47$, $p = .001$, $d = .318$, 95% CI [10.09, 36.95], consistent with the global account. Despite a slightly different numerical trend for younger and older adults, the PC effect did not differ between the age groups, $F < 1$, $BF_{\text{inclusion}} = 0.096$, suggesting age-equivalence in the ability to acquire an initial, global control setting based on early list experience.

Experience-guided shifting of control.

Inducer items. Trend analyses were conducted on the Stroop effect for inducer items using a 2 (PC) × 3 (list segment) × 2 (age group) mixed-design ANOVA. This analysis demonstrated that Stroop effect trends differed depending on the bias in the early list segment, and this effect did differ by age, with older adults, but not younger adults, showing a PC effect in the late list segment. The critical pattern of interest is seen in Panel A of Figure 4. When the early list segment was MC, the mean Stroop effect was 149 ms during the early list segment and 148 ms during the middle list segment, dropping to 131 ms during the late list segment. When the early list segment was MI, the mean Stroop effect was 119 ms during the early list segment, 115 ms during the middle list segment, and 120 ms in the late list segment. The analysis indicated that the change in the Stroop effect across list segments differed depending on early list condition as indicated by significant linear, $F(1, 117) = 5.32$, $MSE = 1792$, $p = .023$, $\eta_p^2 = .044$, and quadratic, $F(1, 117) = 4.05$, $MSE = 1502$, $p = .047$, $\eta_p^2 = .033$, trends. The linear trend interacted marginally with age $F(1, 117) = 3.13$, $MSE = 1792$, $p = .079$, $\eta_p^2 = .026$, but the quadratic trend did not, $F < 1$, $BF_{\text{inclusion}} = 0.206$. The PC effect was still detectable in the late list segment, $F(1, 117) = 7.91$, $MSE = 465$, $p = .006$, $\eta_p^2 = .063$, and differed by age, $F(1, 117) = 7.44$, $MSE = 465$, $p = .007$, $\eta_p^2 = .060$. This was because of a 22-ms PC effect in older adults, compared with a 1-ms PC effect in younger adults.

Transfer items. Trend analyses were next conducted on the Stroop effect for transfer items using a 2 (PC) × 3 (list segment) × 2 (age group) mixed-design ANOVA. Like the inducer items, Stroop effect trends differed depending on the bias in the early list segment, and this differed by age group. Shown in Panel B of Figure 4, the Stroop effect changed linearly, $F(1, 117) = 4.16$, $MSE = 3666$, $p = .044$, $\eta_p^2 = .034$, and quadratically, $F(1, 117) = 4.76$, $MSE = 2273$, $p = .031$, $\eta_p^2 = .039$, across lists differentially depending on early list PC, which interacted with age group, $F(1, 117) = 4.20$, $MSE = 2273$, $p = .043$, $\eta_p^2 = .035$. In younger adults, no difference was found between early list PC conditions either linearly, $F(1, 62) = 2.03$, $MSE = 2201$, $p = .159$, $\eta_p^2 = .032$, or quadratically, $F < 1$. In older adults, a quadratic effect modulated by early list PC was found, $F(1, 55) = 8.51$, $MSE = 2260$, $p = .005$, $\eta_p^2 = .134$. On early MC lists, the Stroop effect declined linearly from 206 to 178 to 152 ms. On early MI lists, the Stroop effect dropped from 187 ms during the early list segment to 142 ms during the middle list segment before rising to 162 ms during the late list segment.

Experience-guided shifting of control in participants who displayed an early list PC effect. The trend analyses for inducer items revealed several departures from Experiment 1. Most notably, the shift in the MC list took longer to develop with the reduction in the Stroop effect not appearing until the late list segment, and there was little modulation of the Stroop effect in lists that were initially MI (i.e., Stroop effect did not increase from early to later segments). While there was not an age difference in these shifting patterns (consistent with Experiment 1) and they might simply be attributable to the larger number of stimuli (color-word combinations) to be learned in Experiment 2, the patterns muddy interpretation of changes in transfer trial performance across list segments. A major concern is that, relative to Experiment 1, there was a substantial reduction in the percentage of participants who showed a positive PC effect (defined as any participant with a PC effect [MC Stroop effect—MI Stroop effect] greater than zero) for inducer items in the early segment (indicative of initial acquisition of control settings in the early MC and MI segments). Forty-three (63%) younger adults and 30 (54%) older adults showed a positive PC effect, compared with 70 and 83%, respectively, in Experiment 1. While this reduction is consistent

[5] Transfer items, for which there were far fewer observations than inducer items, were analyzed separately from inducer items following previous studies (Bugg, 2014a, 2014b; Bugg & Chanani, 2011; Bugg & Hutchison, 2013; Bugg, Jacoby, & Chanani, 2011; Funes et al., 2010; Gonthier et al., 2016; Hutchison, Bugg, Lim, & Olsen, 2016; Torres-Quesada et al., 2013).

Table 4
Experiment 2 Reaction Times Across List Segments for Each PC, Congruency, and Item Set in Younger and Older Adults

			Early[a]		Middle[b]		Late[b]	
PC	Age group	Item Set	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
MC								
	Younger							
		Inducer	600 (86)	705 (100)	598 (88)	701 (98)	618 (91)	707 (98)
		Transfer	612 (100)	697 (109)	619 (100)	697 (99)	630 (104)	703 (106)
	Older							
		Inducer	726 (101)	918 (151)	731 (95)	923 (159)	744 (101)	918 (153)
		Transfer	757 (110)	963 (177)	760 (104)	939 (180)	783 (113)	934 (187)
MI								
	Younger							
		Inducer	615 (94)	688 (94)	615 (92)	695 (95)	613 (88)	701 (99)
		Transfer	634 (102)	691 (95)	627 (101)	685 (108)	632 (93)	694 (92)
	Older							
		Inducer	737 (103)	903 (142)	741 (96)	891 (132)	743 (100)	895 (138)
		Transfer	767 (111)	955 (174)	777 (130)	918 (160)	773 (131)	935 (168)

Note. PC = proportion congruency; MC = mostly congruent; MI = mostly incongruent. Mean outside parentheses, *SD*s within.
[a] Inducer item set was biased. [b] Inducer item set became unbiased.

with the subtler difference between PCs of the early segments in Experiment 2 because of inclusion of PC50 transfer items (e.g., PCs of 75 and 25% in Experiment 2, compared with 83 and 17% in Experiment 1), it limits comparisons to Experiment 1 and more importantly, it limits conclusions that can be drawn about the shifting of control in Experiment 2. That is, if a participant did not initially establish a control setting in the early portion of the list based on the inducer items, then it is implausible to expect a shift (or measure a shift) in control that aligns with the change in experience in the middle segment. Thus, we reanalyzed the critical patterns for both inducer and transfer items considering only participants who showed a positive PC effect in the early list segment.[6] Although this cutoff included some participants with a very small PC effect (range: 0.01 to 245 ms), the majority of participants showed a robust early PC effect: $M = 73$ ms, $Mdn = 70$ ms, 10th percentile = 17 ms, and 25th percentile = 28 ms.[7]

Inducer items. For inducer items, shown in Figure 5 Panel A, Stroop effects differed depending on early list condition and this did not interact with age. These observations were supported by a significant overall linear trend, $F(1, 71) = 4.72$, $MSE = 1339$, $p = .033$, $\eta_p^2 = .062$, which was modulated by early list PC, $F(1, 71) = 79.24$, $MSE = 982$, $p < .001$, $\eta_p^2 = .527$. On early MC lists, the Stroop effect decreased linearly from 171 to 148 to 128 ms by the late list segment. On early MI lists, the Stroop effect increased from 95 to 115 ms, ending at 119 ms during the late list segment. There was no three-way interaction with age, $F < 1$, $BF_{inclusion} = 0.405$. A small but nonsignificant overall PC effect ($M = 9$ ms) was still present in the late list segment, $F(1, 71) = 2.91$, $MSE = 441$, $p = .093$, $\eta_p^2 = .039$. Although there appears to be a numerical trend for a remaining PC effect in that segment for older adults but not younger adults (see Figure 5, Panel A), PC did not significantly interact with age, $F(1, 71) = 1.82$, $MSE = 441$, $p = .181$, $\eta_p^2 = .025$, $BF_{inclusion} = 0.124$.

Transfer items. For transfer items, shown in Figure 5, Panel B, Stroop effects also differed depending on early list condition, and again there was no interaction with age. Overall linear, $F(1, 71) = 9.38$, $MSE = 3165$, $p = .003$, $\eta_p^2 = .117$, and quadratic trends were found, $F(1, 71) = 6.78$, $MSE = 2278$, $p = .011$, $\eta_p^2 = .087$, that were modulated by early list PC, $F(1, 71) = 4.83$, $MSE = 2278$, $p = .031$, $\eta_p^2 = .064$. In early MC lists, the Stroop effect dropped from 148 ms in the early segment to 114 and 115 ms during the middle and late segments. In early MI lists, the Stroop effect dropped from 119 to 96 ms before increasing again to 116 ms. Despite numerical trends again suggesting slightly different patterns for younger and older adults (see Figure 5, Panel B), there was no three-way interaction with age, $F < 1$, $BF_{inclusion} = 0.110$. Furthermore, the PC effect was not significant in the late list segment, $F < 1$, $BF_{inclusion} = 0.099$, and this did not interact with age, $F(1, 71) = 2.80$, $MSE = 1533$, $p = .098$, $\eta_p^2 = .038$, $BF_{inclusion} = 0.045$.

Discussion

Experiment 2 replicated the key phenomena observed in Experiment 1. We now have evidence from two studies that younger and older participants can acquire experience-guided control settings based on just six inducer (biased) trials. This points to a rapid and flexible heightening of control in response to MI experience but a loosening of control in response to MC experience in the beginning of the list. Remarkably, this process appears to be age-invariant.

Additionally, when limiting the analysis to participants who initially acquired the relevant control settings in the early MC

[6] We also examined whether various participant characteristics were associated with showing an early list PC effect. We did not find associations between PC effect status and overall Stroop effect, overall accuracy in the task, or Shipley vocabulary score, nor did we find associations with self-reported variables including number of prescription medicines and general health. Advanced age was not associated with PC effect status either; participants over versus under 75 years old were similarly likely to display an early PC effect.

[7] This may raise the question as to whether Experiment 1 results would differ if shifting was examined selectively for participants who showed a positive PC effect during early list segments. We re-ran the analyses in Experiment 1 and the conclusions were identical. Again, the cutoff did include some participants with a very small PC effect (range: 2 to 354 ms), but the majority of participants showed a robust early PC effect: $M = 87$ ms, $Mdn = 65$ ms, 10th percentile = 18 ms, and 25th percentile = 41 ms.

Table 5
Experiment 2 Error Rates Across List Segments for Each PC, Congruency, and Item Set in Younger and Older Adults

PC	Age group	Item Set	Early[a] Congruent	Early[a] Incongruent	Middle[b] Congruent	Middle[b] Incongruent	Late[b] Congruent	Late[b] Incongruent
MC								
	Younger							
		Inducer	.025 (.027)	.058 (.068)	.019 (.027)	.049 (.044)	.022 (.026)	.043 (.040)
		Transfer	.039 (.064)	.065 (.065)	.054 (.069)	.068 (.081)	.049 (.073)	.051 (.066)
	Older							
		Inducer	.044 (.049)	.102 (.106)	.026 (.039)	.071 (.070)	.037 (.047)	.066 (.052)
		Transfer	.051 (.072)	.087 (.102)	.028 (.065)	.045 (.048)	.045 (.066)	.069 (.099)
MI								
	Younger							
		Inducer	.017 (.038)	.040 (.034)	.025 (.034)	.046 (.039)	.026 (.026)	.047 (.043)
		Transfer	.048 (.059)	.066 (.080)	.050 (.089)	.058 (.067)	.044 (.063)	.069 (.084)
	Older							
		Inducer	.040 (.061)	.081 (.065)	.031 (.048)	.067 (.063)	.037 (.050)	.062 (.058)
		Transfer	.055 (.073)	.069 (.084)	.049 (.065)	.063 (.077)	.052 (.073)	.065 (.067)

Note. PC = proportion congruency; MC = mostly congruent; MI = mostly incongruent. Mean outside parentheses, *SD*s within.
[a] Inducer item set was biased. [b] Inducer item set became unbiased.

and early MI segments of each list (thereby enabling interpretation of any subsequent shifts in control), we replicated the finding that younger and older adults show flexible shifting of control settings for inducer items, as indexed by changes in the Stroop effect from one segment of the list to the next. The Stroop effect decreased from the early to later list segments in MC lists but increased in MI lists for both younger and older adults, as in Experiment 1.

The novel component of Experiment 2 was inclusion of the transfer trials, which uniquely indexed whether the experience-guided control settings generalized from inducer items to novel, unbiased (PC50) items. Consistent with a globally operating control mechanism based on recently accumulated experience (but not an item-specific mechanism), one key finding was that the control settings acquired via brief experience with inducer items in the early segment generalized to the transfer items for younger and older adults. The Stroop effect was larger for transfer items embedded in an early MC list segment than an early MI list segment. Also, consistent with a global account, a second key finding was that for early MC lists, shifts in control brought about by changing experience on inducer items from the early to middle and late list segments generalized to transfer items—Stroop effects for transfer items decreased from the early segment of the list to the middle list segment. In contrast, however, for early MI lists, shifts in control did not appear to generalize to transfer items—unlike inducer items, Stroop effects for transfer items did not increase from the early to later list segments but instead *decreased* in the middle segment before returning to the magnitude of the early list segment. An interesting finding was that this was true for both younger and older adults as there was no age interaction in the analysis of shifting. We will consider this finding further in the General Discussion.

General Discussion

We set out to examine acquisition and flexible shifting of control settings in younger and older adults when these settings are guided by experience using a modified Stroop paradigm. The primary conclusion that can be drawn from the current experiments is that, consistent with our hypothesis, there is age-equivalence in the initial acquisition of control and the flexible shifting of control settings in response to changing experience (here, in the form of changing PC for inducer items). It is notable that in addition to the age effects being nonsignificant in the traditional ANOVA, Bayesian analyses also consistently indicated evidence in favor of the null hypothesis. At a general level, the current experiments support and extend prior research demonstrating older adults' sensitivity to nominally irrelevant information in the environment (here, learning of PC; cf. Amer et al., 2016) and the potential benefits of outsourcing control to the environment (Lindenberger & Mayr, 2014).

A second conclusion that can be drawn pertains to the theoretical mechanisms supporting age-equivalence in the acquisition and flexible shifting of control settings. Although it was not possible to determine if a global or item-specific mechanism best explained the age-equivalence in Experiment 1, the inclusion of transfer items in Experiment 2 enabled us to draw more precise conclusions. The transfer items demonstrated two signatures of control. This included the acquisition of control settings in the early segment of the list (as indicated by larger Stroop effects for transfer items in the MC compared with MI list segment) and the flexible shifting of control across the MC list for transfer items. These signatures allow us to conclude that a global control mechanism contributes to the acquisition and flexible shifting of control rather than being driven solely by item-specific control or item-specific contingency learning. More importantly, this conclusion applies to younger and older adults, as there were no age interactions in these patterns, and the Bayesian analyses again showed support for the null hypothesis. These findings suggest that the view that aging is associated with deficits in control and inflexibility may be selective to paradigms that require shifting via self-initiated, internally-driven processing. Next, we discuss the implications of our results for theoretical accounts of age-related differences in cognitive control, as well as some caveats and limitations of the current study.

Table 6
ANOVA Table for Experiment 2

Analysis	Item set	Effect	Trend	*F*	*df*	*MSE*	*p*	η_p^2
Early list acquisition								
	Inducer items	PC		19.27	(1, 117)	2600	<.001	.141
		Age group		51.14	(1, 117)	9447	<.001	.304
		PC × Age group		.20	(1, 117)	2600	.66	.002
	Transfer items							
		PC		11.67	(1, 117)	2751	.001	.091
		Age group		72.48	(1, 117)	12962	<.001	.383
		PC × Age group		.40	(1, 117)	2751	.53	.003
Shifting of control								
	Inducer items							
		PC		63.68	(1, 117)	1640	<.001	.352
		Age group		51.53	(1, 117)	22982	<.001	.306
		PC × Age group		3.70	(1, 117)	1792	.06	.031
		Segment	Linear	5.72	(1, 117)	1369	.02	.047
			Quadratic	.15	(1, 117)	1424	.70	.001
		PC × Segment	Linear	5.32	(1, 117)	1792	.02	.044
			Quadratic	4.05	(1, 117)	1502	.05	.033
		Segment × Age group	Linear	4.92	(1, 117)	1369	.03	.040
			Quadratic	.32	(1, 117)	1424	.57	.003
		PC × Segment × Age group	Linear	3.13	(1, 117)	1792	.08	.026
			Quadratic	.88	(1, 117)	1502	.35	.007
	Transfer items							
		PC		14.04	(1, 117)	3853	<.001	.107
		Age group		53.07	(1, 117)	35058	<.001	.312
		PC × Age group		.19	(1, 117)	3853	.66	.002
		Segment	Linear	14.17	(1, 117)	3954	<.001	.108
			Quadratic	3.08	(1, 117)	4206	.082	.026
		PC × Segment	Linear	4.16	(1, 117)	3666	.04	.034
			Quadratic	4.76	(1, 117)	2273	.03	.039
		Segment × Age group	Linear	10.14	(1, 117)	3954	.002	.080
			Quadratic	2.30	(1, 117)	4206	.13	.019
		PC × Segment × Age group	Linear	.28	(1, 117)	3666	.60	.002
			Quadratic	4.20	(1, 117)	2273	.04	.035
Shifting of control for participants with an early list PC effect								
	Inducer items							
		PC		157.30	(1, 71)	1021	<.001	.689
		Age group		33.54	(1, 71)	15979	<.001	.321
		PC × Age group		11.86	(1, 71)	1021	.001	.143
		Segment	Linear	4.72	(1, 71)	1339	.03	.062
			Quadratic	.83	(1, 71)	1497	.37	.011
		PC × Segment	Linear	79.24	(1, 71)	982	<.001	.527
			Quadratic	1.35	(1, 71)	1207	.25	.019
		Segment × Age group	Linear	3.83	(1, 71)	1339	.05	.051
			Quadratic	.02	(1, 71)	1497	.88	<.001
		PC × Segment × Age group	Linear	.51	(1, 71)	982	.48	.007
			Quadratic	.28	(1, 71)	1207	.60	.004
	Transfer items							
		PC		8.93	(1, 71)	2765	.004	.112
		Age group		31.66	(1, 71)	28358	<.001	.308
		PC × Age group		1.96	(1, 71)	2765	.17	.027
		Segment	Linear	9.38	(1, 71)	2542	.00	.117
			Quadratic	6.78	(1, 71)	5139	.01	.087
		PC × Segment	Linear	4.83	(1, 71)	3165	.03	.064
			Quadratic	.25	(1, 71)	2278	.62	.004
		Segment × Age group	Linear	7.26	(1, 71)	2542	.01	.093
			Quadratic	1.56	(1, 71)	5139	.22	.021
		PC × Segment × Age group	Linear	.46	(1, 71)	3165	.50	.006
			Quadratic	1.43	(1, 71)	2278	.24	.020

Note. PC = proportion congruence.

Relation to Theories of Age-Related Differences in Cognitive Control

The general notion that age-related differences in cognitive control may involve specific patterns of sparing and deficits rather than widespread deficiencies is consistent with recent theorizing and empirical evidence. The pattern we observed herein of intact control in older adults when it is acquired and shifted on the basis of experience is consistent with a number of trends and theories in cognitive aging, including intact implicit or incidental learning (e.g., Campbell et al., 2012). Our findings show that older adults

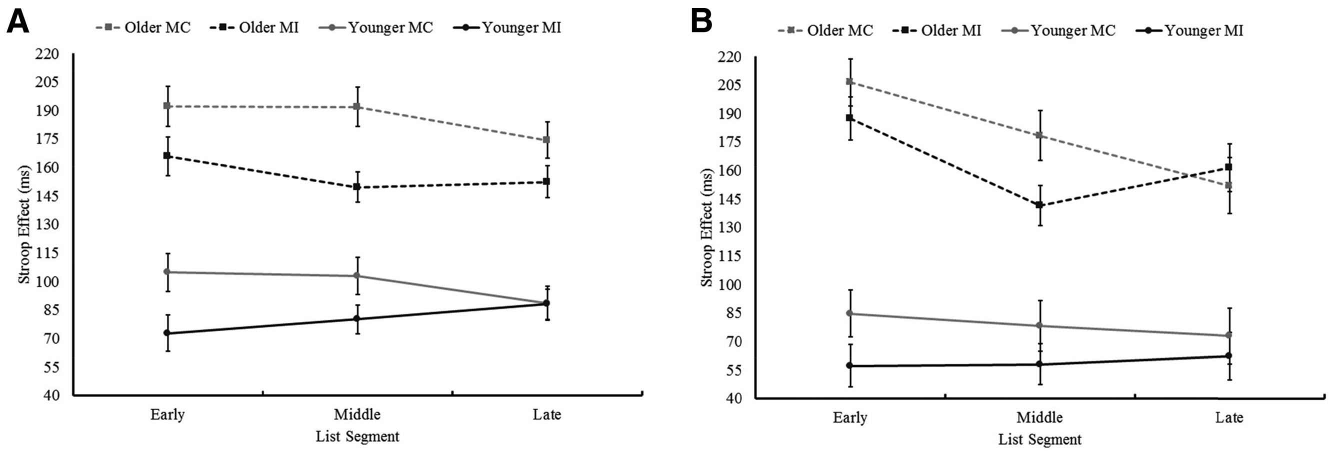

Figure 4. Results for Experiment 2 for (A) inducer items and (B) transfer items with mostly congruent (MC) and mostly incongruent (MI) early list bias in inducer items. Error bars represent *SEM*s.

were able to extract information about PC, which is based on learning the probability that the irrelevant word coincides with the stimulus color, and used this information to efficiently set and shift control settings, including those that were global. These findings further demonstrate potential benefits of attending to and learning from nominally irrelevant information (e.g., Amer et al., 2016; Campbell et al., 2012). They also extend prior findings of age-invariance in habitual attention in a probabilistic visual search task (Jiang et al., 2016) to the learning of an attentional bias (i.e., acquisition of a control setting) in a conflict resolution task. We are reluctant to refer to the present findings as habitual attention, however, because we additionally found that younger and older adults were able to shift control settings with changing experience across the list (i.e., based on implicitly updating PC). In contrast, in the study of Jiang et al. (2016), the initial attentional bias of attending to the quadrant in which targets were more likely to appear persisted for both younger and older adults in a later phase in which target occurrence was equiprobable (unbiased) in all quadrants. The differing findings may reflect that the initial control setting (i.e., established in early segment) in the present study was based only on six trials of experience whereas in Jiang et al., the unbiased task version was presented after 288 trials of experience with the biased quadrant. Future research is needed to examine potential boundary conditions for flexible experience-guided control in both age groups, such as may be the case with (over)learned attentional biases.

The current findings also support literature showing that older adults attend to and outsource control to the environment, possibly because doing so may reduce demands on self-initiated processing (Lindenberger & Mayr, 2014). However, in contrast to some studies showing that older adults have even stronger attention to and reliance on the environment than younger adults (Mayr et al., 2015; Spieler et al., 2006), we found equivalent experience-driven acquisition and shifting of control for younger and older adults. This may reflect that younger adults may be disinclined to attend to environmental information when doing so requires extra effort

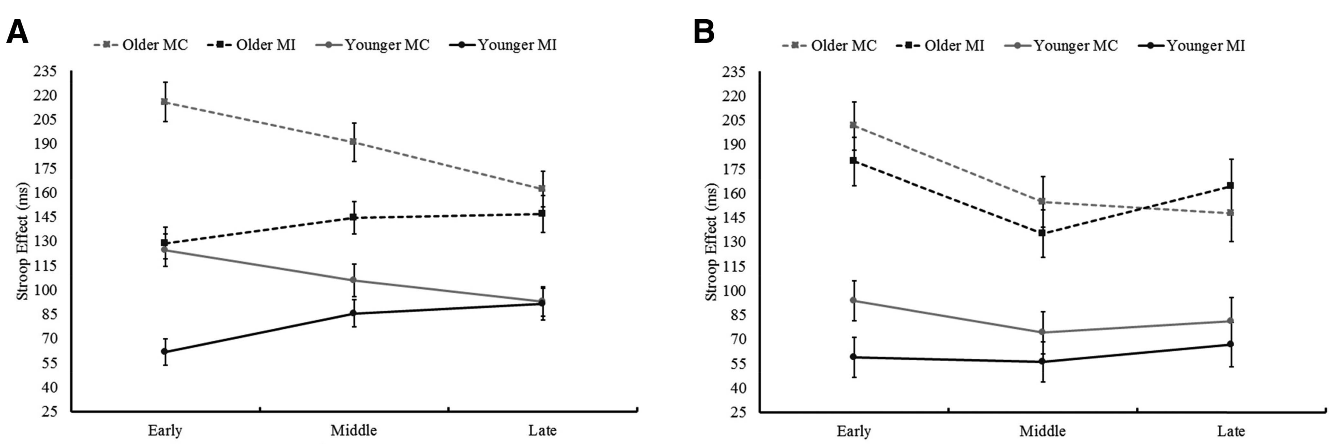

Figure 5. Results for Experiment 2 for (A) inducer items and (B) transfer items for participants who had a positive PC effect following mostly congruent (MC) and mostly incongruent (MI) early list biases. Error bars represent *SEM*s.

and may harm performance (as with inspecting task cues that are no longer needed for task performance; Mayr et al., 2015; Spieler et al., 2006) but they may attend to environmental information when it does not require effort (i.e., because it occurs implicitly) and may benefit performance (as in the case of PC in the present study).

Our results also have implications for the Dual Mechanisms of Control account, and specifically the notion that aging selectively disrupts proactive control but not reactive control (Braver et al., 2007). Proactive control refers to the preparatory, goal-oriented processing characterized as "early selection." It is considered a global control mechanism because it influences all items within a given context thereby producing transfer (Gonthier, Braver, & Bugg, 2016). Reactive control arises as needed (e.g., conflicting response tendencies are activated) and is characterized as "late correction" (see also Braver, 2012). It is based on accumulating *experience* with stimuli, resulting in for example item-specific control. Consistent with the DMC account, prior research has shown that older adults do not effectively engage proactive control (AX-CPT, Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005; Stroop task, Bugg, 2014b) but are equivalent to younger adults in their use of reactive control (AX-CPT, Braver et al., 2001; Braver et al., 2005; Stroop and flanker tasks, Bugg, 2014a). An important question is why age-related decline is apparently more robust for proactive than reactive control. One possibility supported by the current results is that it is not proactive control per se but rather the *basis* on which proactive control routinely operates that may explain the differing age-related effects previously observed for proactive and reactive control. Proactive control, unlike reactive control, often depends on self-initiated processes that are based on instructions, cues, and so forth (Bugg et al., 2015; Bugg & Smallwood, 2016; Entel, Tzelgov, & Bereby-Meyer, 2014; Paxton, Barch, Racine, & Braver, 2008). Similarly, the studies reviewed earlier in the article showing age-related deficits in the flexibility of control incorporated tasks that also can be characterized in this way.

In the current study, in contrast, we used a paradigm that allowed us to examine whether a control setting that is acquired based on experience (and is hence, more like reactive control *a la* the DMC account) might transfer into a form of control that globally affects all trials even those for which the PC of the trials themselves did not direct attention one way or the other (because they were 50% congruent), similar to proactive control (i.e., Gonthier et al., 2016). However, this form of control is potentially unique from proactive control because it is acquired and shifted on the basis of recent *experience* rather than instructions, cues, or other more traditional bases for proactive control (e.g., Bugg et al., 2015; Bugg & Smallwood, 2016; Entel et al., 2014; Paxton et al., 2008). The mostly age-invariant patterns in the current study thus provide preliminary support for the exciting possibility that age-related decrements in proactive control may not reflect an immutable deficiency in implementing proactive control per se but may alternatively reflect a deficit in implementing proactive control when it is based on effortful and often self-initiated processing as opposed to experience. Further research is needed, however, to validate this view as it does contradict at least one relevant extant pattern. Bugg (2014b) found that younger but not older adults generalized control settings from inducer to transfer items in MC and MI lists. A major difference between studies was that Bugg used long lists of 80 trials whereas acquisition and generalization of control settings was based on eight trials in the early list segment in Experiment 2. One possibility is that older adults can initially acquire global control settings based on experience but cannot sustain the same setting over many trials or lengthy periods of time.

Last, our results may motivate further exploration of age-related differences in the neurobiological underpinnings of control. Several studies have found that proactive control is driven by preparatory and sustained lateral prefrontal cortex (PFC) activity and reactive control driven by transient, more widely distributed activation in the anterior cingulate cortex (ACC), PFC, and other brain areas. Jimura and Braver (2010) and Paxton et al. (2008) found that older adults showed reduced preparatory and sustained PFC activation, but enhanced transient PFC activation, relative to younger adults, patterns that were interpreted as evidence that aging is associated with a shift away from proactive control in favor of reactive control. At first glance this appears difficult to reconcile with the results of the current study showing evidence for global control (i.e., PC effect on transfer trials) that is experience-based in older as well as younger adults. However, no functional magnetic resonance imaging (fMRI) study has examined the current paradigm including in younger adults so it is difficult to know whether the regions activated in paradigms in which proactive control is based on cues (e.g., task-switching; AX-CPT) would also support performance in the current Stroop paradigm in which control was based on experience. In fact, it may be interesting to examine this paradigm with fMRI to explore whether the regions activated in prior work relate to proactive versus reactive control per se, or whether they are related to the bases on which that control is established (e.g., explicit cues vs. experience).

Some Caveats and Limitations

Although the present experiments provide initial evidence for age invariance in the experience-guided acquisition and shifting of control settings including at the global level, there are several caveats and limitations. First, our analyses may overestimate older adults' ability to engage and flexibly shift control at a global level because in Experiment 2 about 46% of older adult participants did not show early list PC effects for the inducer items and were excluded from further analyses off which our primary conclusions were based. However, 37% of younger adult participants were also excluded for this reason. Therefore, conclusions about age-equivalence were based on both a selective group of younger and older adults. Nonetheless, we may be overestimating the intact nature of these processes in the broader population of younger and older adults. An interesting avenue for future research concerns the individual differences associated with intact versus impaired cognitive control setting acquisition and shifting, particularly with respect to aging.

Second, although across many analyses we found strong support for the null hypothesis, with F values less than 1 and Bayes Factors indicating support for the null, there were two cases in Experiment 2 in which the statistical values were somewhat ambiguous. Both cases pertained to the PC × Age interaction in the late list segment (whereas the $BF_{\text{inclusion}}$ values clearly supported the null, the F values were not less than 1 for either inducer or transfer items). These results suggest caution in claiming that there was age-equivalence across the board in the current study. It is possible that a larger sample size might elucidate age-related differences in returning to baseline Stroop effects by the late list segment that we failed to detect in the current study, so future research is necessary to examine whether these specific patterns truly reflect age-equivalence.

Third, the flexible shifting of control at a global level in Experiment 2 was observed for younger and older adults in the early MC lists but for neither age group in the early MI lists. That is, the expected pattern of increases in the Stroop effect across the middle and later segments of initially MI lists was observed only for inducer items. For transfer items, the Stroop effect *decreased* in the middle list segment, then rose backup in the later segment. One potential explanation is that item-specific mechanisms dominate in MI lists. However, there are two counterpoints to this explanation. First, this pattern was statistically equivalent for younger and older adults and there is not an obvious explanation as to why younger adults would not implement a global (proactive) control mechanism in the MI lists. Second, both age groups demonstrated acquisition of PC effects in the early list segment that did generalize to the transfer items. Thus, it appears that at least initially during the early list MI segment, a global control mechanism was implemented. In line with this observation, an alternative explanation is that the global control setting induced by early MI experience may have interfered with the experience-guided accumulation of information signaling that the PC is changing in the middle and late part of the list. This aligns with the view that an MI list may lead to use of a global word filter (i.e., a setting that minimizes processing of the word dimension; Bugg, McDaniel, Scullin, & Braver, 2011; Jacoby, McElree, & Trainham, 1999). Because PC is essentially determined by the frequency with which the word corresponds to the color, a global word filter would make shifting from MI to PC50 segments harder or slower to initiate than shifting from MC (where control is presumably loosened and participants are not strongly filtering out word information) to PC50. However, it is unclear why this pattern would occur for transfer items only, and not inducer items in the MI condition (in either experiment). This may suggest that item-specific processes contributed to performance in addition to the global processes that were evidenced in this task.

A final limitation of the current study is that we have no direct comparison with a similar task in which control is necessarily guided by internally-driven representations. With respect to the WCST, one clear similarity is that in the current Stroop task and in the WCST participants apply the same rule/setting for several trials (6 or 8 in Stroop vs. 10 in WCST) before a new rule/setting is needed. Perhaps the most comparable extant task, however, is the task-switching version of Stroop in which participants are cued trial-by-trial to respond either to the word or color. Older adults are less flexible as indicated by increased switch costs on trials on which they must self-initiate a switch between reading the word and naming the color (Hutchison, Balota, & Duchek, 2010). Although this pattern is consistent with the overarching hypothesis of the current study, the comparison is still not perfect because it is unlikely that participants are switching between reading per se and naming when moving from one segment to the next in the current experiments; more likely they are switching between paying more versus less attention to the word dimension. Additional research is, therefore, needed to more comprehensively examine whether age-related declines in control and flexibility are more evident in tasks for which shifting is guided by internally-mediated as opposed to experience-based processes.

Conclusion

The current study provided a novel demonstration of age-invariance in the rapid acquisition and flexible shifting of control in response to changing experience in an abbreviated lists Stroop paradigm. The study also provided preliminary evidence that this experience-guided control may operate at a global level that generalizes to transfer items and not solely at an item-specific level for younger and older adults. We propose that this pattern of age invariance may be observed in tasks that afford *experience* to guide the acquisition and shifting of control, a proposal that will be informed further by future research. Taken together, the current findings suggest that age-related deficits in control are nuanced and patterns of inflexibility may depend on the extent to which control is driven by internally- versus externally-mediated processing.

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