Age affects the adjustment of cognitive control after a conflict:
Evidence from the bivalency effect

Alodie Rey-Mermet & Beat Meier

University of Bern, Switzerland

IN PRESS: AGING, NEUROPSYCHOLOGY & COGNITION

Author Note

Alodie Rey-Mermet and Beat Meier, Institute of Psychology and Center for Cognition, Learning, and Memory**,** University of Bern, Switzerland.

This work was supported by the Center for Cognition, Learning and Memory, University of Bern.

Correspondence concerning this article should be addressed to Beat Meier, Institute of Psychology**,** University of Bern, Fabrikstr. 8, 3012 Bern, Switzerland.

E-mail: beat.meier@psy.unibe.ch

Abstract

Age affects cognitive control. When facing a conflict, older adults are less able to activate goal-relevant information and inhibit irrelevant information. However, cognitive control also affects the events after a conflict. The purpose of this study was to determine whether age affects the adjustment of cognitive control following a conflict. To this end, we investigated the bivalency effect, that is, the performance slowing occurring after the conflict induced by bivalent stimuli (i.e., stimuli with features for two tasks). In two experiments, we tested young adults (aged 20-30) and older adults (aged 65-85) in a paradigm requiring alternations between three tasks, with bivalent stimuli occasionally occurring on one task. The young adults showed a slowing for all trials following bivalent stimuli. This indicates a widespread and long-lasting bivalency effect, replicating previous findings. In contrast, the older adults showed a more specific and shorter-lived slowing. Thus, age affects the adjustment of cognitive control following a conflict.

Keywords: older adults, bivalent stimuli, incongruent stimuli, task switching, episodic context binding

Word count: 12983 words

Age affects the adjustment of cognitive control after a conflict:

Evidence from the bivalency effect

Aging is associated with a decline in higher cognitive functions, such as cognitive control (e.g., Hasher & Zacks, 1988; West, 1996). Cognitive control refers to the ability to adjust ourselves in the face of conflict by activating goal-relevant information while suppressing irrelevant information. Older adults are less able to exert cognitive control in the face of conflict and thus are more prone to interference to irrelevant information (e.g., Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Verhaeghen, 2011; Verhaeghen & Cerella, 2002). Research in young adults has shown that cognitive control is adjusted not only for the current conflict-loaded event but also for the subsequent events (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Egner, 2007; Logan & Zbrodoff, 1979; Woodward, Meier, Tipper, & Graf, 2003). The purpose of the present study was to investigate whether age affects the adjustment of cognitive control following a conflict.

Previous aging research has mainly focused on the impact of age on the conflict-loaded event (e.g., Andrés, Gherrini, Phillips, & Perfect, 2008; Hsieh, Liang, & Tsai, 2012; Rush, Barch, & Braver, 2006; Van der Lubbe & Verlger, 2002; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). For example, the *congruency effect* in the Stroop task was largely examined (e.g., Borella, Delaloye, Lecerf, Renaud, & De Ribeaupierre, 2009; Hartley, 1993; Ludwig, Borella, Tettamanti, & de Ribaupierre, 2010; Mayas, Fuentes, & Ballesteros, 2012; Verhaeghen & De Meersman, 1998; West & Alain, 2000). In this task, participants are asked to name the color of color words. Trials on which the color and the word match (e.g., the word “red” printed in red) are congruent. Trials on which the color and the word does not match (e.g., the word “red” printed in blue) are incongruent and thus are conflict-loaded. Typically, the congruence effect (i.e., the performance decrement on incongruent trials compared to congruent trials) is larger for older adults than for young adults (e.g., Andrés et al., 2008; Mayas et al., 2012; Rush et al., 2006; West & Alain, 2000; but see Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998). This finding has been interpreted as a decline of cognitive control in older age.

Only few studies have investigated the impact of age on the adjustment of cognitive control following a conflict (Mutter, Naylor, & Patterson, 2005; Puccioni & Vallesi, 2012; Trewartha, Penhuse, & Li, 2011; West & Baylis, 1998; West & Moore, 2005; Yoshizaki, Kuratomi, Kimuar, & Kato, 2013). These studies investigated either the *congruence sequence effect* or the *proportion congruence effect*. The congruence sequence effect refers to the reduction of the congruence effect after incongruent trials compared to congruent trials (see e.g., Botvinick et al., 2001; Egner, 2007). The proportion congruence effect refers to the reduction of the congruence effect when the proportion of incongruent trials increases in the block (see e.g., Gratton, Coles, & Donchin, 1992; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). For both effects, the results were inconsistent. While some studies found an age-related change (Trewartha et al., 2011; West & Baylis, 1998), other studies reported no change (Mutter et al., 2005; Puccioni & Vallesi, 2012; Yoshizaki et al., 2013; West & Moore, 2005).

Thus, only a few aging studies have explored the adjustment of cognitive control following a conflict and these studies have focused on two different effects (i.e., the proportion congruence effect and the sequence congruence effect). These studies showed inconsistent findings, and in those studies that reported a difference between young and older adults, its source was not clear. For example, it is possible that the difference stemmed from a general slowing in processing speed (e.g., Salthouse, 1996; Salthouse & Babcock, 1991) or from a deficit in inhibiting the conflict-overlapping features (e.g., Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Persad, Abeles, Zacks, & Denburg, 2002). As a matter of fact, in those studies, the trials following a conflict entailed conflict-overlapping features and thus required the inhibition of previously relevant task set. Accordingly, compared to young adults, older adults were more slowed on all trials, which can be explained by an inhibition deficit in older age. However, this overall performance slowing can also be explained by a general slowing in processing speed. Together, this raises the necessity to investigate in more detail the adjustment of cognitive control following a conflict. To this end, we investigated in the present study the *bivalency effect* (see Meier & Rey-Mermet, 2012a, for a review).

The bivalency effect refers to the long-lasting performance slowing that occurs on univalent trials following bivalent stimuli, even on those univalent trials that share no overlapping features with the bivalent stimuli (e.g., Meier, Woodward, Rey-Mermet, & Graf, 2009; Rey-Mermet & Meier, 2012a; 2012b; 2013; 2014; Woodward et al., 2003; Woodward, Metzak, Meier, & Holroyd, 2008). The paradigm typically used to investigate this effect involves three blocks with regular switches between three tasks, such as a parity decision (odd vs. even), a color decision (red vs. blue), and a case decision (uppercase vs. lowercase; see Figure 1a). In the first and third blocks (the pure blocks), all stimuli are univalent (i.e., black numerals for the parity decision, colored symbols for the color decision, and black letters for the case decision). In the second block (the mixed block), some letters for the case decisions appear in red or blue color, which turn them into bivalent stimuli (i.e., stimuli with relevant features for two different tasks, that is, the color and case decisions in the present paradigm). The bivalency effect is the performance slowing that occurs on all univalent trials following bivalent stimuli, including those sharing no relevant features with bivalent stimuli (i.e., the parity-decision trials). Thus, this effect represents an adjustment of cognitive control following the conflict induced by bivalent stimuli.

Previous research has shown that the bivalency effect occurs with different types of tasks, different types of bivalent stimuli, across different modalities, and with overlapping as well as with non-overlapping response sets (Meier et al., 2009; Rey-Mermet & Meier, 2012a). Moreover, it is associated with activation in the dorsal anterior cingulate cortex, a brain area recruited for the adjustment of cognitive control (Grundy, Benarroch, Woodward, Metzak, Whitman, & Shedden, 2013; Woodward et al., 2008) and it draws on memory resources because amnesic patients fail to show the typical pattern of a long-lasting performance slowing (Meier, Rey-Mermet, Woodward, Müri, & Gutbrod, 2013).

Theoretically, current cognitive control accounts are not sufficient to explain the bivalency effect. Accounts that focus on the overlap between stimulus, response, and task representations can explain the performance slowing on the tasks with univalent stimuli sharing features with bivalent stimuli (i.e., the color and case decisions; see, e.g., Allport & Wylie, 2000; Hommel, 2004; Rogers & Monsell, 1995; Waszak, Hommel, & Allport, 2003). However, the bivalency effect also occurs on the task with univalent stimuli sharing no relevant stimulus or response features with bivalent stimuli (see e.g., Rey-Mermet & Meier, 2012a; Woodward et al., 2003). Moreover, an account assuming an orienting response towards infrequent events (i.e., the bivalent stimuli in the bivalency effect paradigm) can explain the performance slowing on the first univalent trials immediately following bivalent stimuli (Metzak, Meier, Graf, & Woodward, 2013; Rey-Mermet & Meier, 2013; cf. Notebaert, Houtman, Van Opstal, Gevers, Fias, & Verguts, 2009; Notebaert & Verguts, 2011; Nùñez Castellar, Kühn, Fias, & Notebaert, 2010), but as the bivalency effect is long-lasting, persisting over at least twelve univalent trials (i.e., for approximately twenty seconds), an orienting response is not sufficient to explain the full pattern of the bivalency effect (Meier et al., 2009; Rey-Mermet & Meier, 2013).

To account for the long-lasting nature of the bivalency effect, we have put forward the hypothesis that the bivalency effect is caused by “episodic context binding” (Meier et al., 2009; 2013). Responding to a particular trial results in a memory representation that is bound to the proximate context (e.g., the particular task triplet in the case of the paradigm used to investigate the bivalency effect). This context is retrieved and updated each time a task is performed. When a bivalent stimulus occurs within a task triplet, the whole context becomes conflict-loaded and thus on subsequent trials, the retrieval of this representation causes interference. As the representation included the whole task triplet, performance is generally slowed for several subsequent trials. Episodic context binding thus refers to the memory processes involved in the adjustment of cognitive control and it is supported by results from amnesic patients who fail to show a bivalency effect (Meier et al., 2013). Moreover, it is consistent with findings from an electrophysiological study that showed that the bivalency effect is associated with an event-related-potential-component that signals interference (Rey-Mermet, Koenig, & Meier, 2013).

Importantly, with the bivalency effect, we can investigate more than a simple change in reaction times (RTs). As previous research has mainly focused on an age-related change in the magnitude of RTs, it has been difficult to disentangle age-related changes in cognitive control from general age-related slowing in processing speed (Salthouse, 1996; Salthouse & Babcock, 1991; see also Verhaeghen, 2011). In the present study, we adopted a different strategy by investigating whether older adults show a bivalency effect with the same properties as young adults. So far, two main properties have been documented for the bivalency effect. First, the bivalency effect is *widespread*, because it occurs on all tasks, irrespective of whether the task shares relevant stimulus or response features with bivalent stimuli (Rey-Mermet & Meier, 2012a; Woodward et al., 2003). Second, the bivalency effect is *long-lasting*, persisting at least twelve univalent trials, (Meier et al., 2009; Rey-Mermet & Meier, 2013). We thus investigated whether older adults show a widespread and long-lasting bivalency effect. To this end, we conducted two experiments in which young adults (aged between 20 and 30) and older adults (aged over 65) were asked to switch successively between three tasks (i.e., a parity decision, a color decision, and a case decision). In Experiment 1, bivalent stimuli were red or blue letters occasionally occurring on case decisions. In Experiment 2, we counterbalanced the bivalent stimuli so that they occurred on color decisions.

We hypothesized that if age has no impact on the adjustment of cognitive control underlying the bivalency effect, young and older adults would show a similar, widespread and long-lasting bivalency effect (cf. Mutter et al., 2005; Puccioni & Vallesi, 2012; West & Moore, 2005; Yoshizaki et al., 2013). In contrast, if aging is associated with a change in this adjustment of cognitive control, older adults would show a different performance slowing after bivalent stimuli than young adults (Trewartha et al., 2011; West & Baylis, 1998). According to the general slowing in processing speed account (Salthouse, 1996: Salthouse & Babcock, 1991), older adults would be more slowed after bivalent stimuli than young adults. Thus, the whole bivalency effect would be larger for older adults. According to the inhibition deficit account (see, e.g., Hasher & Zacks, 1988; Hasher et al., 1999; Persad et al., 2002; see also Kramer et al., 1994), older adults would be more slowed on the conflict-overlapping trials because these trials require inhibition, that is, on those univalent trials sharing relevant features with the bivalent stimuli (i.e., the univalent color- and case-decision trials). Responding to these univalent trials activates the bivalent stimulus features and as this activation is irrelevant for task execution, it must be inhibited (see Allport & Wylie, 1999; 2000; Wylie & Allport, 2000). Due to age-related inhibition deficit, older adults might be less efficient than young adults in inhibiting the conflict-overlapping features, which would result in a larger performance slowing for the color- and case-decision trials. Thus, for the older adults, the performance slowing after bivalent stimuli would be more specific than the bivalency effect observed in young adults. Third, given the binding deficit in aging (e.g., Chalfonte & Johnson, 1996; Rabbitt & Vyas, 1980), older adults would be less able to maintain episodic context binding across univalent trials. Thus, their performance slowing after bivalent stimuli would be shorter-lived compared to the typically long-lasting bivalency effect.

Experiment 1

Method

Participants. Forty-two young adults (aged between 20 and 30) and forty-two older adults aged over 65 years (range 65 – 82) participated in Experiment 1. All participants were sampled from the circle of acquaintances of the experimenters and they volunteered free of charge. The study was approved by the local ethical committee of the University of Bern and all participants gave informed consent.

The demographic information for each age group (young and older adults) is summarized in Table 1 (left half). In order to assess the cognitive status, all participants performed five additional tests, that is, a standardized German vocabulary test (MWT-A; Lehrl, Merz, Burkhard, & Fischer, 1991) to assess verbal intelligence quotient (IQ), the forward and backward digit span tests (Tewes, 2001) to assess working memory functions, and the Victoria Stroop Test (VST; Regard, 1981) to assess executive functions. These results are also presented in Table 1 (left half).

(Table 1 about here)

Materials. For the parity decision, the stimuli were the numerals 1 through 8, each displayed in black. For the color decision, the stimuli were the symbols %, #, $, and §, each displayed in either blue or red. For the case decision, the stimuli were the upper- or lowercase consonants d, f, r, t, each displayed in black. We created a set of eight bivalent stimuli by presenting the same four consonants (d, f, r, t) either in blue or red and either in upper- or lowercase. In order to control for performance on bivalent stimuli, uppercase and lowercase stimuli were colored such that they required an incongruent response. All stimuli were presented at the center of the computer screen in 60-point Times New Roman font (cf. Meier et al., 2009; Woodward et al., 2003).

Procedure. Participants were tested individually. They were informed that the experiment involved three different tasks: parity decisions about numerals, color decisions about symbols, and case decisions about letters. They were instructed to respond by pressing one of two computer keys (*b* and *n*) with their left and right index fingers respectively, for each of the three tasks. The mapping information, printed on paper, was presented below the computer screen throughout the experiment. Participants were informed that, for some of the case decisions, the letters would be presented in either blue or red. They were instructed to ignore the color and to continue making case decisions.

After the instructions, a block of 30 task triplets was presented for practice. Each task triplet required making a parity decision, a color decision, and a case decision, as illustrated in Figure 1a. These tasks were always presented in this fixed order. For each task, a stimulus was selected randomly and was displayed until the participant responded. Then, the screen blanked for 500 ms before the next stimulus appeared. After each task triplet, an additional blank appeared for 500 ms. After the practice block and a brief break, each participant completed three experimental blocks without break between blocks. The first block included 32 task triplets, with the first two task triplets serving as “warm-up” triplets which were discarded from the analyses. The second and third blocks had 30 task triplets each.

(Figure 1 about here)

For the first and third blocks (the pure blocks), only univalent stimuli were presented. For the second block (the mixed block), univalent stimuli were presented except on 20% of the case decisions in which bivalent stimuli (i.e., colored letters) appeared. The specific letter selected for this purpose was determined randomly and without replacement. Task triplets with bivalent stimuli were evenly interspersed among the 30 triplets of the block; occurring in every fifth triplet, specifically in the 3rd, 8th, 13th, 18th, 23rd, and 28th triplets.

The testing session consisted of the experiment (i.e., the instructions plus the practice block and the three experimental blocks) and the administration of the cognitive tests. The whole session lasted about 60 minutes.

Data analysis. For each participant and each task, the accuracy rates and the median RTs for correct responses were computed for each task triplet following a bivalent stimulus in the mixed block and for each corresponding task triplet in the pure blocks 1 and 3. Specifically, a bivalent stimulus was presented on every fifth task triplet in the mixed block, and this task triplet was designated with the label N, with succeeding task triplets labeled N+1, N+2, N+3, and N+4. To account for general training effects, we averaged the data from the pure blocks 1 and 3 for each task, each task triplet, and each participant. For the RT analyses only correct responses were included.

An alpha level of 0.05 was used for all statistical tests. Greenhouse-Geisser corrections are reported where appropriate and effect sizes are expressed as partial η^2 values.

Design. Independent within-subject variables were block (pure, mixed), task (parity, color, case), and task triplet (N+1, N+2, N+3, N+4). In the mixed block, stimulus valence (bivalent case, univalent case) was an additional independent within-subject variable. Age group (young adults, older adults) was a between-subjects variable. Dependent variables were RTs, log-transformed RTs, and accuracy rates. We applied a natural logarithm transformation to RTs in order to account for baseline differences between young and older adults and to minimize the inter-subject variability (see, e.g., Kray & Lindenberger, 2000; Meiran, 1996; Ratcliff, 1993).

Results

Costs of bivalent stimuli. As in the previous bivalency effect studies (e.g., Meier et al., 2009; Rey-Mermet & Meier, 2012a; 2012b; 2013; 2014; Woodward et al., 2003), we first investigated the cost produced by bivalent stimuli (i.e., the colored letters of the case decisions from the task triplets N of the mixed block). That is, we assessed whether performance on bivalent stimuli was lower than performance on the corresponding univalent stimuli (i.e., the black letters of the case decisions from the task triplets N+1 until N+4 of the mixed block), and whether this cost differs between both age groups (young and older adults).

Reaction times. For the *young* adults, performance was slower on bivalent case decisions (*M* = 948 ms, *SE* = 62) than on univalent case decisions (*M* = 631 ms, *SE* = 31). Similarly, for the *older* adults, performance was slower on bivalent case decisions (*M* = 2112 ms, *SE* = 224) than on univalent case decisions (*M* = 1342 ms, *SE* = 115). A two-way ANOVA with stimulus valence (bivalent case, univalent case) as a within-subject factor and age group (young adults, older adults) as a between-subjects factor showed a significant main effect of stimulus valence (RTs: F (1, 82) = 52.83, $p < .001$, $\eta^2 = .39$; and log RTs: F (1, 82) = 125.08, $p < .001$, $\eta^2 = .60$) and of age group (RTs: F (1, 82) = 30.89, $p < .001$, $\eta^2 = .27$; and log RTs: F (1, 82) = 52.82, $p < .001$, $\eta^2 = .39$). Moreover, the interaction between stimulus valence and age group was significant in RTs, F (1, 82) = 9.23, $p < .01$, $\eta^2 = .10$, but not in log-transformed RTs, F (1, 82) = 0.003, $p = .95$, $\eta^2 < .001$. Thus, although the cost produced by bivalent stimuli seems larger for older adults (*M* = 770 ms, *SE* = 144, with t (41) = 5.36, $p < .001$, for RTs, and t (41) = 6.79, $p < .001$, for log RTs) than for young adults (*M* = 316 ms, *SE* = 42, with t (41) = 7.61, $p < .001$, for RTs, and t (41) = 9.81, $p < .001$, for log RTs), this observation was not confirmed when baseline differences between young and older adults were controlled.

Accuracy. For the *young* adults, accuracy was lower on bivalent case decisions (*M* = .86, *SE* = 0.02) than on univalent case decisions (*M* = .99, *SE* = 0.003). Similarly, for the *older* adults, accuracy was lower on bivalent case decisions (*M* = .76, *SE* = 0.04) than on univalent case decisions (*M* = .98, *SE* = 0.01). A similar two-way ANOVA showed a significant main effect of stimulus valence, *F* (1, 82) = 67.73, $p < .001$, $\eta^2 = .45$, of age group, *F* (1, 82) = 6.95, $p < .05$, $\eta^2 = .08$, and a significant interaction, *F* (1, 82) = 4.40, $p < .05$, $\eta^2 = .05$. Thus, for accuracy rates, the cost produced by bivalent stimuli was larger for the older adults (*M* = .22, *SE* = 0.04, with *t* (41) = 6.06, $p < .001$) than for the young adults (*M* = .13, *SE* = 0.02, with *t* (41) = 5.86, $p < .001$).

Bivalency effect. The main objective was to examine the bivalency effect in young and older adults. That is, we aimed to determine on how many task triplets following bivalent stimuli performance decreased in both age groups.

Reaction times. The most relevant results are the RTs from the univalent stimuli of the mixed block compared to those of the pure block for the task triplets N+1 to N+4 in both age groups. These results are depicted in Figure 2a. We carried out a four-way ANOVA with block (pure, mixed), task (parity, color, case) and task triplet (N+1, N+2, N+3, N+4) as within-subject factors and age group (young adults, older adults) as a between-subjects factor.

(Figure 2 about here)

The ANOVA showed a significant main effect of task (RTs: *F* (1.82, 149.45) = 9.83, $p < .001$, $\eta^2 = .11$; and log RTs: *F* (2, 164) = 24.27, $p < .001$, $\eta^2 = .23$) and of task triplet (RTs: *F* (2.53, 207.71) = 23.85, $p < .001$, $\eta^2 = .22$; and log RTs: *F* (2.59, 212.04) = 35.51, $p < .001$, $\eta^2 = .30$) as well as a significant interaction between task and task triplet (RTs: *F* (4.05, 331.77) = 3.39, $p < .01$, $\eta^2 = .04$; and log RTs: *F* (4.81, 394.85) = 4.63, $p < .001$, $\eta^2 = .05$). As expected, the main effect of age group was significant (RTs: *F* (1, 82) = 42.07, $p < .001$, $\eta^2 = .34$; and log RTs: *F* (1, 82) = 76.95, $p < .001$, $\eta^2 = .48$). Furthermore, the interaction between task and age group was significant (RTs: *F* (1.82, 149.45) = 8.10, $p < .01$, $\eta^2 = .09$; and log RTs: *F* (2, 164) = 14.85, $p < .001$, $\eta^2 = .15$).

More importantly, there were a significant main effect of block (RTs: *F* (1, 82) = 26.70, $p < .001$, $\eta^2 = .25$; and log RTs: *F* (1, 82) = 51.73, $p < .001$, $\eta^2 = .39$) and significant interactions between block and task (RTs: *F* (1.30, 106.93) = 5.88, $p < .05$, $\eta^2 = .07$; and log RTs: *F* (1.78, 146.13) = 7.11, $p < .01$, $\eta^2 = .08$), between block and task triplet (RTs: *F* (2.58, 211.58) = 21.15, $p < .001$, $\eta^2 = .20$; and log RTs: *F* (2.59, 212.21) = 25.65, $p < .001$, $\eta^2 = .24$), as well as between block, task and task triplet (RTs: *F* (3.48, 285.34) = 2.68, $p < .05$, $\eta^2 = .03$; and log RTs: *F* (4.62, 378.56) = 4.28, $p < .01$, $\eta^2 = .05$). Thus, performance on univalent stimuli was slowed in the mixed block compared to the pure block. However, this performance slowing decreases across tasks and task triplets (from 360 ms for the first decision following bivalent stimuli, that is, the parity decision of task triplet N+1, to 17 ms for the last decision, that is, the case decision of task triplet N+4).

The four-way interaction between block, task, task triplet and age group did not approach the conventional level of significant in RTs, *F* (3.48, 285.34) = 1.95, $p = .11$, $\eta^2 = .02$. Critically, however, this interaction was significant when using log-transformed RTs, *F* (4.62, 378.56) = 2.93, $p < .05$, $\eta^2 = .03$. No other interaction was significant, *F*s < 2.57, *p*s > .07, $\eta^2 < .03$. Thus, when controlling baseline differences between young and older adults, the four-way interaction indicates that both age groups differed in the performance slowing following bivalent stimuli and that tasks and task triplets affected the trajectory of this performance slowing differently (see Figure 2a). To specify the trajectory of this performance slowing for each age group, we conducted a follow-up three-way repeated-measures ANOVA for each age group, with block (pure, mixed), task (parity, color, case) and task triplet (N+1, N+2, N+3, N+4).

Young adults. For the young adults, the three-way ANOVA revealed a significant main effect of task (RTs: F (1.75, 71.92) = 16.88, $p < .001$, $\eta^2 = .29$; and log RTs: F (2, 82) = 26.10, $p < .001$, $\eta^2 = .39$), and of task triplet (RTs: F (1.53, 62.74) = 15.64, $p < .001$, $\eta^2 = .28$; and log RTs: F (2.21, 90.51) = 20.06, $p < .001$, $\eta^2 = .33$). More importantly, there was a significant main effect of block (RTs: F (1, 41) = 29.53, $p < .001$, $\eta^2 = .42$; and log RTs: F (1, 41) = 40.85, $p < .001$, $\eta^2 = .50$), and there were significant interactions between block and task (RTs: F (1.53, 62.61) = 4.14, $p < .05$, $\eta^2 = .09$; and log RTs: F (2, 82) = 3.76, $p < .05$, $\eta^2 = .08$), between block and task triplet (RTs: F (1.64, 67.44) = 9.71, $p < .001$, $\eta^2 = .19$; and log RTs: F (2.33, 95.73) = 10.14, $p < .001$, $\eta^2 = .20$), as well as between block, task, and task triplet (RTs: F (3.03, 124.30) = 3.35, $p < .05$, $\eta^2 = .08$; and log RTs: F (4.68, 191.90) = 5.16, $p < .001$, $\eta^2 = .11$). Thus, for the young adults, the performance slowing following bivalent stimuli decreased across tasks and task triplets (see Figure 2a).

To determine this decrease more precisely, we carried out follow-up two-way repeated-measures ANOVAs with the factors block (pure, mixed) and task (parity, color, case) for each task triplet. For task triplets N+1, there were a main effect of block (RTs: F (1, 41) = 20.43, $p < .001$, $\eta^2 = .33$; and log RTs: F (1, 41) = 31.56, $p < .001$, $\eta^2 = .43$) and a significant interaction between block and task (RTs: F (1.53, 62.64) = 4.71, $p < .05$, $\eta^2 = .10$; and log RTs: F (2, 82) = 8.43, $p < .001$, $\eta^2 = .17$). Thus, performance on task triplets N+1 was slowed on all three tasks (i.e., on parity decisions with t (41) = 4.99, $p < .001$, for RTs, and t (41) = 5.71, $p < .001$, for log

RTs; on color decisions with t (41) = 3.42, $p < .01$, for RTs, and t (41) = 4.28, $p < .001$, for log RTs; and on case decisions with t (41) = 1.44, $p < .08$, one-tailed, for RTs, and t (41) = 1.72, $p < .05$, one-tailed, for log RTs). However, this performance slowing was larger on parity and color decisions (*M* = 254 ms, *SE* = 51, and *M* = 260 ms, *SE* = 76, respectively) than on case decisions (*M* = 68 ms, *SE* = 47). For subsequent task triplets (i.e., N+2 until N+4), the main effect of block was significant (N+2: F (1, 41) = 14.50, $p < .001$, $\eta^2 = .26$, for RTs, and F (1, 41) = 14.79, $p < .001$, $\eta^2 = .26$, for log RTs; N+3: F (1, 41) = 4.92, $p < .05$, $\eta^2 = .11$, for RTs, and F (1, 41) = 6.73, $p < .05$, $\eta^2 = .14$, for log RTs; and N+4: F (1, 41) = 7.45, $p < .01$, $\eta^2 = .15$, for RTs, and F (1, 41) = 11.88, $p < .01$, $\eta^2 = .22$, for log RTs). Across these task triplets, no interaction between block and task was significant, Fs < 2.91, ps > .06, $\eta^2 < .06$. Thus, for the young adults, the performance slowing following bivalent stimuli occurred in all three tasks (with 87, 117, and 48 ms for the parity, color, and case decisions, respectively). Moreover, although it decreased across the task triplets from 194 ms to 59 ms to 34 ms and to 50 ms for N+1, N+2, N+3 and N+4, respectively, it was significant in all four task triplets. This indicates a widespread and long-lasting bivalency effect, replicating previous findings (e.g., Meier et al., 2009; 2013; Rey-Mermet et al., 2013).

Older adults. For the older adults, the three-way repeated-measures ANOVA with block (pure, mixed), task (parity, color, case) and task triplet (N+1, N+2, N+3, N+4) revealed a significant main effect of task (RTs: F (2, 82) = 7.89, $p < .01$, $\eta^2 = .16$; and log RTs: F (2, 82) = 15.12, $p < .001$, $\eta^2 = .27$), and of task triplet (RTs: F (2.58, 105.95) = 11.84, $p < .001$, $\eta^2 = .22$; and log RTs: F (3, 123) = 16.68, $p < .001$, $\eta^2 = .29$) as well as a significant interaction between task and task triplet (RTs: F (4.09, 167.77) = 3.06, $p < .05$, $\eta^2 = .07$; and log RTs: F (4.34, 181.78) = 3.62, $p < .01$, $\eta^2 = .08$). More importantly, there was a significant main effect of block (RTs: F (1, 41) = 12.84, $p < .01$, $\eta^2 = .24$; and log RTs: F (1, 41) = 17.10, $p < .001$, $\eta^2 = .29$), and there were significant interactions between block and task (RTs: F (1.29, 52.72) = 3.79, $p < .05$, $\eta^2 = .08$; and log RTs: F (1.73, 70.86) = 3.47, $p < .05$, $\eta^2 = .08$), as well as between block and task triplet (RTs: F (3, 123) = 12.21, $p < .001$, $\eta^2 = .23$; and log RTs: F (3, 123) = 16.22, $p < .001$, $\eta^2 = .28$). Thus, performance was slowed after bivalent stimuli, but this performance slowing differed between tasks and decreased across task triplets (see Figure 2a).

In the follow-up two-way repeated-measures ANOVAs with block (pure, mixed) and task (parity, color, case), the main effect of block was significant for the task triplets N+1 and N+2 (N+1: F (1, 41) = 30, $p < .001$, $\eta^2 = .42$, for RTs, F (1, 41) = 40.09, $p < .001$, $\eta^2 = .49$, for log RTs; and N+2: F (1, 41) = 7.36, $p < .05$, $\eta^2 = .15$, for RTs, and F (1, 41) = 7.42, $p < .01$, $\eta^2 = .15$, for log RTs), but not for subsequent task triplets, Fs < 2.12, ps > .15, $\eta^2 < .05$. Moreover, for N+3, the interaction between block and task approached significance for RTs, F (1.40, 57.59) = 3.41, $p < .06$, $\eta^2 = .08$, and was significant when using log-transformed RTs, F (2, 82) = 4.91, $p < .05$, $\eta^2 = .11$. As depicted in Figure 2a, performance on task triplets N+3 was significantly slowed on color decisions (M = 258 ms, SE = 137 with t (41) = 1.89, $p < .05$, one-tailed, for RTs, and t (41) = 2.80, $p < .01$, for log RTs) but not on parity and case decisions (M = -52 ms, SE = 43, and M = 8 ms, SE = 56, respectively, with ts < 1.20, ps > .24). Thus, performance was slowed on the first two task triplets following bivalent stimuli (345 and 153 ms for N+1 and N+2, respectively) and on the color decisions of the task triplets N+3 (258 ms). This indicates that for the older adults, the performance slowing following bivalent stimuli was shorter-lived and more specific.

Accuracy. Accuracy of univalent stimuli was generally high (*M* = .96, *SE* = 0.003), with young adults (*M* = .97, *SE* = 0.003) being slightly more accurate than older adults (*M* = .96, *SE* = 0.01). This was confirmed in the four-way ANOVA, with block (pure, mixed), task (parity, color, case) and task triplet (N+1, N+2, N+3, N+4) as within-subject factors and age group (young adults, older adults) as a between-subjects factor. In fact, the ANOVA revealed a significant main effect of age group, *F* (1, 82) = 4.40, $p < .05$, $\eta^2 = .05$. Moreover, the main effects of task and task triplet were significant, *F* (1.54, 126) = 31.57, $p < .001$, $\eta^2 = .28$, and *F* (3, 246) = 3.70, $p < .05$, $\eta^2 = .04$, respectively. No other main effect or interactions were significant, *F*s < 1.52, *p*s > .21, $\eta^2 < .02$. Thus, accuracy was higher on parity and case decisions (*M* = .97, *SE* = 0.004, and *M* = .98, *SE* = 0.003, respectively) than on color decisions (*M* = .94, *SE* = 0.01). Furthermore, it was higher on task triplets N+2 and N+3 (both *M* = .97, *SE* = 0.004) than on N+1 and N+4 (*M* = .96, *SE* = 0.004, and *M* = .96, *SE* = 0.005, respectively). Critically, interactions between age and any of the experimental factors were far from significant, which indicates no speed-accuracy trade-off for the critical RTs effects.

Discussion

In Experiment 1, we compared the trajectory of the bivalency effect in young and older adults. For the young adults, the results showed a performance slowing on all tasks for all four task triplets following bivalent stimuli. This effect lasted at least for 17 sec (required for making four task triplets, i.e., 12 decisions, each requiring approximately 750 ms, plus 8 blanks of 500 ms, plus 4 blanks of 1000 ms). This indicates a widespread and long-lasting bivalency effect, replicating previous findings (cf. Meier et al., 2009; 2013; Rey-Mermet et al., 2013). In contrast, for the older adults, the results revealed a widespread performance slowing for the first two task triplets following bivalent stimuli only. For the subsequent task triplet (i.e., N+3), performance was still slowed but only on the color-decision trials. Compared to the young adults, no longer-lasting effect materialized. Thus, for the older adults, the performance slowing following bivalent stimuli was shorter-lived and more specific. This indicates that for the older adults, performance was slowed after the conflict induced by bivalent stimuli, but this performance slowing differed from the typical bivalency effect.

Moreover, the specific performance slowing occurring on the univalent color-decision trials of task triplets N+3 challenges the view that the decline in cognitive control observed in older adults is caused by a general slowing in processing speed (Salthouse, 1996; Salthouse & Babcock, 1991). Rather, this finding seems to be in line with the inhibition deficit in older age (Hasher & Zacks, 1988; Hasher et al., 1999; Persad et al., 2002). However, it is not in line with a “pure” account of an inhibition deficit according to which older adults would have been slowed on all tasks involving conflict-overlapping features, including the case-decision trials. Rather, the performance slowing on the univalent color-decisions trials of task triplets N+3 might be explained by a more specific inhibition deficit. For example, older adults may have been slowed on the univalent color decisions because the color feature was the feature to be inhibited when responding to bivalent stimuli. Alternatively, older adults may have been slowed on the univalent color decisions and not on the case decisions because the color feature is more salient and thus requires more inhibition than the case feature.

Experiment 2

In order to replicate and extend the results of Experiment 1, we conducted a second experiment. In this experiment, different groups of young and older adults were recruited. They were asked to switch between a parity decision, a case decision, and a color decision. The bivalent stimuli were red or blue letters occasionally occurring on color decisions (rather than red or blue letters on case decisions as in Experiment 1). Therefore, when responding to bivalent stimuli, participants had to activate the color decision and to inhibit the case decision. With this variation, we can distinguish between the two explanations for the slowing of the color decisions in triplet N+3 proposed in Experiment 1. In general, as in Experiment 1, we expected that in Experiment 2 older adults would show a shorter-lived and a more task-specific performance slowing following bivalent stimuli compared to young adults. In addition, if older adults are less able to inhibit the feature that had to be inhibited in order to respond to bivalent stimuli, older adults would be slowed on the case decisions on triplet N+3 in Experiment 2 because this is the feature to be inhibited in bivalent stimuli. In contrast, if older adults are less able to inhibit salient features, they would be slowed on color decisions as in Experiment 1.

Method

Participants. Twenty young adults (aged between 18 and 26) and twenty older adults aged over 65 years (range 65 – 85) participated in Experiment 2. In order to recruit the participants faster, we provided compensation (i.e., a course credit for young adults and 20 Swiss Francs for older adults). Three older adults had to be excluded because they consistently performed the case decision instead of the color decision when responding to bivalent stimuli.

This resulted in a sample of 17 participants for the older adults. The demographic information for each age group and the results of the cognitive tests are presented in Table 1 (right half).

Materials. The materials were identical to Experiment 1.

Procedure. The procedure was similar to Experiment 1 except for the following modifications. First, the fixed task order was changed to parity – case -- color (see Figure 1b). Second, bivalent stimuli were red or blue letters occurring on color decisions. Third, participants were instructed to ignore the case decision and to make a color decision when encountering a bivalent stimulus.

Data analysis and Design. The data analysis and design were identical to Experiment 1.

Results

Costs of bivalent stimuli. As in Experiment 1, we first investigated the cost produced by bivalent stimuli (i.e., the colored letters of the color decisions from the task triplets N of the mixed block). To this end, we assessed whether performance on bivalent stimuli was lower than performance on the corresponding univalent stimuli (i.e., the colored symbols of the color decisions from the task triplets N+1 until N+4 of the mixed block), and whether this cost differed between age groups (young vs. older adults).

Reaction times. For the *young* adults, performance was slower on bivalent color decisions (*M* = 992 ms, *SE* = 99) than on univalent color decisions (*M* = 676 ms, *SE* = 40). Similarly, for the *older* adults, performance was slower on bivalent color decisions (*M* = 1494 ms, *SE* = 176) than on univalent color decisions (*M* = 1178 ms, *SE* = 139). A two-way ANOVA with stimulus valence (bivalent color, univalent color) as a within-subject factor and age group (young adults, older adults) as a between-subjects factor showed a significant main effect of stimulus valence (RTs: F (1, 35) = 21.63, $p < .001$, $\eta^2 = .38$; and log RTs: F (1, 35) = 23.89, $p < .001$, $\eta^2 = .41$) and of age group (RTs: F (1, 35) = 10.78, $p < .01$, $\eta^2 = .24$; and log RTs: F (1, 35) = 13.58, $p < .01$, $\eta^2 = .28$). The interaction was not significant, Fs < 1.02, ps > .32, $\eta^2 < .0.3$. Thus, for RTs, the cost produced by bivalent stimuli was similar for young and older adults (M = 316 ms, SE = 72, and M = 316 ms, SE = 120).

Accuracy. For the *young* adults, accuracy was lower on bivalent color decisions (M = .84, SE = 0.05) than on univalent color decisions (M = .96, SE = 0.02). Similarly, for the *older* adults, accuracy was lower on bivalent color decisions (M = .53, SE = 0.07) than on univalent color decisions (M = .97, SE = 0.01). A similar two-way ANOVA showed a significant main effect of stimulus valence, F (1, 35) = 39.99, $p < .001$, $\eta^2 = .45$, of age group, F (1, 35) = 12.61, $p < .01$, $\eta^2 = .26$, and a significant interaction, F (1, 35) = 13.32, $p < .01$, $\eta^2 = .28$. Thus, for accuracy rates, the cost produced by bivalent stimuli was larger for the older adults (M = .44, SE = 0.07, with t (16) = 6.32, $p < .001$) than for the young adults (M = .12, SE = 0.06, with t (19) = 2.11, $p < .05$).

Bivalency effect. As in Experiment 1, the main objective was to examine the bivalency effect in young and older adults. That is, we aimed to determine how long-lasting the bivalency effect was.

Reaction times. The most relevant results are the RTs from the univalent stimuli of the mixed block compared to those of the pure block for the task triplets N+1 to N+4 in both age groups. These results are depicted in Figure 2b. We carried out a four-way ANOVA with block (pure, mixed), task (parity, case, color) and task triplet (N+1, N+2, N+3, N+4) as within-subject factors and age group (young adults, older adults) as a between-subjects factor.

The ANOVA showed a significant main effect of task (RTs: F (1.35, 47.15) = 9.01, p < .01, η^2 = .20; and log RTs: F (1.58, 55.27) = 18.84, p < .001, η^2 = .35) and of task triplet (RTs: F (3, 105) = 17.19, p < .001, η^2 = .33; and log RTs: F (3, 105) = 17.60, p < .001, η^2 = .33) as well as a significant interaction between task and task triplet (RTs: F (3.65, 127.89) = 8.68, p < .001, η^2 = .20; and log RTs: F (6, 210) = 9.38, p < .001, η^2 = .21). As expected, the main effect of age group was also significant (RTs: F (1, 35) = 19.23, p < .001, η^2 = .35; and log RTs: F (1, 35) = 23.63, p < .001, η^2 = .40). Furthermore, there were significant interactions between task and age group (RTs: F (1.35, 47.15) = 3.47, p < .06, η^2 = .09; and log RTs: F (1.58, 55.27) = 7.33, p < .01, η^2 = .17) as well as between task, task triplet, and age group (RTs: F (3.65, 127.89) = 2.74, p < .05, η^2 = .07; and log RTs: F (6, 210) = 1.92, p < .08, η^2 = .05).

More importantly, there was a significant main effect of block (RTs: F (1, 35) = 18.20, p < .001, η^2 = .34; and log RTs: F (1, 35) = 20.24, p < .001, η^2 = .37) and there were significant interactions between block and task (RTs: F (2, 70) = 5.25, p < .05, η^2 = .13; and log RTs: F (2, 70) = 5.95, p < .01, η^2 = .14), between block and task triplet (RTs: F (2.36, 82.58) = 14.29, p < .001, η^2 = .29; and log RTs: F (3, 105) = 12.95, p < .001, η^2 = .27), as well as between block, task and task triplet (RTs: F (3.74, 130.99) = 8.08, p < .001, η^2 = .19; and log RTs: F (6, 210) = 7.75, p < .001, η^2 = .18). Thus, performance on univalent stimuli was slowed in the mixed block compared to the pure block and this performance slowing decreased across tasks and task triplets (from 453 ms for the first decision following bivalent stimuli, that is, the parity decision of task triplet N+1, to 50 ms for the last decision, that is, the color decision of task triplet N+4).

Most critically, the four-way interaction between block, task, task triplet and age group was also significant (RTs: F (3.74, 130.99) = 2.54, $p < .05$, $\eta^2 = .07$; and log RTs: F (6, 210) = 2.48, $p < .05$, $\eta^2 = .07$). No other interaction was significant, Fs < 1.65, ps > .20, $\eta^2 < .04$. Thus, the four-way interaction indicates that both age groups differed in the performance slowing following bivalent stimuli and that tasks and task triplets affected the trajectory of this performance slowing in a different manner (see Figure 2b). As in Experiment 1, we specified the trajectory of this performance slowing for each age group by conducting a three-way repeated-measures ANOVA for each age group, with block (pure, mixed), task (parity, case, color) and task triplet (N+1, N+2, N+3, N+4).

Young adults. For the young adults, the three-way ANOVA revealed a significant main effect of task (RTs: F (2, 38) = 24.89, $p < .001$, $\eta^2 = .57$; and log RTs: F (2, 38) = 28.15, $p < .001$, $\eta^2 = .60$), and of task triplet (RTs: F (1.94, 36.91) = 13.65, $p < .001$, $\eta^2 = .42$; and log RTs: F (3, 57) = 11.19, $p < .001$, $\eta^2 = .37$) as well as a significant interaction between task and task triplet (RTs: F (2.31, 43.87) = 13.30, $p < .001$, $\eta^2 = .41$; and log RTs: F (6, 114) = 9.40, $p < .001$, $\eta^2 = .33$). More importantly, there was a significant main effect of block (RTs: F (1, 19) = 16.30, $p < .01$, $\eta^2 = .46$; and log RTs: F (1, 19) = 16.62, $p < .01$, $\eta^2 = .47$), and there were significant interactions between block and task (RTs: F (1.33, 25.22) = 6.25, $p < .05$, $\eta^2 = .25$; and log RTs: F (2, 38) = 3.25, $p < .05$, $\eta^2 = .15$), between block and task triplet (RTs: F (1.87, 35.57) = 11.13, $p < .001$, $\eta^2 = .37$; and log RTs: F (2.32, 44.17) = 7.27, $p < .01$, $\eta^2 = .28$), as well as between block, task, and task triplet (RTs: F (2.34, 44.43) = 9.89, $p < .001$, $\eta^2 = .34$; and log RTs: F

(3.92, 74.51) = 7.16, $p < .001$, $\eta^2 = .27$). Thus, for the young adults, the performance slowing following bivalent stimuli decreased across tasks and task triplets (see Figure 2b).

To determine this decrease more precisely, we carried out further follow-up two-way repeated-measures ANOVAs with the factors block (pure, mixed) and task (parity, case, color) for each task triplet. For task triplets N+1, there was a main effect of block (RTs: F (1, 19) = 23.49, $p < .001$, $\eta^2 = .55$; and log RTs: F (1, 19) = 32.85, $p < .001$, $\eta^2 = .63$), and a significant interaction between block and task (RTs: F (1.08, 20.59) = 12.35, $p < .01$, $\eta^2 = .39$; and log RTs: F (1.37, 26.04) = 12.16, $p < .01$, $\eta^2 = .39$). Thus, performance on task triplets N+1 was slowed on all three tasks (i.e., on parity decisions with t (19) = 4.13, $p < .01$, for RTs, and t (19) = 5.11, $p < .001$, for log RTs; on case decisions with t (19) = 1.96, $p < .05$, one-tailed, for RTs, and t (19) = 1.72, $p < .05$, one-tailed, for log RTs; and on color decisions with t (19) = 1.73, $p < .05$, one-tailed, for RTs, and t (19) = 1.74, $p < .05$, one-tailed, for log RTs). However, this performance slowing was larger on parity decisions (M = 577 ms, SE = 40) than on case and color decisions (M = 53 ms, SE = 27, and M = 60 ms, SE = 34, respectively). For the two subsequent task triplets (i.e., N+2 and N+3), the main effect of block was also significant or at least approached significance (N+2: F (1, 19) = 3.26, $p < .09$, $\eta^2 = .15$, for RTs, and F (1, 19) = 4.18, $p = .05$, $\eta^2 = .18$, for log RTs; and N+3: F (1, 19) = 5.21, $p < .05$, $\eta^2 = .21$, for RTs, and F (1, 19) = 5.22, $p < .05$, $\eta^2 = .22$, for log RTs). Across these task triplets, no interaction between block and task was significant, Fs < 1.62, ps > .21, $\eta^2 < .08$. For the task triplet N+4, neither the main effect of block nor the interaction between block and task was significant, Fs < 1.37, ps > .26, $\eta^2 < .07$. Thus, for the young adults, the performance slowing following bivalent stimuli occurred on all three tasks (with 183, 34, and 59 ms for the parity, case, and color decisions, respectively). Moreover, it decreased across the task triplets from 230 ms to 47 ms to 61 ms and to 29 ms for N+1, N+2, N+3 and N+4, respectively, and it was significant until N+3. This indicates a widespread and long-lasting bivalency effect and it replicates previous studies (see Meier et al., 2009; 2013; Rey-Mermet et al., 2013).

Older adults. For the older adults, the three-way repeated-measures ANOVA with block (pure, mixed), task (parity, case, color) and task triplet (N+1, N+2, N+3, N+4) revealed that the main effect of task was not significant when using RTs, F (1.09, 17.41) = 1.93, $p = .18$, $\eta^2 = .11$, but it was significant when using log-transformed RTs, F (1.19, 19.12) = 4.43, $p < .05$, $\eta^2 = .22$. Furthermore, the main effect of task triplet was significant (RTs: F (3, 48) = 5.55, $p < .01$, $\eta^2 = .26$; and in log RTs: F (3, 48) = 7.17, $p < .001$, $\eta^2 = .31$). More importantly, there was a significant main effect of block (RTs: F (1, 16) = 5.31, $p < .05$, $\eta^2 = .25$; and log RTs: F (1, 16) = 5.41, $p < .05$, $\eta^2 = .25$) and a significant interaction between block and task triplet (RTs: F (3, 48) = 4.82, $p < .01$, $\eta^2 = .23$; and log RTs: F (3, 48) = 5.87, $p < .01$, $\eta^2 = .27$). Moreover, the interactions between block and task as well as between block, task, and task triplet were not significant when using RTs, F (1.48, 23.65) = 1.93, $p = .17$, $\eta^2 = .11$, and F (3.47, 55.51) = 1.87, $p = .14$, $\eta^2 = .10$, respectively. However, both interactions were significant when using log-transformed RTs, F (2, 32) = 3.81, $p < .05$, $\eta^2 = .19$, and F (6, 96) = 2.83, $p < .05$, $\eta^2 = .15$, respectively. The latter analyses indicate that performance was slowed after bivalent stimuli, but this performance slowing decreased across task triplets and seemed to differ across tasks (see Figure 2b).

In the follow-up two-way repeated-measures ANOVAs with block (pure, mixed) and task (parity, case, color), the main effect of block was significant for the task triplets N+1 (RTs: *F* (1, 16) = 10.60, $p < .01$, $\eta^2 = .40$; and log RTs: *F* (1, 16) = 15.29, $p < .01$, $\eta^2 = .49$), but not for subsequent task triplets, *F*s < 1.42, *p*s > .25, $\eta^2 < .08$. Moreover, for N+1, the interaction between block and task was not significant when using RTs, *F* (2, 32) = 1.23, $p = .30$, $\eta^2 = .07$, but it was significant when using log-transformed RTs, *F* (2, 32) = 3.55, $p < .05$, $\eta^2 = .18$. Performance on task triplet N+1 was slowed on all three tasks (i.e., on parity decisions with *t* (16) = 3.07, $p < .01$, for RTs, and *t* (16) = 3.82, $p < .001$, for log RTs; on case decisions with *t* (16) = 2.05, $p < .05$, one-tailed, for RTs, and *t* (16) = 2.25, $p < .05$, for log RTs; and on color decisions with *t* (16) = 1.43, $p < .08$, one-tailed, for RTs, and *t* (16) = 1.97, $p < .05$, one-tailed, for log RTs). This performance slowing was larger on parity decisions (*M* = 329 ms, *SE* = 107) than on case and color decisions (*M* = 139 ms, *SE* = 68, and *M* = 167 ms, *SE* = 117, respectively).

In addition, for N+3, the interaction between block and task approached significance for RTs, *F* (1.45, 23.26) = 3.40, $p < .06$, $\eta^2 = .17$, and was significant when using log-transformed RTs, *F* (2, 32) = 4.92, $p < .05$, $\eta^2 = .23$. As depicted in Figure 2b, performance on task triplets N+3 was significantly slowed on color decisions (*M* = 205 ms, *SE* = 122 with *t* (16) = 1.68, $p < .06$, one-tailed, for RTs, and *t* (16) = 2.17, $p < .05$, for log RTs) but not on parity and case decisions (*M* = 36 ms, *SE* = 73, and *M* = 78 ms, *SE* = 51, respectively, with *t*s < 1.53, *p*s > .14). Thus, performance was slowed on the first task triplets following bivalent stimuli (212 ms) and on the color decisions of the task triplets N+3 (205 ms). As in Experiment 1, this indicates that for the older adults, the performance slowing following bivalent stimuli was shorter-lived and more specific.

Accuracy. Accuracy of univalent stimuli was generally high ($M = .97$, $SE = 0.004$). The four-way ANOVA with block (pure, mixed), task (parity, color, case) and task triplet (N+1, N+2, N+3, N+4) as within-subject factors and age group (young adults, older adults) as a between-subjects factor revealed a significant main effect of task, F (1.42, 49.86) = 5.70, $p < .05$, $\eta^2 = .14$, and a significant interaction between task and task triplet, F (6, 210) = 3.55, $p < .01$, $\eta^2 = .09$. No other main effects or interactions were significant, *F*s < 2.81, *p*s > .07, $\eta^2 < .07$. Thus, accuracy was higher on case decisions ($M = .98$, $SE = 0.005$) than on parity decisions ($M = .97$, $SE = 0.004$), which was, in turn, higher than on color decisions ($M = .96$, $SE = 0.01$). We further investigated the significant interaction between task and task triplet by averaging the data across the two block types as well as across both age groups and by carrying out follow-up one-way repeated-measures ANOVAs with the factor task triplet (N+1, N+2, N+3, N+4) for each task separately. Only for the parity decisions, the one-way ANOVA showed a significant main effect of task triplet, F (3, 108) = 2.95, $p < .05$, $\eta^2 = .08$, with a significant quadratic component, F (1, 36) = 10.64, $p < .05$, $\eta^2 = .23$. Thus, for the parity decisions, accuracy was higher in the task triplets N+2 and N+3 (both *M*s = .98, $SE = .01$) than in the task triplets N+1 and N+4 (both *M*s = .96, $SE = .01$). Critically, there was no main effect or interaction involving block or age group. This indicates that no speed-accuracy trade-off compromised the critical RTs effects and that accuracy did not differ between young and older adults ($M = .97$, $SE = 0.01$, and $M = .98$, $SE = 0.003$, respectively).

Discussion

The results of Experiment 2 replicated the general pattern of results that we have found in Experiment 1. They showed that for young adults, performance was significantly slowed on each of the three tasks after the occurrence of bivalent stimuli. Moreover, this performance slowing decreased across the four task triplets and was still significant for the third task triplet (i.e., N+3). Thus, the performance slowing lasted for at least 13 sec (required for making three task triplets, i.e., 9 decisions, each requiring approximately 750 ms, plus 6 blanks of 500 ms, plus 3 blanks of 1000 ms), which replicates the widespread and long-lasting bivalency effect observed in young adults (see Meier et al., 2009; 2013; Rey-Mermet et al., 2013). For the older adults, the results of Experiment 2 revealed a performance slowing for the first task triplet following bivalent stimuli and then for the color decisions of the task triplets N+3. This last finding is interesting because it rules out the explanation that older adults show a specific inhibition deficit for the feature that had to be inhibited to respond to bivalent stimuli. Rather, it is line with the explanation that older adults are slowed on the color decisions of triplet N+3 because the color feature is salient and thus needs to be more inhibited than the case feature.

General Discussion

The purpose of the present study was to determine whether age affects the adjustment of cognitive control following a conflict. To this end, we performed two experiments in which the bivalency effect (i.e., the performance slowing that occurs on all univalent trials following the conflict induced by bivalent stimuli) was investigated in a group of young adults (aged 20-30) and in a group of older adults (aged over 65 years). In both experiments, participants had to switch between a parity decision on black numerals, a color decision on red or blue symbols, and a case decision on black letters. Bivalent stimuli were red or blue letters occurring on some case decisions in Experiment 1 and red or blue letters occurring on some color decisions in Experiment 2. In both experiments, the results showed that for the young adults, performance was slowed on all tasks for all task triplets following bivalent stimuli. Moreover, this performance slowing decreased across the task triplets and was significant until the fourth task triplet in Experiment 1 and until the third task triplet in Experiment 2. Therefore, the present results replicate previous findings by showing a widespread and long-lasting bivalency effect for the young adults (cf. Meier et al., 2009; 2013; Rey-Mermet et al., 2013; Rey-Mermet & Meier, 2013). In contrast, for the older adults, the results showed only a short-lived performance slowing after the occurrence of bivalent stimuli (i.e., for the first two task triplets in Experiment 1 and for the first task triplet in Experiment 2). Moreover, in the third task triplet (i.e., N+3), performance was only slowed on the univalent color-decision trials. Thus, compared to young adults, older adults showed a shorter-lived and more specific performance slowing following bivalent stimuli. Together, the results of the present study indicate that for older adults, performance was slowed after the conflict induced by bivalent stimuli. However, this performance slowing differed from the typical pattern of the bivalency effect observed in young adults.

While the main results were similar in both experiments, the results of the cognitive tests were slightly different between experiments (see Table 1). In Experiment 1, young adults performed significantly better than older adults in the working memory tests as well as in the executive functions test. In contrast, in Experiment 2, young adults performed significantly better than older adults in both working memory tests, but not in the executive functions test. This suggests that older adults were somewhat higher-functioning in Experiment 2 than in Experiment

1. However, this difference did not affect the main results of the present study. Thus, irrespective of the differences in these tests, older adults showed a shorter-lived and more task-specific slowing than young adults. This supports the generality and robustness of our findings.

We would like to emphasize that, if we had only analyzed the change in the magnitude of the bivalency effect, we would not have found a difference between age groups. In fact, when the performance slowing after bivalent stimuli is considered irrespective of the tasks and of its long-lasting nature, it does not differ significantly between groups, neither in Experiment 1 (young adults: *M* = 84 ms, *SE* = 15; and older adults: *M* = 160 ms, *SE* = 45, with *t* (50.75) = 1.60, *p* = .11, for RTs, and *t* (82) = 0.67, *p* = .50, for log RTs) nor in Experiment 2 (young adults: *M* = 92 ms, *SE* = 23; and older adults: *M* = 79 ms, *SE* = 34, with *t* (35) = 0.33, *p* = .75, for RTs, and *t* (35) = 1.25, *p* = .22, for log RTs). Therefore, it is particularly enlightening to investigate the trajectory of the bivalency effect, not only its magnitude.

The results of the present study replicate the typical pattern of the bivalency effect for young adults (Meier et al., 2009; 2013; Meier & Rey-Mermet, 2012b; Rey-Mermet & Meier, 2013). As indicated by the previous bivalency effect studies, this effect most probably results from a combination of two different sources: The performance slowing on the first task triplet following bivalent stimuli stems from an orienting response caused by the infrequence of bivalent stimuli (see Rey-Mermet & Meier, 2013; see also Metzak et al., 2013). The performance slowing on the subsequent tasks triplets (i.e., N+2 until N+4) is caused by the reactivation of the conflict-loaded context, as predicted by the episodic context binding account (Meier et al., 2009; 2013; Meier & Rey-Mermet, 2012a; Rey-Mermet et al., 2013). Older adults also show the orienting response as reflected by the performance slowing on the first task triplet following bivalent stimuli. However, they seem to show a deficit in episodic context binding because the performance slowing was shorter-lived than for young adults. This is in line with the well-documented age-related decline in memory (Craik & Salthouse, 2008; Hasher et al., 1999; Meier, Rey-Mermet, Rothen & Graf, 2013; Salthouse , 1996). It is also consistent with the lack of a bivalency effect in amnesic patients who are characterized by profound memory impairments (Meier et al., 2013). In addition to the reduced persistence of the bivalency effect, older adults showed a specific deficit in inhibiting salient features. This was expressed as a performance slowing on the univalent color-decision trials of task triplets N+3 (see Hasher & Zacks, 1988; Hasher et al., 1999; Persad et al., 2002).

These results suggest that after encountering a conflict in young adults cognitive control is adjusted for an extended period of time while in older adults this is not the case. The latter result may be related to the continuing performance requirements, that is, switching between tasks and task sets, which absorbs the capacity required to form and retain an enduring conflict-loaded memory representation. In real life, forgetting to execute an intention over a short delay can be considered as a consequence of this reduced persistence of adjustment of cognitive control (e.g., Einstein, McDaniel, Manzi, Cochran, & Baker, 2000; McDaniel, Einstein, Stout, & Morgan, 2003; Zimmermann & Meier, 2006; 2010). Specifically, in some situations, a person may successfully retrieve the intention upon encountering a prospective memory cue – which is typically a bivalent stimulus (cf. Meier & Rey-Mermet, 2012b) -- but have to briefly delay the execution of the task.

To summarize, the results of the present study show that age has an impact on the adjustment of cognitive control following the conflict induced by bivalent stimuli. Specifically, with older age, this adjustment of cognitive control becomes short-lived and more task-specific. Thus, age does not only affect the processing of a conflict-loaded trial as already demonstrated in previous studies but also affects how subsequent stimuli are processed.

Acknowledgments

We thank Yannik Faes, Simone Ingold, Anja Lanz, Leonie Müller, Martina Studer, and Lea Waldis for testing the participants of Experiment 1, and Inci Demir and Stefan Walter for testing the participants of Experiment 2. We also thank Stefan Walter for helpful comments on an earlier version.

References

Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G. W. Humphrey, J. Duncan, & A. Treisman (Eds.), *Attention, space and action: Studies in cognitive neuroscience* (pp. 273–296). New York, NY: Oxford University Press.

Allport, A., & Wylie, G. (2000). Task-switching, stimulus-response bindings, and negative priming. In S. Monsell & J. S. Driver (Eds.), *Control of Cognitive Processes: Attention and Performance XVIII* (pp. 35–70). Cambridge, MA: MIT Press.

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

Borella, E., Delaloye, C., Lecerf, T., Renaud, O., & de Ribaupierre, A. (2009). Do age differences between young and older adults in inhibitory tasks depend on the degree of activation of information? *European Journal of Cognitive Psychology*, *21*(2-3), 445–472. doi:10.1080/09541440802613997

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. doi:10.1037//0033-295X.108.3.624

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. *Memory & Cognition*, *24*(4), 403–416.

Craik, F.I.M., & Salthouse, T. (2008). Handbook of aging and cognition. NY: Psychology Press.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(4), 380–390. doi:10.3758/CABN.7.4.380

Einstein, G. O., McDaniel, M. A., Manzi, M., Cochran, B., & Baker, M. (2000). Prospective memory and aging: Forgetting intentions over short delays. *Psychology and Aging, 15,* 671–683.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*(4), 480–506.

Grundy, J. G., Benarroch, M. F. F., Woodward, T. S., Metzak, P. D., Whitman, J. C., & Shedden, J. M. (2013). The bivalency effect in task switching: Event-related potentials. *Human Brain Mapping*, *34*(5), 999–1012. doi:10.1002/hbm.21488

Hartley, A. A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychology and Aging*, *8*(3), 371–379.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hasher, L., Zacks, R., & May, C. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII. Cognitive regulation of performance: Interaction of theory and application* (pp. 653–675). Cambridge, MA: MIT Press.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494–500. doi:10.1016/j.tics.2004.08.007

Hsieh, S., Liang, Y.-C., & Tsai, Y.-C. (2012). Do age-related changes contribute to the flanker effect? *Clinical Neurophysiology, 123*(5), 960–972. doi:10.1016/j.clinph.2011.09.013

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*(4), 491–512.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*(1), 126–147. doi:10.1037/0882- 7974.15.1.126

Lehrl, S., Merz, J., Burkhard, G., & Fischer, B. (1991). *MWT-A: Mehrfachwahl-Wortschatz-Intelligenztest. Parallelform zum MWT-B.* Erlangen: Perimed.

Lien, M.-C., Ruthruff, E., & Kuhns, D. (2008). Age-related differences in switching between cognitive tasks: Does internal control ability decline with age? *Psychology and Aging, 23*(2), 330–341. doi:10.1037/0882-7974.23.2.330

Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition, 7*(3), 166–174. doi:10.3758/BF03197535

Lowe, D. G., & Mitterer, J. O. (1982). Selective and divided attention in a Stroop task. *Canadian Journal of Psychology, 36*(4), 684–700. doi:10.1037/h0080661

Ludwig, C., Borella, E., Tettamanti, M., & de Ribaupierre, A. (2010). Adult age differences in the Color Stroop Test: A comparison between an item-by-item and a blocked version.

Archives of Gerontology and Geriatrics, 51(2), 135–142. doi:10.1016/j.archger.2009.09.040

Mayas, J., Fuentes, L. J., & Ballesteros, S. (2012). Stroop interference and negative priming (NP) suppression in normal aging. *Archives of Gerontology and Geriatrics*, *54*(2), 333–338. doi:10.1016/j.archger.2010.12.012

McDaniel, M. A., Einstein, G. O., Stout, A. C., & Morgan, Z. (2003). Aging and maintaining intentions over delays: Do it or lose it. *Psychology and Aging, 18,* 823–835.

Meier, B., & Rey-Mermet, A. (2012a). Beyond feature binding: Interference from episodic context binding creates the bivalency effect in task-switching. *Frontiers in Psychology, 3,* 386–394. doi:10.3389/fpsyg.2012.00386

Meier, B., & Rey-Mermet, A. (2012b). Beyond monitoring: After-effects of responding to prospective memory targets. *Consciousness and Cognition*, *21*(4), 1644–1653. doi:10.1016/j.concog.2012.09.003

Meier, B., Rey-Mermet, A., Rothen, N. & Graf, P. (2013). Recognition memory across the lifespan: the impact of word frequency and study-test interval on estimates of familiarity and recollection. *Frontiers in Psychology, 4:*787. doi: 10.3389/fpsyg.2013.00787

Meier, B., Rey-Mermet, A., Woodward, T. S., Müri, R., & Gutbrod, K. (2013). Episodic context binding in task switching: Evidence from amnesia. *Neuropsychologia*, *51*(5), 886–892. doi:10.1016/j.neuropsychologia.2013.01.025

Meier, B., Woodward, T. S., Rey-Mermet, A., & Graf, P. (2009). The bivalency effect in task switching: General and enduring. *Canadian Journal of Experimental Psychology, 63*(3), 201–210. doi:10.1037/a0014311

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1423–1442. doi:10.1037/0278-7393.22.6.1423

Metzak, P. D., Meier, B., Graf, P., & Woodward, T. S. (2013). More than a surprise: The bivalency effect in task switching. *Journal of Cognitive Psychology*, *25*(7), 833–842. doi:10.1080/20445911.2013.832196

Mutter, S. A., Naylor, J. C., & Patterson, E. R. (2005). The effects of age and task context on Stroop task performance. *Memory & Cognition*, *33*(3), 514–530. doi:10.3758/BF03193068

Notebaert, W., Houtman, F., Van Opstal, F., Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: An orienting account. *Cognition*, *111,* 275-279. doi: 10.1016/j.cognition.2009.02.002

Notebaert, W., & Verguts, T. (2011). Conflict and error adaptation in the Simon task. *Acta Psychologica*, *136,* 212-216. doi: 10.1016/j.actpsy.2010.05.006

Nùñez Castellar, E., Kühn, S., Fias, W., & Notebaert, W. (2010). Outcome expectancy and not accuracy determines post-error slowing: ERP support. *Cognitive, Affective, & Behavioral Neuroscience*, *10*, 270-278. doi: 10.3758/CABN.10.2.270

Persad, C. C., Abeles, N., Zacks, R. T., & Denburg, N. L. (2002). Inhibitory changes after age 60 and their relationship to measures of attention and memory. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *57*(3), 223–232. doi:10.1093/geronb/57.3.P223

Puccioni, O., & Vallesi, A. (2012). Conflict resolution and adaptation in normal aging: The role of verbal intelligence and cognitive reserve. *Psychology and Aging*, *27*(4), 1018–1026. doi:10.1037/a0029106

Rabbitt, P. (1979). How old and young subjects monitor and control responses for accuracy and speed. *British Journal of Psychology*, *70,* 205–311.

Rabbitt, P., & Vyas, S. M. (1980). Selective anticipation for events in old age. *Journal of Gerontology, 35*(6), 913–919.

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin*, *114*(3), 510–532. doi:10.1037/0033-2909.114.3.510

Regard, M. (1981). *Cognitive rigidity and flexibility: A neuropsychological study* (Unpublished Ph.D. dissertation). University of Victoria.

Rey-Mermet, A., Koenig, T., & Meier, B. (2013). The bivalency effect represents an interference-triggered adjustment of cognitive control: An ERP study. *Cognitive, Affective, & Behavioral Neuroscience*. Advance online publication. doi:10.3758/s13415-013-0160-z

Rey-Mermet, A., & Meier, B. (2012a). The bivalency effect: Adjustment of cognitive control without response set priming. *Psychological Research*, *76*(1), 50–59. doi:10.1007/s00426-011-0322-y

Rey-Mermet, A., & Meier, B. (2012b). The bivalency effect: Evidence for flexible adjustment of cognitive control. *Journal of Experimental Psychology: Human Perception and Performance, 38*(1), 213–221. doi:10.1037/a0026024

Rey-Mermet, A., & Meier, B. (2013). An orienting response is not enough: Bivalency not infrequency causes the bivalency effect. *Advances in Cognitive Psychology*, *9*(3), 146–155. doi:10.2478/v10053-008-0142-9

Rey-Mermet, A., & Meier, B. (2014). More conflict does not trigger more adjustment of cognitive control for subsequent events: A study of the bivalency effect. *Acta Psychologica*, *145*, 111–117. doi:10.1016/j.actpsy.2013.11.005

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*(2), 207–231. doi:10.1037/0096-3445.124.2.207

Rush, B. K., Barch, D. M., & Braver, T. S. (2006). Accounting for cognitive aging: Context processing, inhibition or processing speed? *Aging, Neuropsychology, and Cognition*, *13*(3-4), 588–610. doi:10.1080/13825580600680703

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403–428.

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology*, *27*(5), 763–776. doi:10.1037/0012-1649.27.5.763

Tewes, U. (1991). *Hamburg-Wechsler Intelligenztest für Erwachsene, Revision 1991, HAWIE-R*. Bern: Huber.

Trewartha, K. M., Penhune, V. B., & Li, K. Z. H. (2011). Movement kinematics of prepotent response suppression in aging during conflict adaptation. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *66*(2), 185–194. doi:10.1093/geronb/gbq090

Van der Lubbe, R. H. J., & Verleger, R. (2002). Aging and the Simon task. *Psychophysiology*, *39*(1), 100–110.

Verhaeghen, P. (2011). Aging and executive control: Reports of a demise greatly exaggerated. *Current Directions in Psychological Science*, *20*(3), 174–180. doi:10.1177/0963721411408772

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience & Biobehavioral Reviews*, *26*(7), 849–857. doi:10.1016/S0149-7634(02)00071-4

Verhaeghen, P., & De Meersman, L. (1998). Aging and the Stroop effect: A meta-analysis. *Psychology and Aging*, *13*(1), 120–126.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., & Cerella, J. (2003). Aging and dual-task performance: A meta-analysis. *Psychology and Aging*, *18*(3), 443–460. doi:10.1037/0882-7974.18.3.443

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology*, *46*(4), 361–413. doi:10.1016/S0010-0285(02)00520-0

West, R. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*(2), 272–292.

West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. *Psychophysiology*, *37*(2), 179–189. doi:10.1111/1469-8986.3720179

West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging*, *13*(2), 206–217.

West, R., & Moore, K. (2005). Adjustments of cognitive control in younger and older adults. *Cortex*, *41*(4), 570–581. doi:10.1016/S0010-9452(08)70197-7

Woodward, T. S., Meier, B., Tipper, C., & Graf, P. (2003). Bivalency is costly: Bivalent stimuli elicit cautious responding. *Experimental Psychology*, *50*(4), 233–238. doi:10.1026//1618-3169.50.4.233

Woodward, T. S., Metzak, P. D., Meier, B., & Holroyd, C. B. (2008). Anterior cingulate cortex signals the requirement to break inertia when switching tasks: A study of the bivalency effect. *NeuroImage*, *40*(3), 1311–1318. doi:10.1016/j.neuroimage.2007.12.049

Wylie, G., & Allport, A. (2000). Task switching and the measurement of “switch costs.” *Psychological Research*, *63*(3-4), 212–233. doi:10.1007/s004269900003

Yoshizaki, K., Kuratomi, K., Kimura, Y., & Kato, K. (2013). Age-related change of location-based visual selectivity depending on conflict frequency. *Japanese Psychological Research*, *55*(1), 72–83. doi:10.1111/j.1468-5884.2012.00534.x

Zimmermann, T. & Meier, B. (2006). The rise and decline of prospective memory across the lifespan. *The Quarterly Journal of Experimental Psychology, 59*, 2040-2046. doi:10.1002/acp.1576

Zimmermann, T.D., & Meier, B. (2010). The effect of implementation intentions on prospective memory performance across the lifespan. *Applied Cognitive Psychology, 24,* 645-658. doi:10.1002/acp.1576

Table 1

Experiments 1 and 2: Characteristics of the participants

	Experiment 1			Experiment 2		
	Young adults	Older adults	independent samples *t*-test	Young adults	Older adults	independent samples *t*-test
n	42	42	-	20	17	-
Gender (male:female)	20:22	17:25	-	4:16	10:7	-
Age (years)	23.3 (2.7)	72.8 (4.7)	**	21.1 (2)	73.7 (6.6)	**
Years of education	14 (1.9)	12 (3.0)	**	12.8 (3.9)	14.6 (3.6)	*ns*
MMSE[a]	-	27.5 (2.2)	-	-	26.1 (1.7)	-
Estimated verbal IQ[b]	112.4 (10.1)	114.4 (11.8)	*ns*	112.7 (8.8)	125.4 (10.1)	**
Forward digit span scores	8.2 (1.9)	6.8 (2.1)	*	7.3 (2.1)	6.1 (1.5)	+
Backward digit span scores	7.8 (1.8)	5.2 (1.4)	**	6.6 (1.5)	4.8 (1)	**
VST interference score[c]	1.5 (0.2)	1.8 (0.4)	*	1.5 (0.3)	1.6 (0.3)	*ns*

Note. Standard deviations in parentheses. + < .05, * p < .01, ** p < .001.

[a] MMSE: Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975).

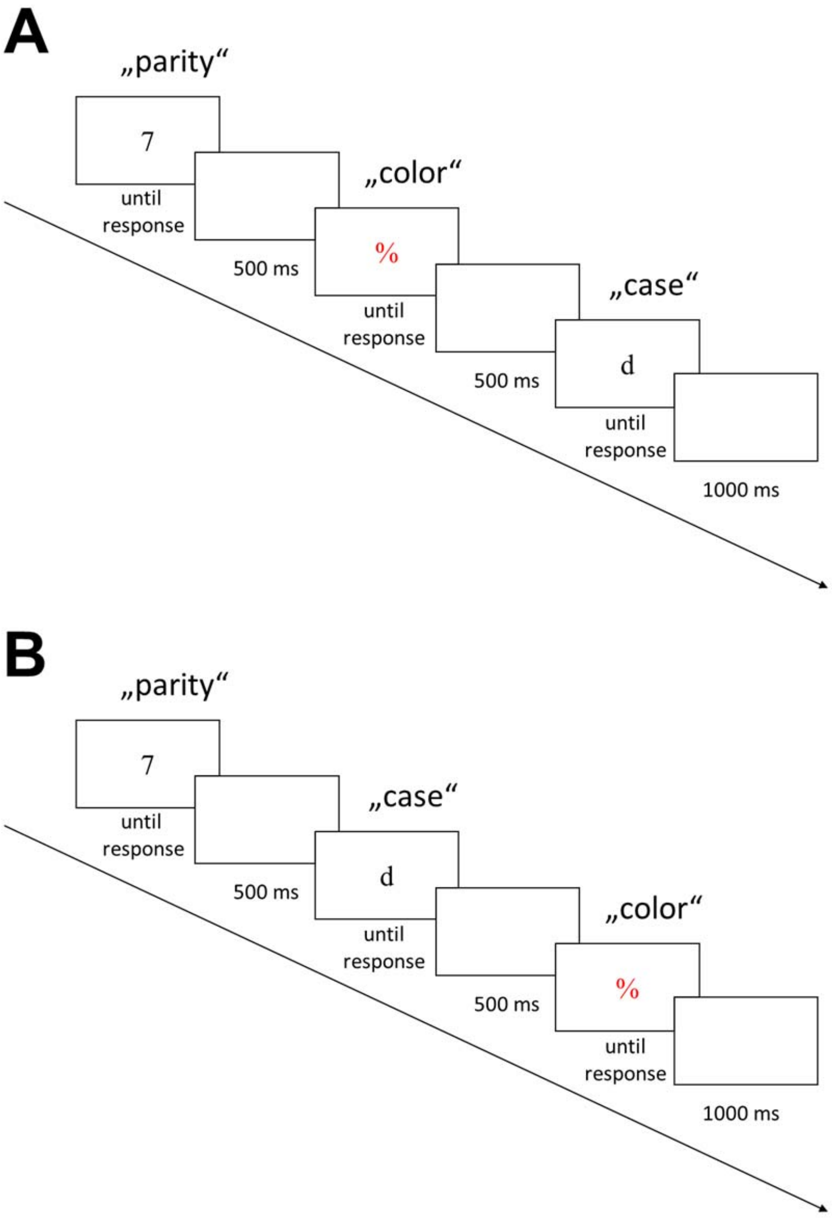
[b] Verbal IQ was assessed by the MWT-A, a standardized German vocabulary test (Lehrl, Merz, Burkhard, & Fischer, 1991).

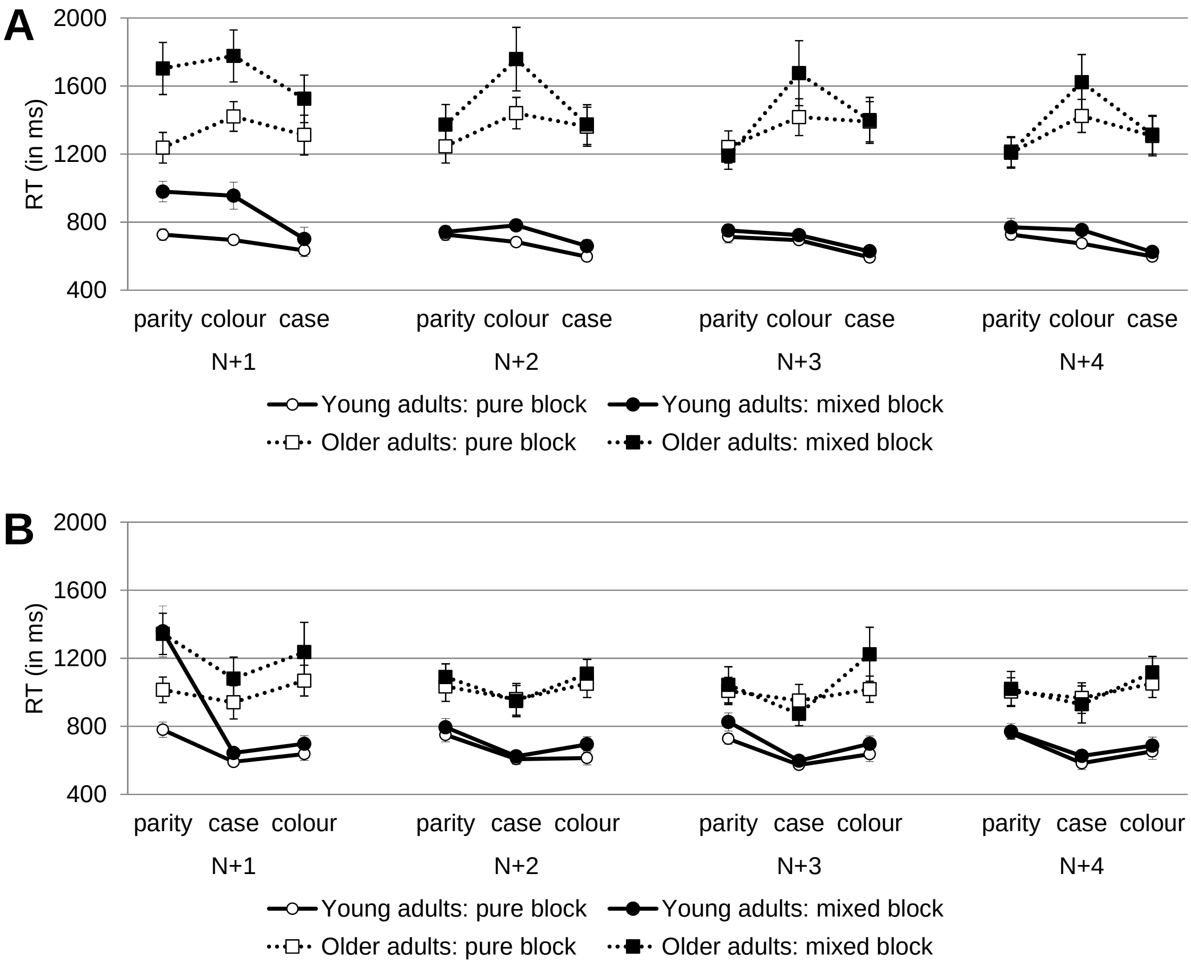
[c] VST: Victoria Stroop Test (Regard, 1981). Interference scores were calculated as the number of seconds required to name color words divided by the number of seconds required to name colored dots.

Figure captions

Figure 1. Example of one univalent task triplet: Participants carried out a parity decision (odd vs. even) on numerals, a color decision (red vs. blue) on symbols, and a case decision (upper- vs. lowercase) on letters. A) Experiment 1: On a bivalent task triplet (not pictured here), red or blue letters were presented in the case decision. B) Experiment 2: On a bivalent task triplet (not pictured here), red or blue letters were presented in the color decision.

Figure 2. Mean reaction times for task triplets from the mixed block (filled symbols) and for corresponding task triplets from the pure block (empty symbols) in young adults (circles) and older adults (squares). Task triplet N refers to the triplet containing a bivalent decision in the mixed block; subsequent task triplets (represented here) are labeled N+1, N+2, N+3, and N+4, respectively. Error bars represent standard errors. A) Experiment 1. B) Experiment 2.


A
„parity“
7
until response
500 ms
„color“
%
until response
500 ms
„case“
d
until response
1000 ms
B
„parity“
7
until response
500 ms
„case“
d
until response
500 ms
„color“
%
until response
1000 ms


A
2000
1600
1200
800
400
RT (in ms)
parity colour case
N+1
parity colour case
N+2
parity colour case
N+3
parity colour case
N+4
Young adults: pure block
Young adults: mixed block
Older adults: pure block
Older adults: mixed block
B
2000
1600
1200
800
400
RT (in ms)
parity case colour
N+1
parity case colour
N+2
parity case colour
N+3
parity case colour
N+4
Young adults: pure block
Young adults: mixed block
Older adults: pure block
Older adults: mixed block