Effects of Age and Cognitive-control Availability on the Deactivation of Completed Intentions

Marcus Möschl¹, Rico Fischer², Thomas Goschke¹, Mareike Altgassen³, Karina Burger³, & Moritz Walser¹

¹Department of Psychology, Technische Universität Dresden, Dresden, Germany

²Department of Psychology, University of Greifswald, Greifswald, Germany

³Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, The Netherlands

Corresponding author:

Marcus Möschl

Technische Universität Dresden

Department of Psychology

D-01062 Dresden, Germany

E-mail: marcus.moeschl@tu-dresden.de

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Abstract

In everyday life, we frequently postpone intended actions (prospective memory; PM), but also need to deactivate completed intentions in order to flexibly adapt to subsequent activities. Recent findings of an increased risk to erroneously repeat completed actions (i.e., commission errors) in older adults with cognitive-control deficits suggest that successful intention deactivation hinges on the availability of cognitive control. It is unclear, however, whether transient availability of cognitive control during encounters of no-longer-relevant PM retrieval cues is critical for intention deactivation. Here we investigated this with varying levels of cognitive-control availability during no-longer-relevant PM cues in older and younger adults. Replicating previous findings, in Experiment 1 we found that older adults exhibited a tendency for impaired intention deactivation in terms of nominally higher performance costs in no-longer-relevant PM trials and a higher commission-error risk than younger adults. While performance costs and commission-error rates in no-longer-relevant PM trials did not differ between extremes of cognitive-control availability, slightly loading cognitive-control resources drastically reduced performance costs. Importantly, this effect was not replicated with a more fine-grained variation of cognitive-control availability in Experiment 2, in which we exclusively tested younger adults. These findings suggested that intention deactivation is not modulated by transient cognitive-control availability. Surprisingly, however, we also found that the rather low number of commission errors in Experiment 2 even dropped with decreasing cognitive-control availability. We discuss conditions under which transient cognitive-control availability may affect intention deactivation and review alternative sources of age effects on intention deactivation besides global cognitive-control impairments.

Keywords: aging, prospective memory, intention deactivation, cognitive control, commission errors

Introduction

Several times throughout a day, we form intentions that are postponed until the right circumstances are met to perform them (Kliegel & Martin, 2003). This ability, known as prospective memory (PM), comes into play, for instance, when we plan to give a friend a call at 6 p.m. (time-based PM) or when coming home (event-based PM). While PM enables us to perform everyday tasks like these, deactivating intentions after their completion makes it possible to flexibly re-adjust behavior according to novel intentions or current situational demands (e.g., Goschke, 2003; Goschke & Bolte, 2018; Mayr & Keele, 2000). Surprisingly, completing an intention does not necessarily lead to a direct deactivation of the intention representation, but can impair subsequent task performance and even trigger erroneous repetitions of completed intentions (commission errors) when encountering no-longer-relevant PM cues (PM_{REPEATED} cues) that previously signaled the opportunity to retrieve an intention (e.g., Anderson & Einstein, 2017; Pink & Dodson, 2013; Scullin, Bugg, & McDaniel, 2012; Walser, Fischer, & Goschke, 2012; cf. Cohen, Gordon, Jaudas, Hefer, & Dreisbach, 2017; Scullin, Einstein, & McDaniel, 2009). Previous findings suggest that especially older adults exhibit difficulties in disengaging from no-longer-relevant tasks (e.g., Boywitt, Rummel, & Meiser, 2015; Scullin, Bugg, McDaniel, & Einstein, 2011), which in some cases might translate to commission errors like accidental overmedication (Gray, Mahoney, & Blough, 2001; Kimmel et al., 2007). Importantly, the mechanisms behind these so-called aftereffects of completed intentions and successful intention deactivation are still not well understood.

In the present study, we aimed at elucidating the role of cognitive-control availability during encounters of PM_{REPEATED} cues for intention deactivation. To this aim, we investigated aftereffects of completed intentions under varying degrees of cognitive-control demands for ongoing-task processing during PM_{REPEATED}-cue encounters. Additionally, to further clarify

under which conditions aging may affect intention deactivation we investigated the potential interplay between cognitive-control availability and aging effects on the deactivation of completed intentions.

While intention deactivation does not seem to simply rely on availability of time (Scullin & Bugg, 2013; Walser, Plessow, Goschke, & Fischer, 2014) or cognitive resources after intention completion (Walser, Goschke, & Fischer, 2014), as was suggested by earlier work (Beckmann, 1994; Penningroth, 2011), more recent findings suggest that successful intention deactivation hinges on cognitive-control availability during encounters of PM_{REPEATED} cues. More specifically, according to a dual mechanisms account, commission errors are the result of an initial spontaneous and almost automatic retrieval of an intention in response to PM_{REPEATED} cues that is followed by a failure to deactivate or inhibit *retrieval* of the no-longer-relevant intention via cognitive-control mechanisms (Bugg, Scullin, & Rauvola, 2016; Scullin & Bugg, 2013; see also Meiser & Rummel, 2012).

Importantly, even in the absence of a commission error, failures of *complete* intention deactivation frequently lead to slowed or more erroneous ongoing-task performance in PM_{REPEATED} trials compared to neutral control trials (Scullin, Bugg, McDaniel, & Einstein, 2011; Walser, Fischer, & Goschke, 2012). One source of these aftereffects is that encountering PM_{REPEATED} cues triggers a conflict between the to-be-performed ongoing-task response and the no-longer-relevant PM response. This for instance, was demonstrated by a neuroimaging study (Beck, Ruge, Walser, & Goschke, 2014): PM_{REPEATED} cues triggered increased activation of the anterior cingulate cortex and transient activation of rostrolateral prefrontal cortex. The authors argued that this pattern reflects mobilization of reactive control by a response conflict (Braver, 2012). Since resolving this conflict takes time and cognitive resources, Beck et al. (2014) observed response slowing in PM_{REPEATED} trials.

The notion of a cognitive-control dependent intention deactivation is corroborated by several additional findings: First, commission errors were observed more frequently under conditions that tax cognitive control after intention completion, like divided attention (Boywitt, Rummel, & Meiser, 2015; Pink & Dodson, 2013; cf. Schaper & Grundgeiger, 2017) and fatigue (Scullin & Bugg, 2013) or under increased intention-deactivation demands due to implementation-intention encoding of PM tasks (Bugg, Scullin, & McDaniel, 2013) or a lack of retrieval opportunities for intended actions (Bugg & Scullin, 2013; Bugg et al., 2016). Second, increased RT aftereffects were also linked to impaired cognitive flexibility, as has been observed in state-oriented individuals (Walser, Goschke, et al., 2014; see also Penningroth, 2011). Third and most prominently, the notion of a control-dependent intention deactivation is corroborated by findings of older adults being more prone to making a commission error after intention completion than younger adults (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin, Bugg, & McDaniel, 2012; Scullin et al., 2011; cf. Bugg et al., 2013; Cohen, Dixon, & Lindsay, 2005) or older adults showing RT aftereffects under certain conditions where younger adults did not (Scullin et al., 2011). The increased frequency and magnitude of aftereffects of completed intentions in older adults has mostly been attributed to a supposed age-related decline in inhibitory cognitive-control functions (e.g., Hasher, Quig, & May, 1997; Lustig, Hasher, & Zacks, 2007; cf. Verhaeghen, 2011; Bugg, 2014). In some studies it was also linked to impaired performance in Stroop color naming, Trail Making Test B and Wisconsin Card Sorting Test in older but not younger adults (Scullin & Bugg, 2013; Scullin et al., 2012).

Although the above findings seem to corroborate the dual-mechanisms account of commission errors they do not provide unambiguous support for a general cognitive-control dependence of intention deactivation, given the diversity of variables that seem to affect intention deactivation. First, the effects of aging, divided attention, implementation-intention

encoding, fatigue and state orientation can be considered relatively long lasting and may thus not only affect intention deactivation, but also PM performance and task performance after intention completion. This in turn might influence aftereffects of completed intentions. Second, it is debatable whether the observed modulators of intention deactivation primarily target cognitive-control availability: At least with active intentions, divided attention manipulations for instance have been shown to affect spontaneous intention retrieval but not cognitive control over executing intended actions (Harrison, Mullet, Whiffen, Ousterhout, & Einstein, 2014). That is, demanding divided attention task (random number generation) only impaired PM performance when intention retrieval was presumably not fully automatic—i.e., with non-salient PM cues. With salient PM cues, however, divided attention manipulations had no effect on PM performance. Hence, increased aftereffects under divided attention might not reflect impaired inhibition of no-longer-relevant intended actions but rather impaired intention retrieval. Most importantly, so far there is no *direct* test of a potential cognitive-control dependency of intention deactivation and little is known about the effects of cognitive-control availability during encounters of PM_{REPEATED} cues and intention deactivation. Hence, based on previous studies it is not only difficult to pinpoint the mechanism(s) responsible for successful intention deactivation. It is also unclear whether intention deactivation is simply affected by general task demands prior to or after intention completion or whether it is particularly susceptible to cognitive-control availability during encounters of PM_{REPEATED} cues, as suggested by the dual mechanisms account of PM commission errors (Bugg et al., 2016).

The present study

Here, we directly tested the effects of transient cognitive-control availability during PM_{REPEATED}-cue encounters on the deactivation of completed intentions. For this, in two experiments we parametrically varied trial-by-trial cognitive-control demands during task

performance and presented PM_{REPEATED} cues in trials that induced varying degrees of conflict in stimulus processing (e.g., Fan, 2014) (Figure 1). This allowed us to elucidate the relationship between the transient availability of cognitive control after intention completion and intention deactivation beyond the two-step manipulations of cognitive-control demands in previous studies (e.g., Bugg & Scullin, 2013; Bugg et al., 2013, 2016). Additionally, we aimed at separating potential effects of transient versus enduring cognitive-control demands on intention deactivation to further investigate under which conditions aging might affect intention deactivation. To this aim, in Experiment 1, we compared the effects of trial-by-trial cognitive-control demands on aftereffects of completed intentions between younger and older adults. In Experiment 2, we assessed only younger adults and extended the control-demand manipulation to allow for a more fine-grained analysis of cognitive-control-availability effects on aftereffects of completed intentions.

To reduce the risk of confounding potential effects of age or cognitive-control availability with effects of PM performance differences on aftereffects of completed intentions (Bugg & Scullin, 2013; Bugg et al., 2016), we used a design that should reliably produce both high PM performance and strong aftereffects of completed intentions: First, we used salient PM cues (i.e., red symbols) that have been shown to result in high PM performance (Beck et al., 2014; Scullin et al., 2012), reduce age differences in event-based PM performance (Kretschmer-Trendowicz & Altgassen, 2016; Rendell, McDaniel, Forbes, & Einstein, 2007) and seem to reliably produce strong aftereffects of completed intentions (Beck et al., 2014; Scullin et al., 2012). Second, we strongly emphasized the importance of the PM task during task instructions to foster PM performance (Walter & Meier, 2014). Third, to increase the size of aftereffects of completed intentions, we used the same ongoing task during PM-task performance and aftereffects measurement (Scullin et al., 2012).

In both experiments, we adapted a paradigm during which participants performed multiple cycles of a PM block and a subsequent test block (see also Walser et al., 2012). Participants' ongoing task was to judge the direction of the majority of horizontal arrows that were presented in a circular display (majority function task; Fan, Guise, Liu, & Wang, 2008; Wu, Dufford, Mackie, Egan, & Fan, 2016) (Figure 1). In PM blocks, participants received additional instructions to press the spacebar instead of making directional judgments in response to a pre-specified PM cue. In subsequent test blocks that served to measure aftereffects of completed intentions, no-longer-relevant PM cues from the completed PM task (PM_{REPEATED} cues) were presented as irrelevant distractors (e.g., Anderson & Einstein, 2017; Pink & Dodson, 2013; Scullin et al., 2012; Walser et al., 2012). Our primary measures of interest were aftereffects of completed intentions during test blocks in terms of commission errors and ongoing-task performance costs (i.e., response slowing and increased error rates) during PM_{REPEATED} compared to control (i.e., oddball) trials that served as a baseline to assess orientation reactions to novel stimuli (Walser et al., 2012).

To induce different degrees of cognitive-control availability during processing of PM_{REPEATED} cues, we manipulated the ratio of arrows pointing to the same or opposite direction during the ongoing majority-function task (e.g., trials in ratio 3:2 comprised 3 left and 2 right arrows; Figure 1B). This manipulation of arrow ratio goes beyond the qualitative manipulation of cognitive-control demands (conflict vs. no-conflict) in typical conflict tasks like Stroop color naming (Stroop, 1935) or Flanker tasks (Eriksen & Eriksen, 1974) in that it allows to induce different degrees of conflict and cognitive-control demands (i.e., computational load, Fan et al., 2008). We reasoned that inducing this kind of computational load in PM_{REPEATED} trials should mobilize and bind cognitive-control resources for ongoing-task performance (Goschke & Dreisbach, 2008; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011) and draw resources away from processes required for intention deactivation.

In line with previous findings of conflict-strength dependent adjustments of executive functions (e.g., Wendt, Kiesel, Geringswald, Purmann, & Fischer, 2014), this control mobilization should be proportionate to the degree of conflict induced by ongoing-task stimuli. Accordingly, we hypothesized that if intention deactivation requires available cognitive control during $PM_{REPEATED}$ cue encounters, aftereffects of completed intentions in terms of commission errors and/or performance costs in $PM_{REPEATED}$ compared to oddball trials should rise with increasing cognitive-control demands on ongoing-task performance (i.e., conflict strength) in $PM_{REPEATED}$ trials.

Additionally, based on previous findings of impaired intention deactivation in older adults (Bugg et al., 2016), in Experiment 1, we expected a main effect of age with increased aftereffects of completed intentions in older compared to younger adults. Furthermore, since age effects on commission errors have been shown to increase under high demands on cognitive control (Bugg et al., 2016) and were linked to impaired cognitive-control functioning in older adults (Scullin et al., 2012, 2011), we assumed that aging would exacerbate effects of cognitive-control demands on aftereffects of completed intentions.

Figure 1. Procedure. (A) Illustration of trial sequences during PM and test blocks in the majority function task. Participants had to determine the direction of the majority of arrows in all ongoing-task trials except for prospective memory (PM) trials, in which they were required to press the spacebar instead. PM and $PM_{REPEATED}$ cues were red symbols that were presented in the center of the screen. Aftereffects of completed intentions were assessed during test blocks by comparing ongoing-task performance between $PM_{REPEATED}$ and oddball trials. (B) Illustration of possible arrow locations and arrow ratios in Experiment 1. In Experiment 2, arrows could appear at 12 possible locations and arrow ratios were 7:0, 6:1, 5:2, and 4:3.

Experiment 1

To assess the effects of cognitive-control availability and aging on intention deactivation, we compared aftereffects of completed intentions in PM_{REPEATED} trials between arrow ratios 5:0 (no control demand), 4:1 (low demand), and 3:2 (high demand) in younger and older adults.

Methods

Ethics statement. The study was approved by the Institutional Review Board of the Technische Universität Dresden. All participants provided informed consent prior to performing any study procedures.

Participants. Twenty-four younger (18 female, 19–28 years, $M_{\text{age}} = 24.1$, $SD_{\text{age}} = 2.2$ years) and 24 older adults (13 female, 57–75 years, $M_{\text{age}} = 68.3$, $SD_{\text{age}} = 5.7$ years) took part in two sessions of the experiment lasting approximately 1.5 h each, in exchange for partial course credit or 15 €. Sum scores of the German *Mehrfachwortschatz Intelligenztest MWT-A* (English version: Multiple Choice Word Test-A; Lehrl, Merz, Burkhard, & Fischer, 1991) did not differ significantly between younger ($M = 31.5$, $SD = 3.1$) and older adults ($M = 32.1$, $SD = 1.9$), $t(37.94) = -0.84$, $p = .407$, $d = -0.24$, suggesting that age groups did not differ in premorbid intelligence.

Apparatus and Stimuli. The experiment was performed on a Windows XP SP2 personal computer running Presentation® software (Version 16.3, www.neurobs.com). A standard German (*QWERTZ*) keyboard was used to record participants' responses. Stimuli were presented in Wingdings font against a light gray background on a 19-inch monitor at a resolution of 1280 × 1024 pixels (viewing distance approx. 60 cm). For ongoing-tasks, participants were instructed to press the *X* key with their left index finger if the majority of arrows pointed towards the left and to press the *period* (.) key with their right index finger if the majority of arrows pointed to the right. For PM tasks, participants were instructed to

interrupt the majority judgments and instead press the spacebar in response to a pre-specified symbol (PM cue; e.g.,). Trials were composed of either three or five black arrows (font size 17 pt, visual angle $\approx 5.7^\circ$) that could appear at eight equidistant positions along the outline of an imaginary circle (radius ≈ 1.4 cm, vertical visual angle $\approx 32.8^\circ$; Figure 1B). The position of arrows was determined randomly for each trial. PM cues, PM_{REPEATED} cues and oddballs comprised 30 symbols (e.g., ; font size 53 pt, vertical visual angle $\approx 17.7^\circ$, see Appendix for all stimuli) that were presented in red at the center of the screen.

Procedure. At the beginning of each session, participants gave their informed consent and briefly practiced the ongoing task. Participants then performed eight cycles of a PM block that included an event-based PM task, and a subsequent ongoing-task-only test block. This design—two sessions with several PM-block–test-block cycles—allowed us to increase the number of aftereffect measurements while avoiding the individual session from being too long (Walser, Plessow, et al., 2014).

In order to facilitate PM performance and avoid a potential confound of aftereffect differences with differences in PM performance, we emphasized PM-task importance at the beginning of the experiment and at the start of each PM block (i.e., “*It is important that you concentrate on detecting the symbol [PM cue].*”) (Walter & Meier, 2014). Instructions were displayed for 14 s at the beginning of a block. At the end of PM blocks, participants were informed that the current task was finished (i.e., “*Thank you. The current task is finished now.*”, 3 s) and subsequently moved on to an ongoing-task-only test block.

Each PM and test block consisted of 72 trials (66 standard, 3 PM/PM_{REPEATED}, 3 oddball trials). Standard trials were 54 trials with five arrows (set size 5; 18 trials per arrow ratios 5:0, 4:1 and 3:2), and 12 trials with three arrows (set size 3; 6 trials per arrow ratios 3:0 and 2:1). We reasoned that including trials in set size 3 would reduce monotony during the experiment and could potentially increase general task-difficulty due to unexpected changes

in arrow quantity in ongoing-task trials. PM or PM_{REPEATED} and oddball cues were presented randomly after the first four trials of a block (standard trials only) and appeared only once during a block in each arrow ratio of set size 5 (5:0, 4:1, 3:2).

Trials started with the presentation of a black fixation cross (plus sign, Arial font, size 20 pt, vertical visual angle $\approx 6.7^\circ$) for 1000 ms, followed by the presentation of the imperative stimulus for a maximum of 5000 ms or until a response was given, followed by a blank screen for 400 ms. Errors and response omissions prompted a feedback tone (784 Hz) that was delivered through headphones for the first 200 ms of the blank screen. Deviant symbols for PM, PM_{REPEATED} and oddball trials were drawn randomly from a pool of 30 symbols and were presented simultaneously with onset of ongoing-task stimuli.

Results

We conducted separate analyses for response times (RTs), commission errors and other error types (i.e., erroneous ongoing-task responses or response omissions) in trials of set-size 5 only, since only these contained PM and PM_{REPEATED} stimuli. For RT analyses, errors (8.1% response failure or miss) and trials with RTs ± 2.5 SDs of a participant's mean RT for a given arrow ratio and trial type within each block were excluded (2.3%). The relevant data is set forth in Figure 2 and Table 1.

Manipulation checks. In order to test whether increasing cognitive-control demands decreased cognitive-control availability during task performance and how this was affected by aging, we conducted repeated-measures ANOVAs involving the factors age (younger vs. older adults) and arrow ratio (5:0, 4:1, 3:2) on ongoing-task standard-trial RTs and error rates (excluding erroneous PM responses¹) that were averaged across PM and test blocks.

Subsequently, to determine whether potential effects of cognitive-control demand and/or age

¹ We excluded erroneous PM responses from this manipulation check, since we conducted a separate analysis of commission-errors for our main analyses.

on aftereffects of completed intentions could be the result of differences in PM performance, we conducted similar ANOVAs on PM-trial RTs and error rates.

Ongoing-task performance. Older adults responded slower in standard trials (1280 ms) than younger adults (803 ms), $F(1, 46) = 44.01, p < .001, \eta_p^2 = .49$. As indicated by a significant main effect of arrow ratio, $F(2, 92) = 251.06, p < .001, \eta_p^2 = .85$, increasing the arrow ratio resulted in longer ongoing-task RTs (5:0: 653 ms, 4:1: 1000 ms, 3:2: 1472 ms). A significant Arrow ratio $\times$ Age interaction, $F(2, 92) = 10.88, p = .002, \eta_p^2 = .19$, with a significant linear contrast, $F(1, 46) = 11.31, p = .002, \eta_p^2 = .20$, revealed that increasing the arrow ratio produced a stronger increase in ongoing-task RTs in older than in younger adults.

Error rates were not affected by age (younger adults: 8.3%, older adults: 7.2%), $F(1, 46) = 0.76, p = .387, \eta_p^2 = .02$. Similar to RT data, increasing the arrow ratio increased error rates, $F(2, 92) = 190.37, p < .001, \eta_p^2 = .81$ (5:0: 0.8%, 4:1: 3.6%, 3:2: 18.9%). Arrow ratio did not interact with age, $F(2, 92) = 0.73, p = .483, \eta_p^2 = .02$.

PM performance. Younger adults responded faster to PM cues (755 ms) than older adults (1084 ms), $F(1, 46) = 41.46, p < .001, \eta_p^2 = .47$. We found a small effect of arrow ratio, $F(2, 92) = 5.65, p = .005, \eta_p^2 = .11$. Repeated contrasts revealed slower PM responses in 5:0 (940 ms) compared to 4:1 PM trials (896 ms), $F(1, 46) = 10.93, p = .002, \eta_p^2 = .19$, which were faster than PM responses in 3:2 PM trials (921 ms), $F(1, 46) = 4.10, p = .049, \eta_p^2 = .08$. This effect did not differ between age groups, $F(2, 92) = 0.56, p = .570, \eta_p^2 = .01$.

We found no effect of age on PM-error rates (younger adults: 12.3%; older adults: 14.0%), $F(1, 46) = .40, p = .530, \eta_p^2 = .01$. Surprisingly, PM-error rates declined with increasing arrow ratio, $F(2, 92) = 24.63, p < .001, \eta_p^2 = .35$. Repeated contrasts revealed that this effect was most likely driven by a strong decrease in error rates from 5:0 (19.7%) to 4:1 trials (9.1%), $F(1, 46) = 44.03, p < .001, \eta_p^2 = .49$, since arrow ratio did not affect error rates in 4:1 compared to 3:2 trials (10.7%), $F(1, 46) = 1.18, p = .283, \eta_p^2 = .03$. As indicated by a

significant Arrow ratio $\times$ Age interaction, $F(2, 92) = 5.26, p = .008, \eta_p^2 = .10$, and planned contrasts, increasing the arrow ratio from 5:0 to 4:1 produced a stronger decrease in PM errors in the younger (14.2%) than in older adults (5.9%), $F(1, 46) = 8.22, p = .006, \eta_p^2 = .15$. The difference between 4:1 and 3:2 trials did not differ between groups (younger adults: -1.5% , older adults: -1.5%), $F(1, 46) = 0.00, p = 1.000, \eta_p^2 = .00$.

Aftereffects of completed intentions. In order to investigate the effects of age and cognitive-control demand on intention deactivation, we conducted Arrow ratio (5:0, 4:1, 3:2) $\times$ Age (younger vs. older adults) repeated-measures ANOVAs on aftereffects of completed intentions in terms of performance differences between PM_{REPEATED} and oddball trials in RTs, error rates (erroneous ongoing-task responses and response omissions) and commission-error rates during test blocks (see Walser, Goschke, Möschl, & Fischer, 2017, for a similar analysis). Additionally, in line with previous research on commission errors (Anderson & Einstein, 2017; Bugg et al., 2016), we also analyzed the proportion of participants who made at least one commission error during test blocks. To determine statistical significance of our hypotheses-relevant effects, age effects on intention deactivation were tested at a Bonferroni-corrected alpha level of .0125 (.05/4), whereas cognitive-control demand effects and Arrow ratio $\times$ Age interactions were tested at an alpha level of .0167 (.05/3), respectively. Note that p values for tests at the Bonferroni-corrected alpha levels are denoted as p^* . Effect sizes for aftereffects of completed intentions and paired-samples t -tests refer to standardized within-subject mean differences (d_{rm} ; Lakens, 2013).

RTs. Due to missing RT data in 43 out of 48 PM_{REPEATED} trials, one older adult was excluded from RT analysis. We found that, while older adults exhibited nominally larger aftereffects (98 ms, $d_{rm} = 0.21$) than younger adults (54 ms, $d_{rm} = 0.14$), this difference did not reach significance at the Bonferroni-corrected alpha level, $F(1, 45) = 4.15, p^* = .048, \eta_p^2 = .09$. Aftereffects were affected by arrow ratio, $F(2, 90) = 4.99, p^* = .014, \eta_p^2 = .10$. Planned

comparisons showed that aftereffects in 5:0 trials (110 ms, $d_{rm} = 0.26$) were larger than in 4:1 trials (21 ms, $d_{rm} = 0.05$), $F(1, 45) = 11.72$, $p = .001$, $\eta_p^2 = .21$, which were smaller than aftereffects in 3:2 trials (95 ms, $d_{rm} = 0.18$), $F(1, 45) = 6.79$, $p = .012$, $\eta_p^2 = .004$. Since visual inspection of the data suggested that aftereffects might differ between the extreme poles of cognitive-control availability, we also conducted a post-hoc t test that revealed no difference in aftereffects between 5:0 and 3:2 trials, $t(46) = -0.37$, $p = .714$, $d_{rm} = -0.07$. The effect of arrow ratio on aftereffects did not differ between groups, $F(2, 90) = 0.38$, $p^* = .646$, $\eta_p^2 = .01$.

Errors. We found no significant effects on aftereffects in error rates, all F s ≤ 1.20 , p^* s $\geq .29$, η_p^2 s $\leq .01$.

Commission errors. Erroneous PM responses in test blocks occurred mostly in PM_{REPEATED} trials (younger adults: 4, older adults: 80), with few commission errors in oddball trials (younger adults: 1, older adults: 17) and four commission errors by older adults in standard trials (Table 2). The majority of commission errors in PM_{REPEATED} trials was made by two older adults in either the first (67% [16 out of 24 PM_{REPEATED} trials]) or both experimental sessions (90% [36 out of 48 PM_{REPEATED} trials]). While on a descriptive level, older adults produced larger commission-error aftereffects (5.47%, $d_{rm} = 0.31$) than younger adults (0.3%, $d_{rm} = 0.23$), this difference failed to reach significance at the Bonferroni-corrected alpha level, $F(1, 46) = 3.47$, $p^* = .069$, $\eta_p^2 = .07$. Commission-error aftereffects did not differ statistically between arrow ratios, $F(2, 92) = 1.52$, $p^* = .227$, $\eta_p^2 = .03$ (3.4%, $d_{rm} = 0.25$; 2.3%, $d_{rm} = 0.14$; 2.9%, $d_{rm} = 0.24$, in arrow ratios 5:0, 4:1 and 3:2, respectively). Arrow ratio did not interact with age, $F(2, 92) = 1.14$, $p^* = .309$, $\eta_p^2 = .02$.

In line with previous studies (Anderson & Einstein, 2017; Scullin et al., 2012), we also analyzed the proportion of participants who made at least one commission error in PM_{REPEATED} or oddball trials during test blocks. The analysis revealed that, on a descriptive

level, more older adults ($n = 12$) than younger adults ($n = 4$) made a commission error. This age effect, however, did not reach significance at the Bonferroni-corrected alpha level, $\chi^2(1) = 6.00$, $p^* = .014$, OR = 5.00.

Figure 2. Results from Experiment 1. (A) Mean response times (RT), error rates (erroneous ongoing-task responses and response omissions) for performance in PM blocks and test blocks as a function of trial type (standard, PM, PM_{REPEATED}, oddball), arrow ratio (5:0, 4:1, 3:2) and age (younger adults, older adults). (B) Proportion of younger and older adults who made at least one commission error and mean commission-error (CE) rates during test blocks as a function of trial type, arrow ratio and age group. Error bars represent standard errors of the mean.

Table 1
Mean (SD) Performance during PM- and Test blocks in Experiment 1.

Trial type	Arrow ratio (cognitive-control demand)					
	5:0		4:1		3:2	
	RT (ms)	Errors (%)	RT (ms)	Errors (%)	RT (ms)	Errors (%)
Younger adults						
PM blocks						
Standard	503 (57)	0.6 (0.7)	768 (170)	4.2 (4.4)	1152 (368)	20.8 (11.6)
PM	769 (115)	21.9 (14.4)	739 (109)	6.8 (6.1)	756 (114)	8.3 (7.7)
Oddball	728 (92)	1.0 (4.0)	953 (211)	3.6 (5.5)	1266 (399)	22.4 (16.6)
Test blocks						
Standard	496 (58)	0.9 (1.4)	757 (172)	4.2 (4.6)	1142 (385)	19.3 (10.6)
PM _{REPEATED}	715 (155)	1.0 (2.4)	838 (180)	4.7 (6.5)	1323 (447)	19.8 (14.7)
Oddball	633 (106)	0.8 (2.1)	835 (227)	5.2 (6.3)	1246 (446)	19.3 (16.7)
Aftereffects ^a	82 (72)	0.3 (2.2)	4 (117)	-0.5 (5.2)	77 (228)	0.5 (12.8)
Older adults						
PM blocks						
Standard	811 (151)	1.0 (2.2)	1246 (273)	3.1 (3.0)	1787 (487)	18.1 (8.5)
PM	1111 (238)	17.4 (14.0)	1054 (236)	11.5 (11.3)	1086 (231)	13.0 (10.6)
Oddball	1295 (204)	2.3 (4.0)	1539 (361)	3.4 (4.1)	2020 (591)	16.7 (11.5)
Test blocks						
Standard	802 (151)	0.7 (1.5)	1230 (282)	2.8 (2.5)	1805 (474)	17.3 (8.2)
PM _{REPEATED}	1245 (324)	1.3 (4.1)	1409 (332)	4.9 (5.8)	1864 (518)	16.4 (11.0)
Oddball	1108 (236)	0.8 (2.8)	1392 (310)	4.4 (5.4)	1750 (459)	19.8 (13.8)
Aftereffects ^a	137 (137)	0.5 (4.8)	40 (134)	0.5 (7.1)	114 (405)	-3.4 (13.5)

Note. Error rates represent erroneous ongoing-task responses and response omissions.

^aAftereffects represent performance differences between PM_{REPEATED} and oddball trials.

Table 2
Mean (SD) Commission-error (CE) rates during Test Blocks in Experiment 1.

Trial type	Arrow ratio (cognitive-control demand)		
	5:0	4:1	3:2
	CE (%)	CE (%)	CE (%)
Younger adults			
Test block			
Standard	-	-	-
PM _{REPEATED}	0.8 (2.1)	0.3 (1.3)	-
Oddball	0.3 (1.3)	-	-
Aftereffects ^a	0.5 (2.6)	0.3 (1.3)	-
Older adults			
Test block			
Standard	-	0.0 (0.1)	0.0 (0.1)
PM _{REPEATED}	7.8 (15.0)	6.2 (16.8)	6.8 (18.0)
Oddball	1.6 (4.6)	1.8 (4.7)	1.0 (3.0)
Aftereffects ^a	6.2 (11.5)	4.4 (13.1)	5.7 (16.9)

^aAftereffects represent performance differences between PM_{REPEATED} and oddball trials.

Discussion

In Experiment 1, we compared effects of trial-by-trial cognitive-control availability on intention deactivation between younger and older adults. Regarding our manipulation of cognitive-control demands, results were straight-forward: Increasing the arrow ratio in ongoing-task trials produced the expected decline in ongoing-task performance (see also Fan, 2014; Fan et al., 2008), indicating that increasing cognitive-control demands seems to have decreased cognitive-control availability during task performance. This demand-dependent response slowing in standard trials was more pronounced in older adults, which was not mirrored by error data. Such results might be indicative of a greater susceptibility of older adults for transient cognitive-control-demand effects on response initiation and/or a compensatory performance slowing of elderly to maintain high quality of ongoing-task performance (e.g., Kopp, Lange, Howe, & Wessel, 2014).

As expected, PM performance with salient PM cues was high and PM error rates did not increase as a function of cognitive-control demand. By contrast, we even found an unexpected decrease in PM error rates with increasing cognitive-control demand. As our analysis of ongoing-task performance suggests, however, this was likely the result of overall faster responses during trials in arrow ratio 5:0 leading participants to miss PM cues more often than in other arrow ratios. This overlooking of PM cues in 5:0 trials seems to have been exacerbated by overall faster ongoing-task and PM responses in younger adults, which led to a slightly more pronounced PM-error decrease with increasing arrow ratio in younger compared to older adults.

Older adults exhibited slowed PM performance while PM accuracy was not affected by age. This mirrors findings of comparable accuracy but slowed performance in older compared to younger adults in task switching (Kopp et al., 2014) and provides further evidence for spontaneous PM-retrieval processes with salient PM cues being spared with

aging (e.g., Bugg et al., 2016; Kretschmer-Trendowicz & Altgassen, 2016; Scullin et al., 2011). The latter finding also renders it unlikely that potential age effects on intention deactivation could be confounded by age-related PM-performance differences.

Regarding age effects on intention deactivation, we replicated previous findings of nominally increased aftereffects of completed intentions in terms of performance costs in $PM_{REPEATED}$ compared to oddball trials as well as nominally increased commission-error aftereffects and a tendency for an increased number of participants who made a commission error in the older-adults compared to the younger-adults group (e.g., Scullin & Bugg, 2013; Scullin et al., 2012). Moreover, contrary to our hypothesis, effects of cognitive-control demand on intention deactivation did not differ between younger and older adults. This was especially surprising, given that we found stronger cognitive-control-demand effects on ongoing-task performance in older compared to younger adults. We will discuss potential mechanisms of this age effect on intention deactivation in the general discussion.

Most importantly, regarding the modulation of intention deactivation by transient cognitive-control availability, results were ambiguous. We found no modulation of aftereffects in error or commission-error rates by cognitive-control demands. Similarly, RT aftereffects did not differ between extreme poles of control demands (5:0 vs. 3:2 trials), suggesting that intention deactivation does not depend on trial-by-trial cognitive-control availability. This interpretation is challenged strongly, however, by the absence of aftereffects during low-conflict trials (4:1). As an alternative, one could argue that due to increased processing demands of conflict compared to no-conflict trials (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, 2012), our manipulation of cognitive-control availability might affect intention deactivation only during conflict trials. That is, while low-conflict trials might have attenuated processing of $PM_{REPEATED}$ cues via increased shielding of the ongoing task (Goschke & Dreisbach, 2008), high-conflict trials might have impaired

focusing attention on ongoing-task stimuli (e.g., Lavie, 2005) and consequently exacerbated interference from $PM_{REPEATED}$ cues.

Experiment 2

We conducted Experiment 2 to test if we could replicate the absence of aftereffects during low-conflict trials from Experiment 1, and to allow a more fine-grained investigation (no conflict vs. low conflict vs. medium conflict vs. high conflict) of the potential modulation of intention deactivation by transient cognitive-control demands during conflict trials. We reasoned that if intention deactivation was modulated by cognitive-control availability only during conflict trials, then aftereffects should be decreased in low-, compared to no-conflict trials, but should increase linearly with increasing conflict strength across medium- and high-conflict trials. Since cognitive-control-demand effects on intention deactivation did not differ between younger and older adults in Experiment 1, we only investigated younger adults in Experiment 2.

Methods.

Participants. Forty-eight participants (35 female, 19–29 years, $M_{age} = 23.8$, $SD_{age} = 2.9$ years) took part in two sessions lasting approximately 1.5 h each, in exchange for partial course credit or 15 €.

Stimuli and Procedure. Stimuli and procedure for Experiment 2 were similar to Experiment 1, with the following changes: Ongoing-task trials comprised five or seven arrows that could appear at 12 possible locations on the screen. PM and test blocks consisted of 98 trials (90 standard, 4 $PM/PM_{REPEATED}$, 4 oddball trials), with 80 trials in set size 7 (20 trials per arrow ratios 7:0, 6:1, 5:2 and 4:3) and 18 trials in set size 5 (6 trials per arrow ratios 5:0, 4:1 and 3:2). Deviant symbols for PM, $PM_{REPEATED}$ and oddball trials were drawn randomly from a pool of 32 symbols. Note that PM or $PM_{REPEATED}$ symbols were presented

pseudo-randomly throughout a block, with the restriction, that at least five trials were in between PM or PM_{REPEATED} trial presentations.

Results.

Analyses were conducted on trials of set-size 7 only, since only these contained PM and PM_{REPEATED} stimuli. For RT analyses, errors (10.8% response failure or miss) and trials with RTs ± 2.5 SDs of a participant's mean RT for a given arrow ratio and trial type within each block were excluded (2.5%). The relevant data is set forth in Figure 2 and Table 3.

Manipulation checks. Similar to Experiment 1, we first examined the effects of cognitive-control demands on ongoing-task performance to assess whether increasing control demands decreased cognitive-control availability. To this aim, we conducted repeated-measures ANOVAs on standard-trial RTs and error rates (excluding erroneous PM responses¹) averaged across PM and test blocks as a function of arrow ratio (7:0, 6:1, 5:2, 4:3). Subsequently, we analyzed PM performance (RTs, error rates) in similar ANOVAS to determine whether potential cognitive-control-demand effects on aftereffects of completed intentions could be the result of PM-performance differences between cognitive-control demands.

Ongoing-task performance. Standard-trial RTs increased with increasing arrow ratio, $F(3, 141) = 93.82, p < .001, \eta_p^2 = .67$, (7:0: 530 ms, 6:1: 670 ms, 5:2: 878 ms, 4:3: 1177 ms). This effect was mirrored by error data, $F(3, 141) = 565.02, p < .001, \eta_p^2 = .92$, (7:0: 1.2%, 6:1: 3.1%, 5:2: 9.9%, 4:3: 28.1%).

PM performance. Arrow ratio did not affect RTs in PM trials (Table 2), $F(3, 141) = 1.69, p = .173, \eta_p^2 = .04$. PM-error rates decreased with increasing arrow ratio, $F(3, 141) = 16.11, p < .001, \eta_p^2 = .26$, in a linear fashion from 7:0 PM trials (22.3%) to 6:1 (14.7%) and 5:2 trials (10.8%), with a nominal increase to 4:3 PM trials (12.6%), $F(1, 47) = 33.56, p < .001, \eta_p^2 = .42$ (linear contrast).

Aftereffects of completed intentions. To examine cognitive-control-demand effects on intention deactivation, we conducted repeated-measures ANOVAs involving the factor arrow ratio (7:0, 6:1, 5:2, 4:3) on aftereffects of completed intentions (i.e., performance differences between $PM_{REPEATED}$ and oddball trials) in RTs, commission errors and other error types (i.e., erroneous ongoing-task responses or response omissions). To determine statistical significance of the hypotheses-relevant effects of cognitive-control demands on intention deactivation, we used a Bonferroni-corrected alpha level of .0167 (.05/3). Note that p values for tests at the Bonferroni-corrected alpha levels are denoted as p^* .

RTs. Aftereffects of completed intentions did not differ statistically between arrow ratios, $F(3, 141) = 0.62, p^* = .549, \eta_p^2 = .01$ (69 ms, $d_{rm} = 0.35$; 73 ms, $d_{rm} = 0.30$; 98 ms, $d_{rm} = 0.26$; 49 ms, $d_{rm} = 0.08$ in arrow ratios 7:0, 6:1, 5:2, 4:3, respectively). Testing whether aftereffects differed between extreme poles of cognitive-control availability, as was suggested by visual inspection of the data, revealed no statistically significant difference between arrow ratio 7:0 and 4:3, $t(47) = 0.52, p = .608, d_{rm} = 0.09$.

Errors. Similar to RT data, we found no effect of arrow ratio on aftereffects of completed intentions in error rates, $F(3, 141) = 0.14, p^* = .839, \eta_p^2 = .003$.

Commission errors. Commission errors were rare and occurred almost exclusively in $PM_{REPEATED}$ trials (0.9% [27 trials]); only two commission errors occurred in standard trials (Table 4). Commission-error aftereffects were affected by arrow ratio, $F(3, 141) = 4.50, p^* = .010, \eta_p^2 = .09$ (1.8%, $d_{rm} = 0.82$; 0.9%, $d_{rm} = 0.58$; 0.3%, $d_{rm} = 0.29$; 0.5%, $d_{rm} = 0.42$ in arrow ratios 7:0, 6:1, 5:2, 4:3, respectively). Repeated contrasts revealed only nominally decreased commission-error aftereffects from 7:0 to 6:1 trials, $F(1, 47) = 3.00, p = .090, \eta_p^2 = .06$, and from 6:1 to 5:2 trials, $F(1, 47) = 3.78, p = .058, \eta_p^2 = .07$. Commission-error aftereffects also did not differ significantly between 5:2 and 4:3 trials, $F(1, 47) = 0.66, p = .420, \eta_p^2 = .01$. Additionally, testing the difference in commission-error aftereffects between

our extreme poles of cognitive-control availability (7:0 vs. 4:3), revealed larger aftereffects in 7:0 than in 4:3 trials, $t(47) = 2.34$, $p = .024$, $d_{rm} = 0.52$.

Discussion

In Experiment 2, we investigated effects of trial-by-trial cognitive-control demands on intention deactivation in younger adults. Results were straight-forward: First, similar to Experiment 1, increasing the arrow ratio decreased speed and accuracy of ongoing-task performance; possibly reflecting a demand-dependent decrease in cognitive-control availability. Second, we again found decreasing PM-error rates with increasing cognitive-control demands, which may result from participants missing PM cues more often during trials in arrow ratios 7:0 and 6:1 due to their overall faster ongoing-task performance in these trials. Most importantly and in contrast to Experiment 1, we found no evidence for a modulation of aftereffects of completed intentions in terms of performance costs in $PM_{REPEATED}$ compared to oddball trials by cognitive-control availability. That is, RT and error aftereffects were not modulated by transient cognitive-control demands in $PM_{REPEATED}$ trials. Interestingly, however, we found that commission-error aftereffects decreased with increasing cognitive-control demands. We will discuss these effects in more detail in the general discussion.

Figure 3. Results from Experiment 2. (A) Mean response times (RT) and error rates (erroneous ongoing-task responses and response omissions) for performance in PM blocks and test blocks in Experiment 2 as a function of trial type (standard, PM, PM_{REPEATED}, oddball) and arrow ratio (7:0, 6:1, 5:2, 4:3). (B) Mean commission-error (CE) rates during test blocks as a function of trial type and arrow ratio. Error bars represent standard errors of the mean.

Table 3

Mean (SD) Performance during PM- and Test Blocks in Experiment 2.

Trial type	Arrow ratio (cognitive-control demand)							
	7:0		6:1		5:2		4:3	
	RT (ms)	Errors (%)	RT (ms)	Errors (%)	RT (ms)	Errors (%)	RT (ms)	Errors (%)
PM blocks								
Standard	532 (132)	1.1 (2.2)	676 (211)	2.9 (3.9)	883 (322)	9.7 (7.6)	1190 (542)	28.1 (8.3)
PM	797 (150)	22.3 (14.3)	795 (162)	14.7 (11.6)	810 (155)	10.8 (12)	787 (138)	12.6 (12.7)
Oddball	730 (186)	2.5 (5.1)	840 (262)	4.4 (6.7)	1053 (373)	12.4 (9.9)	1370 (602)	28.8 (12.3)
Test blocks								
Standard	527 (122)	1.4 (2.9)	663 (189)	3.3 (4.2)	874 (297)	10.2 (7.8)	1165 (515)	28.1 (8.0)
PM _{REPEATED}	721 (200)	1.6 (3.8)	806 (253)	4.4 (6.9)	1033 (368)	9.2 (11)	1336 (622)	30.2 (14)
Oddball	652 (179)	2.3 (6)	733 (222)	4.3 (6.6)	935 (377)	10.3 (9.5)	1287 (561)	31.1 (13.1)
Aftereffects ^a	69 (72)	-0.8 (4.8)	73 (118)	0.1 (5.1)	98 (210)	-1.0 (8.3)	49 (273)	-0.9 (16.5)

Note. Error rates represent erroneous ongoing-task responses and response omissions.^aAftereffects represent performance differences between PM_{REPEATED} and oddball trials.

Table 4

Mean (SD) Commission-error (CE) Rates during Test Blocks in Experiment 2.

Trial type	Arrow ratio (cognitive-control demand)			
	7:0	6:1	5:2	4:3
	CE (%)	CE (%)	CE (%)	CE (%)
Test blocks				
Standard	-	-	0.0 (0.1)	0.0 (0.1)
PM _{REPEATED}	1.8 (3.1)	0.9 (2.2)	0.3 (1.3)	0.5 (1.7)
Oddball	-	-	-	-
Aftereffects ^a	1.8 (3.1)	0.9 (2.2)	0.3 (1.3)	0.5 (1.7)

^aAftereffects represent performance differences between PM_{REPEATED} and oddball trials.

General Discussion

The aim of the present study was to investigate the effects of aging and transient availability of cognitive-control resources during encounters of no-longer-relevant PM cues on intention deactivation. We assessed aftereffects of completed intentions under varying degrees of cognitive-control demands in younger and older adults (Experiment 1) and with a more fine-grained parametric variation of cognitive-control demands during PM_{REPEATED} trials (Experiment 2). In line with the dual mechanisms account of PM commission errors (Bugg et al., 2016; Scullin & Bugg, 2013; see also Meiser & Rummel, 2012), we expected that if transient cognitive-control availability during encounters of PM_{REPEATED} cues was crucial for intention deactivation, aftereffects of completed intentions should increase with increasing cognitive-control demands on ongoing-task processing in PM_{REPEATED} trials. Moreover, based on previous findings (e.g., Scullin et al., 2012), we expected that aging should increase aftereffects of completed intentions and exacerbate potential effects of cognitive-control demands on aftereffects of completed intentions.

First, we found evidence for a successful reduction of cognitive-control availability by increasing demands on cognitive control. That is, in both experiments we observed the characteristic increase in ongoing-task RTs and error rates with increasing trial-by-trial cognitive-control demands in a majority-function task (Fan, 2014; Fan et al., 2008). Second, in line with previous findings (e.g., Scullin & Bugg, 2013; Scullin et al., 2012), older adults exhibited a nominally higher risk of making a commission error after intention completion than younger adults. Note that these age effects could not be explained by impaired PM performance in older adults, as both groups did not differ in that regard.

Third and most importantly, regarding the modulation of intention deactivation by transient cognitive-control availability: In Experiment 1, RT and error aftereffects of completed intentions did not differ between extreme-poles of cognitive-control availability

(i.e., between no-conflict and high-conflict trials) in both younger and older adults. Surprisingly, taxing cognitive control only a little (during low-conflict trials), led to an almost complete absence of RT aftereffects. These initial findings suggested that intention deactivation is either not modulated by transient cognitive-control availability during PM_{REPEATED}-cue encounters or only modulated by cognitive-control availability during trials that place an additional burden on cognitive control, for instance by inducing additional conflicts in stimulus processing. Astonishingly, however, even with an extended manipulation of cognitive-control demands in Experiment 2 (i.e., no conflict vs. low conflict vs. medium conflict vs. high conflict), RT and error aftereffects of completed intentions were not affected by transient cognitive-control demands. Surprisingly, we found that commission-error rates in Experiment 2 decreased with increasing cognitive-control demands. While it may be tempting to explain this effect with an attenuated processing of distractor stimuli during conflict trials, as has been observed in conflict-adaptation studies (e.g., Wendt et al., 2014), note that the overall number of commission errors in Experiment 2 was very low and that we did not observe this effect in Experiment 1. It is also important to note that commission errors in PM are notoriously difficult to assess. Even under optimal conditions that foster spontaneous intention retrieval—i.e., using salient focal PM cues, matching ongoing tasks, few PM cue representations (McDaniel et al., 2015)—commission errors after intention completion can be quite rare (Anderson & Einstein, 2017). Although there are task conditions that seemingly produce higher rates of erroneous PM responses than using completed intentions, for instance using active intentions (Boywitt et al., 2015), instructions to suppress PM responses (Meiser & Rummel, 2012), cancelling PM-task performance or providing no opportunities to perform the PM task (Bugg & Scullin, 2013), these manipulations necessarily also shift the topic of investigation away from aftereffects of completed intentions. Thus, additional research is required to determine if and under which

conditions transient cognitive-control demands affect commission-error rates or other measures of intention deactivation after intention completion.

Based on the present findings, we suggest that while aging may increase aftereffects of completed intentions, intention deactivation might not be affected by transient cognitive-control availability during encounters of no-longer-relevant PM cues. Although our findings dovetail with previous reports of age-related declines in intention deactivation (e.g., Bugg et al., 2016) and corroborate the notion that intention deactivation does not rely on available cognitive resources after intention completion (Walser, Goschke, et al., 2014), it remains an open question how age effects on intention deactivation arise and through which mechanisms completed intentions are deactivated.

Effects of age on intention deactivation

Previous reports of increased aftereffects of completed intentions or more frequent commission errors in older adults with completed (Scullin et al., 2012) or suspended intentions (Boywitt et al., 2015) have been attributed to a supposed decline in cognitive-control abilities with cognitive aging (Hasher, Stoltzfus, Zacks, & Rypma, 1991). However, the notion of a general age-related cognitive-control impairment is not undisputed (e.g., Cona, Arcara, Amodio, Schiff, & Bisiacchi, 2013; Lustig & Jantz, 2015; Verhaeghen, 2011). Importantly, given that in the present study aging only modulated cognitive-control-demand effects on ongoing-task performance but not on aftereffects of completed intentions. In light of these selective effects of aging, older adults' impaired intention deactivation cannot be accounted for by an overall impairment of cognitive-control processes. Rather, our findings highlight the necessity to determine which specific cognitive-control functions are affected by aging to elucidate the mechanisms for age effects in PM and intention deactivation. Although, based on the present study, we cannot rule out that age effects on intention deactivation arise due to deficits in response inhibition, there are several alternative

mechanisms through which impaired intention deactivation in older adults could arise, that we believe would be useful for future research.

First, deficits in cognitive flexibility or shifting abilities could account for increased aftereffects in older adults. That is, several studies reported that older adults show impaired shifting abilities in terms of attenuated associations between a cue and a context (e.g., PM cue and PM block) (Lustig & Jantz, 2015), difficulties in activating and updating context information (Braver, Satpute, Rush, Racine, & Barch, 2005) or in disengaging from no-longer-relevant task sets when performing a single task after a period of task switching (i.e., fade-out costs; Mayr & Liebscher, 2001). Applying this logic to the present paradigm, we speculate that the lack of a strong association between the PM cue and the PM block in older adults could have led to increased interference from PM_{REPEATED} cues in test blocks.

Second, increased aftereffects could also stem from older adults' difficulty in ignoring distracting information (Weeks & Hasher, 2014) that seems to increase with age (Giesen, Eberhard, & Rothermund, 2015). More specifically, difficulties in ignoring PM_{REPEATED} cues could increase the risk of accidentally retrieving the completed PM-task set and/or the intended action, which would exacerbate aftereffects of completed intentions.

Lastly, age effects on cognitive control abilities dissociate between a proactive and a reactive mode of control (Manard, François, Phillips, Salmon, & Collette, 2017). Specifically, while older adults exhibit deficits in proactive control in terms of utilizing task information to anticipate conflicts during task performance (Braver et al., 2005; Manard, Carabin, Jaspar, & Collette, 2014), reactive control in terms of the ability to establish, maintain and quickly adapt to novel cue–attention associations is preserved (e.g., Bugg, 2014; Manard et al., 2017). Interestingly, older adults' deficit in proactive control in some cases is compensated by stronger mobilization of reactive control to uphold performance (Kopp et al., 2014). In the present study, high demands on proactive-control (i.e., due to

mostly incongruent ongoing-task trials) might have led to a compensatory recruitment of reactive control in older adults. Consequently, reactive control processes required for intention deactivation would have been reduced and thereby led to an increase in aftereffects. It is unclear, however, whether this logic could also apply to previous studies on intention deactivation in older adults in which ongoing-task items were balanced for congruency (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2012, 2011). It seems at least feasible that older adults' compensatory recruitment of reactive control for ongoing-task performance could explain impairments in reactive control over intention deactivation that may ultimately lead to increased aftereffects of completed intentions.

Effects of cognitive-control availability on intention deactivation

Our findings raise a number of questions regarding the mechanisms of intention deactivation: First, the surprising robustness of RT aftereffects of completed intentions even under extreme cognitive-control demands raises the question whether RT aftereffects can at all be modulated by top-down adjustments of cognitive control. The extent to which this might be possible could likely depend on the degree to which task features foster spontaneous intention retrieval. That is, when reliance on spontaneous retrieval is high (e.g., with salient PM cues), spontaneous intention retrieval might overshadow potential effects of cognitive-control demands on intention deactivation. Testing this, however, is difficult since reducing the likelihood of spontaneous retrieval also reduces the likelihood of observing aftereffects of completed intentions.

Second, the lack of demand-dependent effects on RT aftereffects and our observation of decreasing commission-error rates with increasing cognitive-control demands in the present study seems to be at odds with the dual mechanisms account of PM commission errors and previous reports of control-dependent modulations of aftereffects of completed intentions (Bugg et al., 2016; Scullin & Bugg, 2013; see also Meiser & Rummel, 2012).

Note, however, that in the present study we focused on cognitive control in terms of uncertainty reduction. That is, we targeted the number of computations that are required for response selection in a trial (Fan, 2014; Wang, Liu, & Fan, 2011). Although shared-capacity models of cognitive control (e.g., Fan, 2014) propose that any type of cognitive load or mental operation should usurp cognitive resources that, according the dual-mechanisms account of PM commission errors, might be needed for successful intention deactivation, we found no evidence for this here. Hence, it remains an open question whether intention deactivation and ongoing-task performance after intention completion do rely on shared capacities and/or parallel processing of ongoing tasks and intention-related information. This seems at least feasible, given that the effects of cognitive-control demands in ongoing-task trials and effects of deviant stimuli on task performance in the present study seem to be additive.

Lastly, we would like to point out that a reduction of cognitive-control resources for intention deactivation due to increased ongoing-task shielding during conflict trials (Goschke & Dreisbach, 2008) may not be the only mechanism through which transient cognitive-control demands could affect intention deactivation. Research on conflict-adaptation effects showed that prior experience of conflict can lead to more controlled task processing in terms of increased attention allocation towards target stimuli and decreased interference from distractor stimuli (e.g., Notebaert & Verguts, 2006; Wendt et al., 2014). If this cognitive-control adjustment happened online within a trial, increasing conflict strength in PM_{REPEATED} trials should actually reduce aftereffects of completed intentions. While we did not find conclusive evidence for this here, it is important to note that both mechanisms—(a) reduced cognitive-control resources for intention deactivation and (b) increased attention allocation towards ongoing-task stimuli—might not necessarily be mutually exclusive. It is feasible that, if both processes were affected by manipulations of cognitive-control demands in equal

amounts, their effects on task performance would counteract each other, which could also explain the lack of cognitive-control-demand effects on intention deactivation in the present study. Importantly, however, future studies are required to determine if and under which conditions this is true and what the individual contribution of each process to a cognitive-control dependence of intention deactivation might be.

Conclusion

The present study was the first to investigate the effects of transient availability of cognitive control on intention deactivation in a task that required cognitive control in terms of perceptual grouping attempts for response selection during encounters of PM_{REPEATED} cues. Although this is arguably a critical time-point for intention deactivation, we did not find evidence for a cognitive-control dependence of intention deactivation in terms of RT and error aftereffects of completed intentions. However, we found that older adults tended to be at a higher risk to make a commission error after intention completion, and found preliminary evidence for a cognitive-control dependence of commission-error occurrences. Clearly future research is needed to ascertain (a) whether intention deactivation is modulated by other transient cognitive-control demands, (b) which markers of intention deactivation are affected by cognitive-control demands, (c) during which phases after intention deactivation cognitive-control availability is most critical, and relatedly, (d) which factors differentiate situations or persons that show aftereffects of completed intentions and commission errors from those who do not?

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Appendix

Symbols for PM cues and Oddballs in the majority-function task.