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# Age-related Delay in Reduced Accessibility of Refreshed Items

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# Abstract

Previously we demonstrated that in young adults briefly thinking of (i.e., refreshing) a just-seen word impairs immediate (100ms delay) perceptual processing of the word, relative to words seen but not refreshed. We suggested that such reflective-induced inhibition biases attention towards new information. Here, we investigated whether reduced accessibility of refreshed targets dissipates with a longer delay, and whether older adults would show a smaller and/or delayed effect, versus young adults. Young and older adult participants saw two words, followed by a cue to refresh one. After either a 100ms or 500ms delay, participants read a word that was the refreshed word (refreshed probe), the nonrefreshed word (nonrefreshed probe), or a new word (novel probe). Young adults were slower to read refreshed probes than nonrefreshed probes at the 100ms, but not the 500ms, delay. Conversely, older adults were slower to read refreshed probes than nonrefreshed probes at the 500ms, but not the 100ms, delay. The delayed slowing of responses to refreshed probes was primarily observed in older-old adults (75+ years). A delay in suppressing the target of refreshing may disrupt the fluidity with which attention can be shifted to a new target. Importantly, a long-term memory benefit of refreshing was observed for both ages and delays, regardless of whether we observed a temporary inhibition of the target of refreshing. These results suggest that a full characterization of age-related memory deficits should consider the time course of effects and how specific component cognitive processes affect both working and long-term memory.

## Keywords

refreshing; reflective attention; aging; inhibition; working memory

Aging is associated with cognitive deficits in a number of domains (e.g., Park et al., 2002). One important characteristic of cognitive aging is greater vulnerability to interference from distracting information (e.g., Anderson, Healey, Hasher, & Peterson, 2016; Andres, Guerrini, Phillips, & Perfect, 2008; Connelly, Hasher, & Zacks, 1991; Healey, Hasher, &

Data available at the following link: https://osf.io/zb9qx/

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Campbell, 2013; Higgins & Johnson, 2009; Jonides et al., 2000; Lustig, May, & Hasher, 2001; Raye, Mitchell, Reeder, Greene, & Johnson, 2008; Weeks & Hasher, 2014; Yi & Friedman, 2014; for a review, see Lustig & Jantz, 2015). For example, older adults are more vulnerable than young adults to proactive (e.g., Lustig et al.; Jonides et al.; Yi & Friedman) and semantic (Higgins & Johnson) interference in working memory. Similarly, having more items active in working memory (3 just-seen words vs. 1 just-seen word) disproportionately slows older adults' response times to read a word (Raye et al.). Compared with young adults, older adults are differentially slower to read text when it is interspersed with distracting words (e.g., words presented in a to-be-ignored font) than when it is not (Connelly et al.). The idea that age-related vulnerability to interference reflects a general deficit in neurocognitive inhibitory mechanisms that operate to suppress competition from distracting information (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988) has received support from behavioral (e.g., Healey, Ngo, & Hasher, 2014), EEG (e.g., Haring et al., 2013; Yi and Friedman, 2014), and fMRI (e.g., Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Mitchell, Johnson, Higgins & Johnson, 2010) studies. For example, when briefly and simultaneously shown a face and scene and then immediately cued to think of the face, young but not older adults showed suppression of scene-specific activation in the parahippocampal place area (Mitchell et al.).

Recent neurophysiological research also suggests that it is important to consider the time course of inhibition. Some studies have found that inhibitory mechanisms in older adults may be impaired during early processing of distracting information but then are relatively preserved later on (Gazzaley et al., 2008; Yi and Friedman, 2014; see also, Jost, Bryck, Vogel and Mayr, 2011; Schwarzkopp, Mayr, & Jost, 2016). For example, in a working memory task used by Gazzaley et al., young and older adults were successively shown two faces and two scenes in random order and cued in advance to either remember the faces, remember the scenes, or to simply view the items. Examining EEG signal during the first 200 milliseconds of the encoding sequence, Gazzaley et al. observed that, relative to baseline, both young and older adults showed greater amplitudes of face-specific signals (N1 and P1) when attending to faces; but only the young adults also showed smaller responses of the N1 and P1 when ignoring faces. However, alpha power measured between 500 and 650ms post-stimulus showed enhancement and suppression relative to baseline in both age groups. Hence, a comprehensive understanding of age-related changes in inhibition should take into account the time course over which inhibitory mechanisms operate.

One limitation of prior studies demonstrating delayed inhibition of interference in older adults is that the tasks used are relatively complex, preventing conclusions about what specifically led to the delay in inhibition. For example, in the Gazzaley et al. (2008) study, participants were simultaneously perceptually attending and/or ignoring stimuli currently on the screen, as well as, reflectively attending and/or ignoring representations of previously viewed stimuli currently active in working memory. The delay in inhibition obtained could have arisen from age-related deficits in perceptual attention, reflective attention, or both (e.g., Mitchell et al., 2010). When prior tasks required only reflective attention to items active in working memory (e.g., Yi and Friedman, 2014), multiple items had to be maintained over a relatively long interval (2000 ms in Yi & Friedman), which likely required multiple reflective attention processes (e.g., *refreshing* and *rehearsing*, Chun & Johnson,

2011; Johnson & Hirst, 1993). Hence, the delay in inhibition may be associated with selectively r*efreshing* a single item within working memory, *rehearsing* multiple items in a continuous loop, or both (for evidence concerning the distinction between refreshing and rehearsing, see, e.g., Camos, Mora & Oberauer, 2011; Raye, Johnson, Greene, & Johnson, 2007).

In the current study, we examine whether inhibition associated with a simple act of reflective attention is impaired in aging. To do so, we build on our previous finding in young adults of a reduced accessibility for item information that had just been the target of a simple act of reflective attention, refreshing (Johnson et al., 2013). Young adults saw two words on the screen (one above, one below center) followed by a central arrow pointing either up or down. Participants were instructed to think of (i.e., *refresh*) the word that was just in the location indicated by the cue, and to say that word aloud. After a brief (100ms) delay, a probe word appeared in the center of the screen, which participants read aloud. This word was either the refreshed word from the initial display, the nonrefreshed word from the initial display, or a novel word. We found that probe response times were slower for refreshed words than nonrefreshed words, suggesting that immediate access to the refreshed item was inhibited. In a comparison condition in which participants merely saw a word repeated and read it aloud (instead of refreshing it), there was no slowing of response times to the repeated-word probe, suggesting that this inhibition resulted specifically from the act of reflectively attending to the target, not from perceptually processing it or speaking it. Thus, this task provides evidence for inhibition associated with a specific, reflective component process of cognition. Interestingly, long-term memory was better for refreshed compared to nonrefreshed words, suggesting that the inhibitory effect was short-lived and did not offset the long-term benefit of refreshing a target typically seen in young adults (Johnson, Reeder, Raye, & Mitchell, 2002). Here we test whether such long-term memory benefits of refreshing would be observed even when age-differences in inhibition of refreshed targets are present.

Thus, in the current study, we examined whether older adults show a similar inhibitory effect from a brief act of reflective attention within working memory, using a similar paradigm to that of Johnson et al. (2013). To investigate potential age-related differences in the time course of inhibition of the refreshed item, we included the 100ms delay condition used by Johnson et al., and added a 500ms delay condition. For young adults, we expected to replicate our previous finding of refresh-induced inhibition at the 100ms delay. Given that young adults in our previous study showed a long-term memory benefit from refreshing, suggesting any suppression/inhibitory effect was transient, we predicted that the inhibitory effect would have dissipated by 500ms. We chose 500ms as the longer delay based on findings that older adults show similar neurophysiological responses to interference in working memory tasks compared to young adults starting at delays of 500-600 ms (Gazzaley et al., 2008; Jost et al., 2011; Yi & Friedman, 2014). As such, in older adults, we expected to observe refresh-induced inhibition in the 500ms, but not the 100ms, delay. Of course, failure of older adults to show evidence of inhibition even at the longer delay would suggest a more severe disruption of inhibition of an item that was just in the focus of reflective attention. Additionally, we investigated whether the long-term memory benefits from refreshing observed in Johnson et al. would replicate in young adults at the

100ms delay and extend to young adults in the 500ms delay and older adults at either or both delays.

Multiple factors contribute to changes in cognition associated with aging and many cognitive changes are most pronounced in advanced old age (e.g., Braver & Barch, 2002; Buckner, 2004). Thus, as a post hoc analysis, in addition to an overall comparison between young and older adults, we also split our older group into younger-old (<75 years) and older-old (75+ years) subgroups, and compared young adult participants separately to each of those subgroups with respect to short-term and long-term effects of refreshing.

# Method

#### **Participants**

Participants were 72 older adults recruited from the New Haven community and 72 young adults recruited from Yale University's student body. Participants were randomly assigned to a delay (100ms or 500ms) group, with the restriction that the age distribution in the two groups should be roughly comparable. Data from six participants were excluded for the following reasons: two older adults from the 100ms delay group who reported a history of stroke on a post-task questionnaire; one older adult in the 500ms delay group whose mean response time was greater than 3 standard deviations from the overall mean for both age groups; one young adult from the 100ms delay and two from the 500ms delay for whom English was not their first language, and who made mistakes on a majority of trials. The 138 remaining participants reported no history of neurological impairment or psychiatric illness and had normal or corrected-to-normal vision. Participants received financial compensation for their participation. This study was approved by the Yale University Human Subjects Committee.

Young adults in the two delay conditions did not differ in age [t(67)=-.59, p=.55], years of education [t(50)=-.29, p=.78], or verbal scores [t(59.56)=1.85, p=.07; see Table 1 for descriptive statistics of all demographic variables]. Older adults in the two delay conditions did not differ significantly in age [t(67)=-.13, p=.90], years of education [t(67)=-1.07, p=.29], cognitive status as assessed by the Mini-Mental State Examination [Folstein, Folstein, & McHugh, 1975; t(58.31)=1.34, p=.19], or verbal scores [t(67)=-1.16, p=.25].

To explore potential age differences within the older group, we divided them into two subgroups, "younger-old" (aged 60 to 74 yrs) and "older-old" (aged 75 yrs and older; see Table 1). Younger-old in the two delay conditions did not differ in age [t(28)=.06, p=.96], years of education [t(28)=-1.72, p=.10], cognitive status [t(28)=.85, p=.40], or verbal scores [t(28)=-.263, p=.79]. Older-old participants in the two delay conditions did not differ in age [t(37)=.62, p=.54], years of education [t(37)=.21, p=.83], cognitive status [t(37)=.90, p=.38], or verbal ability [t(37)=-1.27, p=.21].

#### Materials and design

**Main Task.**—The same materials and design from Experiment 1 in Johnson et al. (2013) were used. Words were nouns drawn from the English Lexicon Project (Balota et al., 2007) with an average log frequency, word length, number of syllables, number of phonemes and

pronunciation response time of 7.14, 6.26, 1.76, 5.08, and 657ms, respectively. Words were organized into triplets, and for a particular stimulus list, one word in the triplet was assigned to be the refreshed probe, the nonrefreshed probe, or the novel probe (if present; see Figure 1). To control for possible item effects between lists, each word served as the refreshed probe, the nonrefreshed probe (when present) on different lists, for a total of nine stimulus lists that were rotated across participants. Each stimulus list included 48 instances of each condition (refreshed probe, nonrefreshed probe, novel probe) for a total of 144 trials. Within a list, conditions were equated across the word dimensions (i.e., frequency, number of syllables, etc.; all p > 0.8). Conditions were randomly intermixed and trials were presented in 3 separate blocks, with short breaks between blocks. Before the main task, participants performed a practice session that included 12 trials (4 instances of each trial type) with words that were not included in the main lists.

Recognition Task.—Test items included refreshed words, nonrefreshed words, and probe words from 50% of the trials seen during the main task. Each stimulus list from the main task was associated with two recognition lists that were rotated across participants. To construct the two recognition lists, words from half of each trial type in the main task were assigned to one recognition list, and words from the other half were assigned to the other recognition list. Trial position during the main task (that is, whether it appeared early or late in the session) was balanced across the two lists. Each recognition list included 168 previously seen words and 168 new words (foils). Within each recognition list, word dimensions (frequency, word length, etc.) were similar for the word conditions (e.g., refreshed word, novel probe, etc.) and foils (all p > 0.8). Because memory for all the words from a trial in the main task was tested there were eight different conditions of test words (including foils) on the recognition test. If the test word had been refreshed during the main task, it could have appeared on a trial where the probe was the refreshed word (refreshed item - refreshed probe), the nonrefreshed word (refreshed item - nonrefreshed probe), or a novel word (refreshed item – novel probe). If the test word had appeared in the initial display but had not been refreshed, it could have appeared on a trial where the probe was the refreshed word (nonrefreshed item - refreshed probe), the nonrefreshed word (nonrefreshed item – nonrefreshed probe), or a novel word (nonrefreshed item – novel probe). Additionally, the test word could have appeared in the main task as a novel word (novel probe), or not at all (foil).

#### Procedure

**Main Task.**—White stimuli were presented on a black background (see Figure 1). Each trial started with the presentation of two words, one above and one below center, for 1500ms. Participants were instructed to read these words silently to themselves. After a delay of 500ms during which the screen was blank, an upward or downward pointing arrow appeared in the center of the screen for 1500ms. Participants were instructed to think of the word that had just appeared in the location indicated by the arrow, and to say this word aloud as quickly but as accurately as possible. After the arrow disappeared, the screen was blank for either 100ms or 500ms. After the delay, a word appeared in the center of the screen the word from the initial display that the participants had just refreshed (refreshed probe trial), the word from the initial display that the participants had

not refreshed (nonrefreshed probe trial), or a novel word (novel probe trial). Participants were instructed to read this word aloud as quickly, but as accurately, as possible. The inter-trial interval was 3000ms.

During times when a verbal response from the participant was expected, the item on the screen (the word or arrow) turned green in color to indicate that their responses had been correctly recorded. This feedback allowed participants to monitor their volume to ensure accurate voice recordings.

**Recognition Task.**—After a short break (approximately 8 minutes), participants were administered a surprise long-term yes/no (with confidence) recognition memory test for the words that had appeared during the main task. On each trial, the question "Have you seen this word before?" was followed by a single test word. Participants used the index and middle fingers of both hands to press one of four buttons corresponding to four choice options: "Definitely No", "Maybe No", "Maybe Yes", "Definitely Yes". The test word remained on the screen until the participant responded, and response accuracy was stressed above speed.

**Apparatus.**—Stimuli for both the main task and recognition task were presented using E-Prime software on a PC laptop.

In the main task, verbal responses were measured using a free-standing microphone interfaced with the E-Prime voice key SRT box, and were also recorded digitally. The digital recording was analyzed using a custom Matlab (MathWorks, Natick, MA) script that identified sounds exceeding a specified amplitude and duration threshold and allowed a manual adjustment of the word onset if the automatic detection failed or was triggered early by non-speech sounds.

In the recognition task, responses were collected via labeled buttons on the keyboard.

# Results

#### Main Task Response Times

**Refresh RTs**—After trials in which there were participant errors (wrong word was refreshed, participants misspoke) or technical errors were removed, the percentage of remaining trials was comparable in the 100ms delay (OA=95%, YA=98%, older-old=96%, younger-old=94%) and 500ms delay (OA=95%, YA=97%, older-old=96%, younger-old=95%) conditions.

Response times to refresh (Table 2a) were submitted to a 2 (Age: YA, OA) x 2 (Delay: 100ms, 500ms) ANOVA. Older adults were significantly slower to refresh than young adults [f(1, 134)=74.40, *MSE*=8,291.52, p<.001,  $\eta_p^2=.36$ ]. No other effects were significant. Subgroups of older participants were compared in a 2 (age group: older-old, younger-old) x 2 (Delay: 100ms, 500ms) ANOVA (see Table 2b). Although response times to refresh were 33 ms slower in older-old compared to younger-old, this difference was not significant

**Probe RTs**—After trials in which there were participant errors or technical errors were removed, the percentage of remaining trials was comparable in the 100ms delay (OA=94%, YA=97%, older-old=96%, younger-old=93%) and 500ms delay (OA=94%, YA=95%, older-old=95%, younger-old=94%) groups.

Probe RTs for all conditions are shown in Table 3. Novel probes were included to discourage uncued refreshing and are not of primary interest. However, it is worth noting that, as is clear from Table 3, both older and younger adults showed faster response times on refreshed and nonrefreshed probes compared to novel probes, consistent with other findings of repetition priming on identification tasks (Fleischman & Gabrieli, 1994, but see Wiggs & Martin, 1994). Detailed analyses and data for novel probes are available from the first author.

To test our critical hypothesis that aging may delay inhibition of the refreshed word, we submitted probe RTs from refreshed and nonrefreshed trials to a 2 (Age: YA, OA) x 2 (Delay: 100ms, 500ms) x 2 (Probe: refreshed probe, nonrefreshed probe) ANOVA (Figure 2a, Table 3a). There were significant main effects of Probe [f(1,134)=21.29, *MSE*=463.18, p<.001,  $\eta_p^2=.14$ ] with longer response times to refreshed probes compared to nonrefreshed probes, and Age [f(1,134)=26.07, *MSE*=14,848.73, p<.001,  $\eta_p^2=.16$ ], with longer response times in OA compared to YA. The predicted Age x Delay x Probe interaction was marginally significant [f(1,134)=3.13, *MSE*=463.18, p=.07,  $\eta_p^2=.02$ ]. Young adults were slower to respond to refreshed compared to nonrefreshed probes at the 100ms delay [t(34)=4.03, p<.001, Cohen's d=.68], but not the 500ms delay [t(33)=1.66, p=.11]. In contrast, older adults were slower to respond to refreshed compared to refreshed compared to nonrefreshed probes at the 500ms delay [t(34)=3.16, p<.01, Cohen's d=.53], but not the 100ms delay [p=.34]. No other interactions were significant.

Table 3b and Figure 2b show probe RTs separately for younger-old and older-old participants. Separate 2 (Age: OA, YA) x 2 (Delay: 100ms, 500ms) x 2 (Probe: refreshed, nonrefreshed) ANOVAs comparing young adults with each of the older subgroups found that the three-way interaction was significant in the young vs. older-old analysis [f(1,104)=5.11, *MSE*=488.22, p=.026,  $\eta_p^2 = .05$ ], but not the young vs. younger-old analysis (p=.56). Older-old participants showed no slowing to refreshed probes at the 100ms delay (p=.93) and did show slowing at the 500ms delay [t(20)=2.59, p=.017, Cohen's d=.57]. Younger-old participants were marginally slower to read refreshed compared to nonrefreshed probes at the 100ms [t(15)=1.88, p=.08, Cohen's d=.47] but not at the 500ms delay [t(13)=1.78, p=.10]. In short, the older-old participants showed no evidence of inhibition until the 500ms delay.

#### Long-term Recognition Memory

Long-term recognition data were excluded for one OA in the 500ms delay condition because of a large portion of missing data due to technical error. For old items, there were seven different conditions: words that had been refreshed during the main task on trials in which the probe word was the refreshed word (on refreshed probe trials), nonrefreshed word (on

nonrefreshed probe trials), or a novel word (on novel probe trials); words that had appeared in the initial display but had not been refreshed (i.e., nonrefreshed words) on refreshed probe trials, nonrefreshed probe trials, and novel probe trials; and novel words from novel probe trials. For each of these seven conditions, old/new corrected recognition scores were calculated by subtracting the proportion of false alarms (foils to which participants responded "maybe yes" or "definitely yes") from hits (old items to which participants responded "maybe yes" or "definitely yes").<sup>1</sup> Data for all conditions are shown in Table 4.

Long-term memory for novel probes was not of primary interest here. It is worth noting that, as is clear from Table 4, long-term memory for a nonrefreshed item (that was not probed) was generally lower than for a novel item. This makes sense because in both cases the item was seen once, but the nonrefreshed item had shared attention with another item in the display whereas the novel item had not; also, probed items were read aloud, whereas nonprobed nonrefreshed items were only read silently. As is clear from Table 4, refreshing largely made up for the shared attention deficit from a multiple item display. Detailed analyses of the long-term memory results for novel items are available from the first author.

**Young adults vs. older adults.**—To examine the effect of refreshing a word on long-term memory, corrected recognition scores were submitted to a 2 (Age: YA, OA) x 2 (Delay: 100, 500) x 2 (Refresh: Refreshed, Nonrefreshed) x 2 (Probe: Probed, Nonprobed) ANOVA. Since there were no significant effects involving delay, the data in Figure 3a were collapsed across delay. There was a main effect of Age [f(1,133)=29.17, MSE=.07, p<.001,  $\eta_p^2=.18$ ], with higher recognition in young adults than older adults. There were main effects of Refresh [f(1,133)=186.30, MSE=.01, p<.001,  $\eta_p^2=.58$ ] and of Probe [f(1,133)=272.07, MSE=.01, p<.001,  $\eta_p^2=.67$ ], which were qualified by a significant Refresh x Probe interaction [f(1,133)=69.35, MSE=.01, p<.001,  $\eta_p^2=.34$ ]. The benefit of refreshing (refreshed word minus nonrefreshed word) was larger for nonprobed items than for probed.

**Young vs. younger-old adults.**—Focusing on younger-old adults, corrected recognition scores were submitted to a 2 (Age: YA, Younger-Old) x 2 (Delay: 100, 500) x 2 (Refresh: Refreshed, Nonrefreshed) x 2 (Probe: Probed, Nonprobed) ANOVA. Since there were no significant effects involving delay, the data in Figure 3b were collapsed across delay. There was a main effect of Age [f(1,95)=16.31, MSE=.07, p<.001,  $\eta_p^2=.15$ ] with higher recognition for YA than for younger-old. Main effects of Refresh [f(1,95)=125.07, MSE=.01, p<.001,  $\eta_p=.57$ ] and Probe [f(1,95)=162.02, MSE=.01, p<.001,  $\eta_p^2=.63$ ] were qualified by a significant Refresh x Probe interaction, [f(1,95)=51.06, MSE=.01, p<.001,  $\eta_p=.57$ ]. The refresh benefit was larger for nonprobed than probed items.

**Young adults vs. older-old adults.**—Focusing on older-old adults, corrected recognition scores were submitted to a 2 (Age: YA, Older-Old) x 2 (Delay: 100ms, 500ms) x 2 (Refresh: Refreshed, Nonrefreshed) x 2 (Probe: Probed, Nonprobed) ANOVA. Since

<sup>&</sup>lt;sup>1</sup>We also calculated memory ratings for each item, where "definitely yes" was scored as 4, "maybe yes" was scored as 3, "maybe no" was scored as 2, and "definitely no" was scored as 1. The pattern of results was similar to the corrected recognition presented here except where noted. Details of the memory ratings analyses are available from the first author.

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there were no significant effects involving delay, the data in Figure 3b were collapsed across delay. The main effect of Age [f(1, 103) = 21.57, MSE=.07, p<.001,  $\eta_p^2=.17$ ] showed that recognition scores were higher for YA than for older-old. Main effects of Refresh [f(1, 103)=133.08, MSE=.01, p<.001,  $\eta_p^2=.56$ ] and Probe [f(1, 103)=197.53, MSE=.01, p<.001,  $\eta_p^2=.66$ ] were qualified by Refresh x Probe [f(1, 103)=39.78, MSE=.01, p<.001,  $\eta_p^2=.28$ ] and Refresh x Probe x Age [f(1, 103)=5.16, MSE=.01, p=.03,  $\eta_p^2=.05$ ] interactions. For probed items, young and older-old adult participants showed a similar refresh benefit (p=.4); for nonprobed items, the refresh benefit was larger in young than older-old participants [f(105)=2.4, p=.02, Cohen's d=.49].<sup>2</sup>

### Discussion

The current study investigated whether older adults, like younger adults, demonstrate reduced accessibility of an item that was just previously the target of reflective attention. Participants saw two words, then were cued to think of (i.e., refresh) one of them. After either a 100ms or 500ms delay, they saw and read aloud a probe word that was either the word from the initial display that they had refreshed (refreshed probe), the word from the initial display that they had refreshed probe), or a new word (novel probe). Young adults showed longer response times to refreshed compared to nonrefreshed probes at the 100ms delay, replicating our earlier finding (Johnson et al., 2013), but not at the 500ms delay, thus demonstrating dissipation of refresh-induced inhibition within 500ms in young adults. Of course, to fully characterize the timeline of refresh-induced inhibition, future research parametrically varying the delay is needed.

In contrast to the young adults, refreshing resulted in reduced accessibility of the item in older adults at 500ms, but not 100ms. Interestingly, while the inhibitory effect emerged later in the older adults, it was of similar magnitude (a 17ms slowing in YA at 100ms and a 16ms slowing in OA at 500ms). That is, the timing, but not the degree, of inhibition differed between the age groups. Our post-hoc examination of younger-old and older-old groups revealed that delayed inhibition may be particularly associated with advanced old age. Given that refresh response times did not differ significantly between the younger-old and older-old participants, we cannot simply attribute the later emergence of inhibition in older-old participants to a slowing of refreshing. Or, more precisely, at least not to the *initiation* of refreshing; it could be that older-old participants engage refreshing in a timely fashion but take longer to complete the process.

Regardless, given the post-hoc nature of this analysis, the relatively small samples in the younger-old and older-old subgroups, and the numerically (if not significantly) longer refresh RTs for older-old participants than younger-old, any conclusions regarding differences associated with different stages of aging are necessarily preliminary and suggest the need for further, systematic investigation of how both delay and age are related to deficits in inhibition. Also of interest, of course, would be whether inhibition deficits are related to the presence of sub-clinical histopathology in the brain that are associated with

<sup>&</sup>lt;sup>2</sup>Memory ratings showed an additional Age x Delay x Refresh interaction, reflecting that for young adults the refresh benefit was larger at the 100ms than the 500ms delay, while the older-old adults showed the reverse pattern--a larger refresh benefit at the 500ms than the 100ms delay.

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Alzheimer's disease but may appear in lesser degrees well before the emergence of any symptoms of dementia (e.g., Braak, Thal, Ghebremedhin, 2011).

What are the consequences of delayed inhibition of a just-refreshed item? Refreshing is the act of selectively focusing internal attention towards a single item, enhancing and/or prolonging the refreshed items' activation relative to other items that may be concurrently active (Johnson & Hirst, 1993). In this way, refreshing enhances the accessibility of the item for further cognitive processing (e.g., binding of the item to context, transforming or manipulating the item). However, some mechanism must act to allow attention to move to other potential targets. We propose that temporary refresh-induced inhibition observed in young adults is such a mechanism, allowing cognitive processing to not simply persist on a target that has been privileged by refreshing, but to move towards new information (analogous to the biasing of perceptual attention to uncued locations in inhibition-of-return cuing tasks, Posner & Cohen, 1984, which emerges 300 ms later in older adults compared to young, e.g., Castel, Chasteen, Scialfa, & Pratt, 2003; Langley, Friesen, Saville, & Ciernia, 2011). Delayed inhibition of just-refreshed items could have a number of downstream consequences for older adults; for example, difficulty following a rapidly moving conversation due to interference from incompletely-inhibited information that had been highlighted via refreshing. Similarly, in a working memory task, older adults' working memory capacity could suffer due to increased time required to shift reflective attention from one item to another, thus increasing the probability that other items in working memory will become inaccessible before becoming the target of refreshing or rehearsing.

If, as we propose, the function of inhibiting a just-refreshed item is to increase fluidity of cognitive processing, it must, by necessity, be short-lived. That is, a prior target, that was inhibited in order to allow reflective attention to move towards other items, may become relevant again soon thereafter. Consistent with this idea, the inhibition observed at the 100ms delay in young adults had dissipated by 500ms. Additionally, the short-term inhibition of the refreshed probe did not prevent a long-term memory benefit of refreshing, as evidenced by better long-term memory for refreshed compared to nonrefreshed items in young adults. Although our current paradigm does not allow us to determine at what point inhibition of the refreshed item (observed at the 500ms delay) dissipates in older adults, the finding that older adults also showed a refresh benefit in long-term memory suggests that inhibition is also transient in this age group.

Further specifying the nature of the age-related inhibitory delay associated with refreshing remains an important task/goal. Based on previous fMRI (Raye et al., 2007) and ERP (Johnson, McCarthy, Muller, Brudner, & Johnson, 2015) results, we suggested that an experimental refresh task such as the one used here involves two cognitive sub-components, potentially controlled by different regions of PFC: initiating refreshing (anterior PFC) followed by modulation of posterior representational regions (dorsolateral PFC). Although as noted above, we doubt that delayed initiation of the overall refresh process is a primary driver of the effects we observed, the possibility remains that the later modulatory aspects of refreshing are intact in aging, but are slower to be deployed. The similarity in magnitude of the inhibitory effect between both age groups supports this possibility. However, the similarity in magnitude of inhibition is also consistent with the possibility

that the deployment of inhibition is temporally preserved in aging, but the modulatory mechanisms are weaker in older adults and thus require more time to achieve a comparable suppression of representations. A third possibility is that the onset and/or strength of modulatory mechanisms are intact, but take longer to complete in older adults because of stronger than normal activation of the to-be-suppressed item (i.e., the refreshed item). Future studies using a parametric variation of the post-refreshing delay may help to tease apart these possibilities by examining age differences in the timing and magnitude of the effect in young and older adults.

Our results are generally consistent with neurophysiological evidence of delayed inhibition in more complex working memory tasks (Gazzaley et al., 2008; Jost et al., 2011; Yi & Friedman, 2014). Importantly, unlike other tasks that require some mix of perceptual and reflective attention, comparison of the contents of working memory to a perceptual cue, and/or rehearsal of multiple items across retention intervals of 900 ms or more, the current paradigm was designed to recruit a very simple act of reflective attention, that of refreshing a single item just experienced. Additionally, our participants were not told, and presumably were not specifically motivated, to actively inhibit the refreshed word. That is, participants showed inhibition in response to the probe, a part of the task in which they had to simply read aloud a word that was perceptually present, a task that is less likely to induce a conscious effort to inhibit the contents of working memory. Thus, the current findings demonstrate an age-related delay in inhibition of perceptual processing of an item, resulting from a very recent, discrete and simple act of reflective attention to the item.

Furthermore, the results address another fundamental question: What are the long-term effects of refresh-induced inhibition during encoding? First, in young adults in the 100ms delay group, we replicated the refresh benefit in long-term recognition memory that we found under the same conditions in our earlier study (Johnson et al., 2013). Second, we found that young adults also showed a similar refresh benefit at a longer (500ms) probe delay. Third, older adults also showed a similar refresh benefit at both delays. This overall pattern provides further evidence that refreshing can have a positive impact on long-term memory. It is notable that the older-old participants showed a decreased long-term refresh benefit compared to young adults. As older-old adults also showed the strongest evidence of a delay in refresh-induced inhibition, this suggests that a delay in inhibiting a refreshed word may contribute to deficits in long-term memory in aging. If so, it raises the interesting possibility that refresh-induced inhibition of an item might facilitate long-term memory for the refreshed item. That is, inhibiting an item may not only benefit other items, it may benefit the item itself.

It should be noted that older adults do not always demonstrate a long-term memory benefit for refreshed words (Johnson, Mitchell, Raye, & Greene, 2004; Johnson et al., 2002; Raye et al., 2008) and the impact of refreshing may depend on the nature of the items even in young adults (Johnson et al., 2005). It falls to future research to determine the circumstances (e.g., task expectations, type of information) under which refreshing does or does not benefit long-term memory, and the circumstances affecting the long-term memory effects of inhibition associated with refreshing.

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# Time

### Figure 1. Sample stimuli and timing in the main task.

Participants were presented with two words in a vertical column. After the words disappeared, participants were prompted to think of and say aloud the word that had just appeared in the location indicated by the arrow. After a variable (100ms vs. 500ms) delay, participants read aloud the probe word. The probe was either the word they had just refreshed (refreshed probe), the word they had just seen but not refreshed (nonrefreshed probe), or a new word (novel probe). Note that in the experiment, white stimuli were presented on a black background.



Figure 2. Response times to read refreshed and nonrefreshed probes as a function of delay and age group.

Response times were significantly slower for refreshed compared to nonrefreshed probes at the 100ms, but not the 500ms, delay in young adults, and in the 500ms, but not the 100ms, delay in older adults. Younger-old participants were marginally slower at the 100ms, but not the 500ms delay, while older-old were significantly slower at the 500ms delay, but not the 100ms delay.

\*p<.05

#p=.08



Figure 3. Corrected recognition on the long-term memory task for refreshed vs. nonrefreshed and probed vs. nonprobed items as a function of age group.

The refresh benefit (refreshed compared to nonrefreshed words) was larger for nonprobed words than probed words in all age groups. Older-old participants showed a smaller refresh benefit for nonprobed items compared to young participants.

#### Table 1.

Means (standard deviations) of demographic information for participants as a function of delay condition and age group

				Age		Education <sup>1</sup>		Verbal <sup>2</sup>		MMSE <sup>3</sup>	
	Delay	N	Mean	Range	(SE)	Mean	(SE)	Mean	(SE)	Mean	(SE)
Young Adults	100 ms	35	22	18–29	(3.3)	16	(2.4)	22	(4.1)		
	500 ms	34	22	18–29	(3.2)	16	(2.1)	20	(5.8)		
Older Adults	100 ms	34	76	60–90	(7.2)	17	(2.0)	21	(4.6)	29	(1.0)
	500 ms	35	76	62–92	(6.6)	17	(2.3)	22	(4.1)	29	(1.5)
Younger-Old	100 ms	16	70	60–74	(3.9)	16	(2.0)	21	(4.9)	29	(0.6)
	500 ms	14	69	62–73	(3.1)	17	(2.4)	21	(4.8)	29	(1.4)
Older-Old	100 ms	18	81	75–90	(4.8)	17	(1.9)	22	(4.4)	29	(1.2)
	500 ms	21	80	75–92	(4.6)	17	(2.2)	23	(3.5)	28	(1.5)

Notes.

<sup>I</sup>Years of education missing from 8 young adults in the 100ms delay and 9 young adults in the 500ms delay groups due to experimental error

 $^{2}$ Verbal ability as indexed by an abbreviated version of the verbal subscale of the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1987)

 $\frac{3}{100}$  Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975)

### Table 2.

Response times to refresh a word as a function of delay and age group

	100 ms	Delay	500 ms Delay			
	Mean	(SE)	Mean	(SE)		
A. Young Adults	543	(12)	541	(12)		
Older Adults	681	(20)	670	(16)		
B. Younger-Old	659	(33)	655	(24)		
Older-Old	701	(25)	680	(22)		

#### Table 3.

Response times to say aloud the probe word in the main task as a function of trial type, delay, and age group

А).	Probe Responses								
		Novel		Refreshed		Nonrefreshed		<b>Refreshed - Nonrefreshed</b>	
	Delay	Mean	(SE)	Mean	(SE)	Mean	(SE)	Mean	(SE)
Young Adults	100 ms	590	(15)	534	(12)	517	(11)	17	(4)
Older Adults	100 ms	665	(19)	599	(16)	593	(16)	6	(6)
Young Adults	500 ms	580	(17)	519	(14)	510	(15)	9	(5)
Older Adults	500 ms	670	(18)	602	(17)	586	(17)	16	(5)
<b>B</b> ).		Probe Responses							
		Novel		Refreshed		Nonrefreshed		Refreshed - N	onrefreshed
	Delay	Mean	(SE)	Mean	(SE)	Mean	(SE)	Mean	(SE)
Younger-Old	100 ms	645	(24)	585	(18)	572	(19)	13	(7)
Older-Old	100 ms	684	(28)	611	(26)	612	(24)	-1	(9)
Younger-Old	500 ms	650	(29)	571	(25)	559	(23)	12	(7)
Older-Old	500 ms	684	(22)	622	(22)	604	(23)	19	(7)

#### Table 4.

Corrected recognition scores for each condition as a function of delay and age group



Note. Indicates words that functioned as probes on those trials.