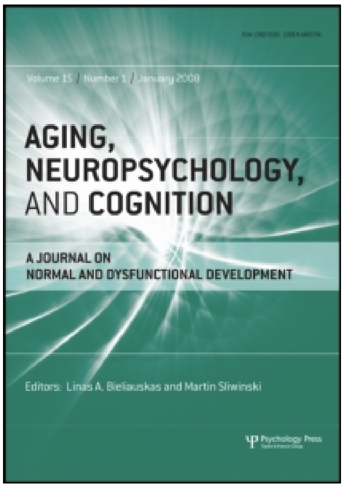

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Sequential Performance in Young and Older Adults: Evidence of Chunking and Inhibition

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Sequential Performance in Young and Older Adults: Evidence of Chunking and Inhibition

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ABSTRACT

Two experiments were conducted to examine possible sources of age-related decline in sequential performance: age differences in sequence representation, retrieval of sequence elements, and efficiency of inhibitory processes. Healthy young and older participants learned a sequence of eight animal drawings in fixed order, then monitored for these targets within trials of mis-ordered stimuli, responding only when targets were shown in the correct order. Responses were slower for odd numbered targets, suggesting that participants spontaneously organized the sequence in two-element chunks. Perseverations (responses to previously relevant targets) served as an index of inhibitory inefficiency. Efficiency of chunk retrieval and self-inhibition were lower for older than for younger adults. Increasing environmental support in Experiment 2 through overt articulation of current chunk elements showed a pattern of results similar to Experiment 1, with particular benefit for older adults. The findings suggest an underlying susceptibility to interference in old age.

Keywords: Aging; Sequential performance; Chunking; Inhibition; Retrieval; Hierarchical structure.

INTRODUCTION

Activities of daily living (e.g., grooming, meal preparation) can be conceptualized as a sequence of steps that must be carried out in a certain order (e.g., Lashley, 1951; Miller, Galanter, & Pribram, 1960; Reason, 1979). The successful execution of such everyday activities is a major consideration in deciding whether older adults can live independently or require assistance

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(Gaugler, Duval, Anderson, & Kane, 2007). Whereas the topic of sequential behavior has been well-researched in terms of computational modeling and neuropsychological impairment (see Schwartz, 2006, for review), less is known about sequential control and healthy aging. Nevertheless, anecdotal reports about aging and absentmindedness, and established findings of age-related frontal/executive control inefficiency (Verhaeghen & Cerella, 2002; West, 1996) converge to suggest that more subtle impairments of sequential control may exist. If so, it is unclear whether such age-related impairments of sequential performance are due to (i) age differences in sequence representation, (ii) inefficient retrieval of the sequence elements, or (iii) inefficient inhibition of no-longer-relevant sequence elements. The current research takes a fine-grained experimental approach to examine these three possibilities.

Sequence Representation and Retrieval

A broadly accepted idea is that action sequences are represented as schema, or hierarchical structures, which are activated as a whole (e.g., Cooper & Shallice, 2000; Estes, 1972; Rumelhart & Norman, 1982; Schneider & Logan, 2007; cf. Botvinick & Plaut, 2004). A frequently used example of an everyday action sequence is making coffee (Botvinick & Plaut, 2004; Cooper & Shallice, 2000; 2006; Giovannetti, Schwartz, & Buxbaum, 2007). Steps for making instant coffee might include putting sugar in the cup, adding milk, adding coffee grounds, etc., with sub-goals for each step. Inherent in the majority of formal models is the assumption that the sub-goals of each step remain in an active state until all elements are completed. It follows that the sub-goals that are active should be more available to working memory than those from an already-completed or yet-to-be-completed step.

While a fixed sequence structure is assumed in formal computational models of sequential action, it is harder to determine from behavioral neuropsychological methods whether there are individual or age differences in sequence representation, or in the efficient access of portions of the sequence. A potential means of assessing these possibilities comes from Logan's (2004) empirical work on task sequences. Logan argued that during the performance of a learned sequence of tasks, participants activate successive subsets or chunks of tasks, which in our view is analogous to the activation of sub-goals within a step (e.g., actions associated with adding sugar). By examining response latencies as a function of serial position, Logan showed that the latencies conformed to a regular scalloping pattern, with each three-element chunk represented by one slow response followed by two faster responses. This was taken to reflect retrieval and unpacking of each chunk from long-term memory (hence, the initial slow response) and faster access of subsequent within-chunk elements from working memory. We presently consider the possibility that young and older adults might differ in terms of sequence structure (i.e., smaller chunk size) and/or efficiency of chunk retrieval (longer latencies for lead chunk elements compared to younger adults).

Inhibitory Processes

An additional assumption of many sequencing models is that inhibitory processes (e.g., *self-inhibition, reflex inhibition, gating)* are invoked to propel attention forward as each step is completed (e.g., Estes, 1972; Houghton, 1990; Houghton & Tipper, 1996; see Arbuthnott, 1995 for review). This assumption has subsequently been supported in a variety of contexts such as spelling (Houghton, Glasspool, & Shallice, 1994), mental arithmetic (Arbuthnott & Campbell, 2003), and serial recall (Maylor & Henson, 2000), showing that future goals are more available in working memory than past goals owing to the recent suppression of completed actions. In the context of everyday action routines, Cooper and Shallice (2000) have proposed that self-inhibition is applied at the level of sub-goals, and that higher order nodes (steps) remain active until the sub-goals are completed, after which they are inhibited.

Self-Inhibition and Aging

There are relatively fewer studies of aging and self-inhibition (see Maylor, Schlaghecken, & Watson, 2005 for review), and among the few studies on the topic, evidence is mixed in terms of finding age-related reductions in self-inhibition (e.g., Maylor & Henson, 2000; cf. Schlaghecken & Maylor, 2005) or the conceptually similar construct of backward inhibition (Li & Dupuis, 2008; Mayr, 2001). Deletion-type inhibition (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999), which also involves the expulsion of no-longer-relevant information from working memory, appears to be weaker in old age, as shown in the context of directed forgetting (e.g., Zacks, Radvansky, & Hasher, 1996) and memory for disambiguated words (e.g., Hartman & Hasher, 1991).

Methods of Assessing Sequential Performance

The behavioral neuropsychological research on sequential action control has largely involved the observation of patients or controls interacting with real objects in order to complete a normatively established action sequence such as wrapping a gift (e.g., Humphreys & Forde, 1998; Schwartz, Buxbaum, Ferraro, Veramonti, & Segal, 2003; Schwartz, Segal, Veramonti, Ferraro, & Buxbaum, 2002). Patients with action disorganization from head injury and stroke display a predominance of omissions errors, particularly with increasing clinical severity and task difficulty (Schwartz, 2006). Other researchers have shown an abundance of perseverative errors

(Humphreys & Forde, 1998) where these errors tend to dissociate between immediate repetition of steps and more distal steps.

Observational methodology precludes finer-grained analyses of responses, which may be more important when examining sequential performance in healthy older adults rather than patient groups. To this end, Li, Lindenberger, Rünger, and Frensch (2000) developed a computerized sequential action control task (S-ACT) which mimics everyday action sequences in several ways: Participants are first trained on a sequence of seven stimulus categories (e.g., letters, numbers, math symbols) in set order. The overlearning of this sequence is analogous to the routinization of common everyday activities. In the subsequent test phase, a succession of exemplars from the categories is shown, but in scrambled order. Embedded within each trial are seven exemplars that conform to the learned sequence. Participants are instructed to monitor for those ordered target exemplars, and to mouse click only when targets are seen in the correct order. Although this experimental procedure does not require the execution of real actions, we assume that recognition of the targets provides an index of the availability of each target, and would be a pre-requisite for enactment of a sequence of actions. Distractor items are drawn from the same categories, such that intrusions can be analyzed as a function of ordinal distance from the currently relevant category. The inclusion of task-relevant distractors is analogous to presenting all task-relevant objects in an observational task. In both cases, the distractors may interfere with sequential performance and trigger anticipation or perseveration errors. Importantly, the type of intrusion errors made (i.e., responding to an item ahead of or behind the current category) can be used to infer the activation status of competing sequence elements. In a study involving young adults only, Li et al. (2000) found that intrusion error rates were higher for anticipations than perseverations, consistent with the concept of self-inhibition.

Objectives and Predictions

Given the practical importance of maintaining efficient sequential action control in old age, we sought to extend previous findings (Li et al., 2000) by comparing young and older adults. Instead of presenting sequences of arbitrarily ordered categories as was done previously (Li et al., 2000), we familiarized participants with a unique series of eight animal drawings, ordered according to size. We assumed that although the sequence did not contain an obvious hierarchical structure, we would observe spontaneous organization (i.e., chunking), as found in previous episodic memory research (Tulving, 1962).

To address the question of whether young and older adults differ in the underlying representation of the sequence or in retrieval efficiency, we used Logan's (2004) method of analysis and predicted that all participants should show a similar pattern of long reaction times for the lead item in each chunk and faster reaction times for subsequent within-chunk items. Alternatively, if older adults have a different representational structure than young adults, this should be evident in examining chunk size. Relative to young adults, we expected older adults to show longer response times for lead items, to indicate less efficient retrieval of chunks from long-term memory (Allen & Coyne, 1988). The analysis of intrusion errors allowed us to further examine evidence for chunking, with the prediction that participants should make more within-chunk than between-chunk intrusions.

To address the question of whether young and older adults differ in the efficiency of self-inhibition, we examined intrusion errors for previously completed items assuming that self-inhibition would be strongest for the just-completed item (Lag –1). We therefore predicted that older adults with less efficient self-inhibition should produce more Lag –1 errors than young adults, in accordance with the inhibitory deficit hypothesis.

EXPERIMENT 1

Method

Participants

Thirty older (M = 68.5, range = 60–75 years old) and 32 younger (M = 23.8, 18–30 years old) adults participated in the study and were paid $10 CDN. The younger participants were recruited from introductory Psychology classes at Concordia University. The older participants were either selected from a subject pool established by researchers in the Adult Development and Aging laboratories at Concordia University, or from community senior centres. Participants who reported neurological disorders, auditory, visual, or motor impairments in the demographic interview, were excluded from the sample. Demographic information and descriptive statistics for the participants are shown in Table 1.

Materials and Design

The demographic questionnaire consisted of questions about chronological age, marital status, years of education and general health. The subjects were administered the Extended Range Vocabulary Test (ERVT, Form V2; Educational Testing Service, 1976) and the WAIS-R Digit Symbol task (Wechsler, 1981), as standardized indicators of verbal ability and cognitive speed, respectively.

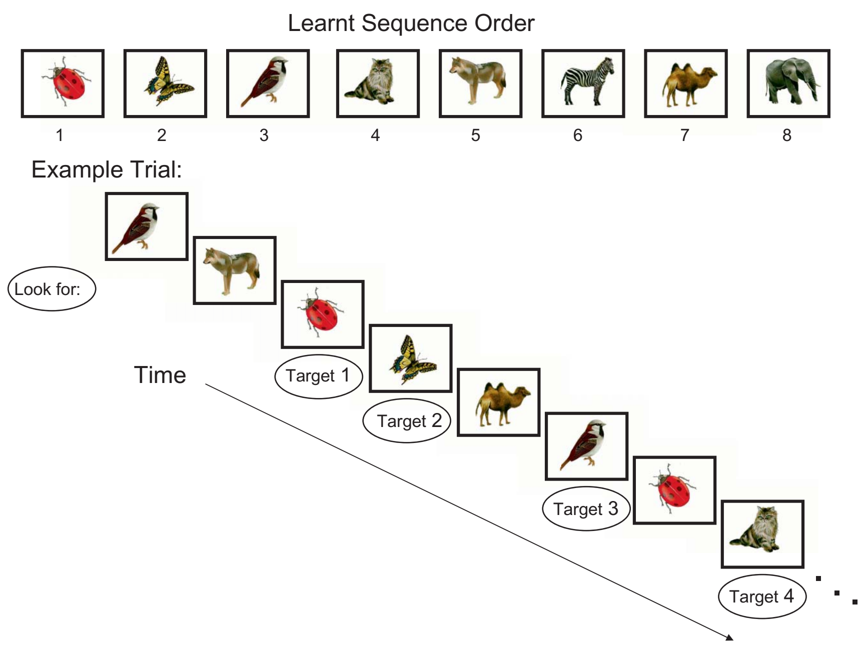
The stimuli for the sequential action control task consisted of eight animal drawings depicting the following: ladybug, butterfly, bird, cat, wolf, zebra, camel, and elephant (Beaumont & Selley, 1990; see Figure 1). All animals appeared in black and white and occupied a space of 11 cm^2 in the

TABLE 1. Demographic and Background Variables by Age Group for each Experiment

	Age group	*n*	Age**	Years of education	Digit symbol**	Vocabulary**
Experiment 1	Young	32	23.8 (4.8)	15.3 (2.1)	71.7 (11.0)	8.0 (4.4)
	Older	30	68.6 (4.4)	15.3 (3.8)	46.8 (11.6)	15.0 (4.7)
Experiment 2	Young	30	21.6 (2.5)	15.0 (1.4)	68.0 (15.4)	7.6 (3.9)
	Older	30	67.6 (5.1)	14.9 (3.0)	52.2 (9.9)	14.0 (5.3)

Note: Values reflect average scores per group; standard deviations are shown in parentheses. **Indicates significant age group differences in both experiments. Digit Symbol refers to WAIS-R Digit Symbol Substitution. Values shown reflect items correctly completed in 90 s. Vocabulary refers to Extended Range Vocabulary Test (accuracy scores, max = 24).

FIGURE 1. Stimuli for the sequential performance task and an example trial. Stimuli were presented in black and white in Experiment 1, and in color in Experiment 2. To view this figure in color, please visit the online version of the paper.



center of the computer screen. The task was programmed using Director Shockwave software on a Macintosh G4 computer.

For each trial, the fixed sequence of eight targets (going from smallest to largest) was interleaved with zero to three distractors. The distractors were instances of target animals that were not currently relevant. To reduce the predictability of sequences, the number of distractors embedded within a trial varied from seven to nine. On trials with nine distractors, one randomly selected distractor appeared twice. As a result, there were 35 trials for each of the different sequence lengths (15, 16, and 17 items), for a total of 105 trials. Each item in the trial appeared one at a time and remained on the screen for 350 ms with an interstimulus interval of 1000 ms.

Procedure

Participants were individually tested in a quiet room. After the participants read and signed the consent form, they answered general questions in a demographic interview. Next, the participants were given the Digit Symbol test to complete within a 90-s period. Participants were then seated in front of a computer to work on the sequential action control task. Finally, participants completed the vocabulary test (ERVT). At the end of the session, all participants were debriefed and paid for their participation. Each session lasted approximately 90 min.

For the sequential action control task, participants completed a training phase and then a test phase. In the training phase, the eight items were shown on paper and participants were asked to study the sheet until they were able to recite the eight items forwards and backwards without error. They then began the computerized practice trials. They were instructed to watch the computer screen for the presentation of Item 1 (i.e., the ladybug) and click the mouse button as quickly as possible if Item 1 (target) was shown, but not to respond if any other item (distractors) appeared. Following a response to Item 1, participants were to begin monitoring for Item 2 (i.e., the butterfly), again mouse clicking if shown but not responding if other items were shown in between targets. An example trial would be: 3-5-**1**-**2**-7-**3**-1-**4**-4-**5**-2-**6**-**7**-5-**8**, where each digit represents the serial position of each sequence element, bolded digits are targets, requiring a mouse click response, and non-bolded digits are distractors (see also Figure 1). In all trials, all eight sequence items were embedded in correct order. All trials terminated following the presentation of the eighth target.

The first five practice trials contained a memory aid indicating the sequence of animal targets, shown in the upper right corner of the screen. An arrow pointed to the animal that the participant should look for at each point in the sequence. For the remaining four practice trials and all test trials, the memory aid was not available.

In the test phase, participants completed two blocks of 48 trials each, in a manner similar to the final four practice trials. For all trials, a feedback screen appeared when the participant committed an error of intrusion or omission. The feedback indicated that an error had occurred and showed a picture of the next animal to which the participant should attend. Participants could resume performance on the trial by pressing a separate key when they were ready to return to the task.

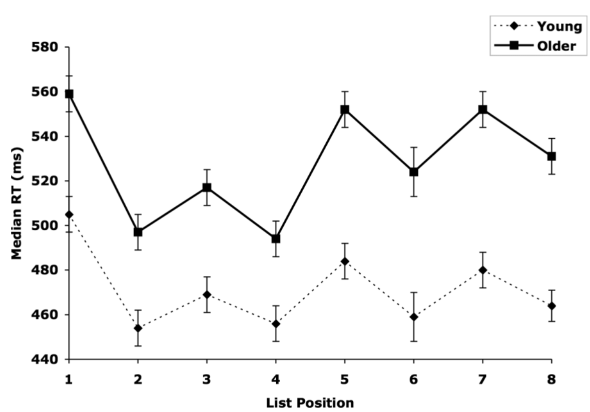
Results and Discussion

Our primary goal for this experiment was to assess whether young and older adults differed in sequence organization, retrieval of sequence elements, and degree of self-inhibition used during the task. Data analysis was only based on performance in test trials.

Chunking

Evidence for chunking was sought by first examining the latencies to correct target responses as a function of list position (see Figure 2). As a preliminary step, we carried out an Age Group (younger, older) × List Position (1 … 8) mixed factorial ANOVA, using median RTs. This yielded a significant main effect of list position, $F(7, 54) = 46.69$, $p < .001$, $\eta^2 = .86$, and age group, $F(1, 60) = 28.87$, $p < .001$, $\eta^2 = .33$. The Position × Age group interaction was also significant, $F(7, 54) = 4.45$, $p = .001$, $\eta^2 = .37$. The effects of list position appear to be driven by a saw tooth pattern, such that even and odd list positions were grouped together. Therefore, in a subsequent ANOVA we separated odd (1, 3, 5, 7) and even (2, 4, 6, 8) sequence elements into two groups, and subjected the latency data to a Sequence Position (odd, even) × Age Group (younger, older) mixed factorial ANOVA. A main effect of sequence position was observed, $F(1, 60) = 191.07$, $p < .001$, $\eta^2 = .76$, due to longer latencies for odd list positions than even positions. This was qualified by a marginal interaction with age group, $F(1, 60) = 3.13$, $p = .08$, $\eta^2 = .05$, such that older adults showed a slightly greater odd–even difference than younger adults ($M\text{diff}_Y = 26$ ms; $M\text{diff}_O = 34$ ms). Not surprisingly, a significant main effect of age group was also observed, $F(1, 60) = 28.87$, $p < .001$, $\eta^2 = .33$, such that older adults produced longer latencies overall.

FIGURE 2. Experiment 1: Median target RTs as a function of list position and age group. Error bars represent one standard error of the mean.



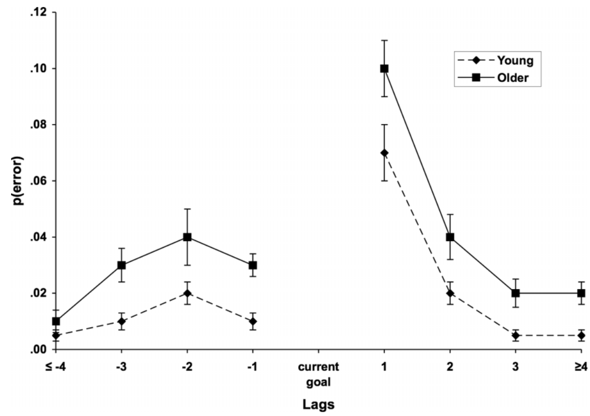
We further evaluated the presence of chunking by examining the pattern of intrusion errors made, with the assumption that if items within a chunk are more active in working memory than those items outside the currently relevant chunk, we should observe a higher rate of intrusion errors when participants were presented with within-chunk distractors than across-chunk distractors. For instance, when looking for Item 1, participants should be more likely to make an error by responding to Item 2, an item belonging to same chunk, than Item 3, which belongs to another chunk. To evaluate this possibility, we split the data into errors made within a chunk versus between chunks. The frequency of each error type was 116 and 651, for within- and between-chunk errors, respectively. In line with this prediction, results from an Age Group (younger, older) × Error type (within chunk, between chunk) ANOVA showed a main effect of error type, $F(1, 60) = 38.42$, $p < .001$, $\eta_p^2 = .39$, due to more within chunk errors ($M = 0.04$, $SEM = 0.004$) than between chunk errors ($M = 0.03$, $SE = 0.003$), $t(61) = 5.83$, $p < .001$. This was qualified by an Age Group × Error Type interaction, $F(1, 60) = 7.19$, $p = .009$, $\eta_p^2 = .11$, due to more within chunk than between chunk errors in older adults (Mdiff = 0.02), $t(29) = 5.5$, $p < .001$ compared to younger adults (Mdiff = 0.01), $t(31) = 2.91$, $p = .01$. As would be expected, the younger group ($M = 0.02$, $SEM = 0.004$) had fewer errors overall than older adults ($M = 0.03$, $SEM = 0.004$) as indicated by a main effect of age group, $F(1, 60) = 6.98$, $p = .011$, $\eta_p^2 = .10$.

The latency findings converge with our intrusion error results in suggesting that participants represented the sequence in two-element chunks. We attribute the longer latencies in odd list positions to the need for executive control when retrieving new chunks from long-term memory (Mayr, 2001; Mayr & Kliegl, 2000). The marginal age-interaction in the latency analyses suggest that there is a slight age-related decrease in long-term memory retrieval efficiency. Retrieval of a new chunk might be hindered in old age by having weaker representations of each chunk, or contending with interference from competing items (Mayr, 2001).

Self-Inhibition

We operationalized self-inhibition in terms of the occurrence of negative lag errors, assuming that efficient self-inhibition would be indicated by a low intrusion error rate for just-completed items (i.e., Lag –1 errors, see Figure 3). In general, lag errors were defined as an incorrect response to an item that was either ahead of the target (positive lag errors) or previously completed (negative lag errors). Thus, participants could make anywhere between Lag +7 and Lag –7 errors. For instance, if when looking for the cat (serial position 4) one responded to the ladybug (serial position 1), this would be classified as a Lag –3 error. Given the low base rates (maximum number of opportunities) to commit lag errors from +4 to +7 and –4 to –7,

FIGURE 3. Experiment 1: Intrusion error rates as a function of age group and lag. Error bars represent one standard error of the mean.



these more extreme lag errors (± 4–7) were pooled to make their base rates more comparable to lags ±1–3. This resulted in eight possible kinds of lag errors (≤–4, –3, –2, –1, 1, 2, 3, ≥4). Intrusion error rates were computed by dividing the number of each type of lag errors committed by a participant by the maximum number of opportunities to make that error (96, 97, 97, 96, 98, 99, 97, 90, for Lags ≤–4 to ≥4, respectively), resulting in a proportion error score for each type of lag error. To examine the effects of age on self inhibition as predicted, an Age Group (younger, older) × Error Type (–4, –3, –2, –1) mixed factorial ANOVA was carried out, restricting the analysis to negative lag errors consistent with self inhibition of previously completed items. Results showed a significant main effect of age group, $F(1, 60) = 4.5$, $p = .038$, $\eta_p^2 = .07$, such that older ($M = 0.03$, $SEM = 0.004$) made more negative lag errors than younger adults ($M = 0.02$, $SEM = 0.004$). A significant main effect of error type was also observed, $F(3, 58) = 23.36$, $p < .001$, $\eta_p^2 = .55$, indicating more Lag –1, –2, and –3 errors compared to Lag –4 errors and more Lag –1 and –2 errors compared to Lag –3 errors, $p < .001$. No other comparisons were significant, $p > .08$. In line with our prediction, a significant Age Group × Negative Lag interaction was observed, $F(3, 58) = 3.12$, $p = .03$, $\eta_p^2 = .14$. Bonferroni corrected *t*-tests (alpha level of .01) showed that younger adults had fewer Lag –1 errors compared to older adults, $t(60) = 3.61$, $p = .001$, but similar Lag –2, –3, and –4 errors, $p > .01$. This result indicates that the item that was just responded to, namely *n* –1, was suppressed to a greater extent in the younger adults than the older group, but earlier items, namely *n* –2, –3, and –4, were equally active between the groups.

To check if the Lag –1 age difference observed above was due to age differences in the time course of self-inhibition (Maylor & Henson, 2000;

Maylor et al., 2005) we analyzed Lag –1 errors as a function of delay from response execution. According to Arbuthnott and Campbell (2003), self-inhibition should be strongest immediately following the execution of a response, but then dissipate over time. If so, we would expect the availability of the task/response to increase as a function of the number of intervening items from a correct target response to the reoccurrence of the same target as a distractor.

Using proportion of Lag –1 errors, a Distractor (0, 1) × Age group (younger, older) mixed factorial ANOVA was carried out to compare the proportion of errors that occurred when item *n* –1 repeated immediately (zero distractor) compared to when there was one distractor between a correct response and an *n* –1 repeat. We did not analyze instances of two or more intervening distractors because of their low frequency. A main effect of distractor was observed, $F(1, 53) = 102.72$, $p < .001$, $\eta_p^2 = .66$, with more intrusions errors when there was a distractor between *n* –1 repeats ($M = 0.11$, $SEM = 0.01$) as opposed to when there was none, i.e., the item responded to repeated immediately, ($M = 0.002$, $SEM = 0.001$). This result suggests self-inhibition was strongest after responding to an item, which led to reduced chances of responding again to this item when it was presented immediately as opposed to when time had elapsed before the item was presented again. In addition, a significant Distractor × Age Group interaction was observed, $F(1, 53) = 12.56$, $p = .001$, $\eta_p^2 = .192$, which was driven by a greater proportion of Lag –1 errors in older adults ($M = 0.15$, $SEM = 0.02$) compared to younger adults ($M = 0.07$, $SEM = 0.01$) following a distractor, $t(53) = 3.59$, $p = .001$, but a similar proportion of lag errors when there was none ($M_O = 0.002$, $SEM_O = 0.001$; $M_Y = 0.001$, $SEM_Y = 0.001$), $t(53) = 1.03$, $p = .31$. This goes against the possibility that older adults have slower-acting self-inhibition than young adults but suggests that self-inhibition may not be as long-lasting in old age. As before, a significant main effect of age group was observed $F(1, 53) = 13.22$, $p = .001$, $\eta_p^2 = .2$, such that younger adults made fewer Lag –1 errors than older adults ($M_Y = 0.04$, $SEM_Y = 0.008$; $M_O = 0.08$, $SEM_O = 0.008$).

Omission Errors

We examined target omissions to assess task proficiency, and check if the observed age group main effect in intrusion error rate was attributable to age differences in response bias (e.g., older adults exhibiting a more lenient criterion). Analysis of the omission error rates revealed that younger adults ($M = 0.02$, $SEM = 0.006$) missed fewer targets than older adults ($M = 0.04$, $SEM = 0.007$), $t(60) = -2.53$, $p = .014$, suggesting that simple age group differences in response bias cannot account for the age differences observed in the intrusion data.

Summary

In this experiment, we found evidence of an age-equivalent chunking structure comprised of two-item chunks. Older adults appear to access each chunk more slowly than young adults. Self-inhibition was more evident in young adults than older adults. Together, these results suggest that age differences in memorial and inhibitory processes might underlie age differences in sequential performance. However, as older adults may have more difficulty activating and maintaining relevant task settings as proposed in task switching (Mayr, 2001), environmental support may improve their performance given reduced processing resources with increasing age (Craik, 1986). Thus, in Experiment 2, environmental support was added using overt rehearsal, which has been posited to maintain target information in sequential tasks (Kray, Eber, & Lindenberger, 2004). In addition, we aimed to directly examine the role of inhibition in the S-ACT task by experimentally inducing self-inhibition in the next experiment. Lastly, as reaction time evidence in favour of the two-item chunking structure was only marginally significant when odd and even serial positions were compared (p = .08), we further investigated this sequence representation by teaching participants a two-item chunking strategy.

EXPERIMENT 2

In this experiment, we aimed to reduce age effects in sequential performance by providing environmental support by means of overt articulation of sequence elements. Participants were trained to chunk the sequence used in Experiment 1 using overt articulation of two-item chunks. Overt articulation has been proposed to keep target items in an active state in working memory (Bryck & Mayr, 2003; Kray et al., 2004), thereby reducing interference from irrelevant information. Overt rehearsal harkens back to Baddeley's (1986) model of working memory in which subvocal rehearsal maintains items in the phonological loop, and hence, readily available in conscious awareness (see also Vygotsky, 1988). More recently, Bryck and Mayr (2003) used articulatory suppression to show that verbalization may play a crucial role in maintaining and updating task relevant information during sequential tasks.

Further, the role of inhibition in the S-ACT task was examined by comparing two possible models of sequential action regulation. The first model assumes the involvement of chunking processes (*full articulation*); the second assumes the involvement of chunking plus self-inhibition (*updated articulation*). In the full articulation condition, participants recited the two items in each chunk until they responded to the respective chunks throughout the list. In the updated articulation condition, participants recited both items in each chunk but then dropped recital of the first item once it was responded to.

Our first expectation was that age effects would be reduced with added environmental support across both articulation conditions. To examine this prediction, it was first necessary to analyze response latency throughout the sequence to ensure that verbalization of two-item chunks resulted in a similar chunking pattern as observed in Experiment 1 (i.e., long RT for lead chunk items and short for within-chunk items). Results along these lines would also provide support for the use of a two-item chunking strategy in Experiment 1. A similar analytic approach to confirm the presence of chunking was used by Schneider (2007), who induced chunking to validate the claim that a hierarchical chunking structure modulated the effects of n –2 repetition costs in a task switching setting (Koch, Philipp, & Gade, 2006).

We further expected that if self-inhibition is involved in the sequential performance task, participants should suppress prior items within the chunk to a greater extent in the updated articulation condition, where self-inhibition was encouraged by dropping rehearsal of sequence elements upon their completion. Thus, our second hypothesis was that Lag –1 and Lag +1 errors should be elevated within a chunk in the full articulation condition because both items in each chunk were kept currently active until a response was made. Conversely, in the updated articulation condition, only the Lag +1 errors should be elevated within a chunk whereas the Lag –1 errors should be suppressed.

Finally, in accordance with models of age-related inhibitory decline (e.g., Hasher et al., 1999) and the results of Experiment 1, we predicted that self-inhibition of prior responses would be more efficient in younger adults as compared to older adults. This would be supported by an age-related increase in Lag –1 errors in the latter group.

Method

Response latencies at each serial position and intrusion errors were computed and aggregated in a similar manner to Experiment 1.

Participants

Demographic information and descriptive statistics for the participants are shown in Table 1. The methods of recruitment and screening were identical to those used in Experiment 1.

Materials and Procedures

The materials for the S-ACT were identical to those used in Experiment 1, and the main task was the same: Participants were instructed to mouse click in response to the presentation of the eight sequence elements in the learned order. The major difference between experiments was the way in which the sequence was introduced in the training phase, and the addition of overt articulation during the test phase. In the training phase, participants initially memorized the same eight-item animal sequence as used in Experiment 1 but items were introduced two at a time rather than all at once to encourage chunking during the test phase. Depending on the articulation strategy participants were assigned, they were instructed to either fully recite out loud both chunk items until they were responded to as they progressed throughout the sequence (full articulation) or rehearse only the last item within the chunk after responding to the first item (updated articulation).

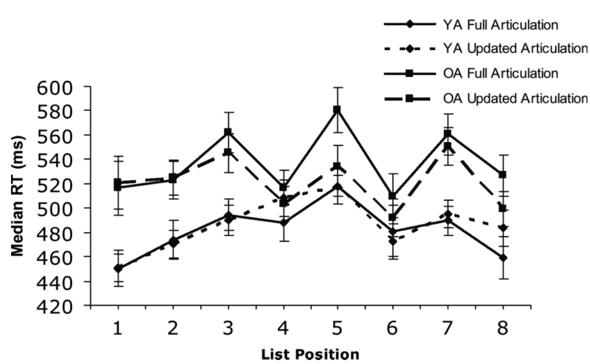
Participants were then given a paper practice trial that simulated the computer trials. As they verbally rehearsed chunk items, they were instructed to tap on the desk once when they saw each target item and not to tap when they saw a distractor item. Following a minimum of two paper practice trials or however many trials were necessary for perfect performance, the computer task and remaining paper and pencil test procedures were the same as Experiment 1, the only exception being the use of articulatory strategies during the computer task. The experimenter sat with the participant to remind him/her to articulate if necessary. Participants were randomly assigned to either the full or updated articulation conditions.

Results and Discussion

Chunking

Before examining the role of environmental support in serial performance, evidence for chunking the sequence using overt articulation in both age groups was investigated by first comparing response latency across serial positions (see Figure 4). Using mean correct RTs, the Age Group (younger, older) × Articulation Strategy (full, updated) × Sequence Position (odd, even) mixed factorial ANOVA showed a significant main effect of age group, $F(1, 56) = 17.31$, $p < .001$, $\eta_p^2 = .24$, such that young adults (M = 482 ms,

FIGURE 4. Experiment 2: Median target RTs as a function of list position, age group, and articulation strategy. Error bars represent one standard error of the mean.



SEM = 8.93) had faster RTs than older adults (*M* = 540 ms, *SE* = 10.21). A significant main effect of sequence position was also observed, $F(1, 56) = 30.37$, $p < .001$, $\eta_p^2 = .35$, such that odd positions (*M* = 523 ms, *SE* = 8.40) were significantly longer than even positions (*M* = 499 ms, *SE* = 7.72). The main effect for articulation was not significant, $p = .86$. A significant Age Group × Sequence Position interaction was obtained, $F(1, 56) = 12.37$, $p = .001$, $\eta_p^2 = .18$.

Following up on the Age group × Sequence Position interaction, Bonferroni corrected (analyzed at alpha level of .025) paired *t*-tests were done to analyze differences in RTs at odd and even positions for younger and older adults separately. For older adults, odd positions (*M* = 560 ms, *SEM* = 11.45) were significantly longer than even positions (*M* = 520 ms, *SEM* = 10.20), $t(29) = 5.53$, $p < .001$, indicating a more exaggerated scalloped pattern across both articulation strategies consistent with two-item chunks. A trend for longer RTs for odd positions (*M* = 487 ms, *SE* = 7.99) compared to even positions (*M* = 478 ms, *SE* = 10.44) was found for younger adults across both articulation strategies, $t(29) = 1.74$, $p = .093$. This result appeared more evident from the third position in the full articulation strategy and the fifth position in the updated articulation strategy as shown in Figure 4.

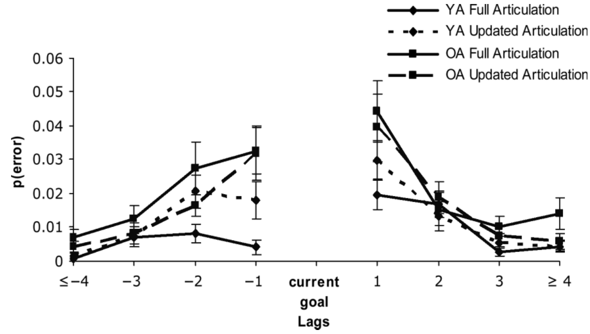
Similar to Experiment 1, we found confirmatory evidence that items within a chunk were more active in working memory than items between chunks. Results from an Age Group (younger, older) × Error Type (within chunk, beteen chunk) × Articulation Strategy (full, updated) mixed factorial ANOVA using proportion errors revealed a main effect of error type $F(1, 56) = 38.69$, $p < .001$, $\eta_p^2 = .41$, with significantly more within chunk errors (*M* = 0.03, *SE* = 0.004) than between chunk errors (*M* = 0.01, *SE* = 0.001). This result was qualified by an Age Group × Error Type interaction $F(1, 56) = 8.1$, $p = .006$, $\eta_p^2 = .13$, which was driven by more within chunk than between chunk errors in older adults (*M*diff = 0.03), $t(29) = 5.34$, $p < .001$, compared to younger adults (*M*diff = 0.01), $t(29) = 3.30$, $p = .003$. Younger adults (*M* = 0.01, *SEM* = 0.002) made fewer errors overall than older adults (*M* = 0.02, *SEM* = 0.002) as indicated by a main effect of age group, $F(1, 56) = 10.15$, $p = .002$, $\eta_p^2 = .15$. As expected, articulation condition did not have an effect on the structure or efficiency of chunking, $p = .53$.

Given evidence consistent with chunking for younger and older adults from the RT and error data, we next considered the benefit of environmental support in the efficiency of sequential performance, particularly for older adults. In line with this prediction, although age differences in response latency and overall errors remained significantly in favour of younger adults as mentioned above, older adults showed greater benefit from overt rehearsal in a cross experimental comparison: Independent samples *t*-test were conducted to compare the performance of older adults across experiments on RT and intrusion errors; a similar comparison was made for younger adults, using a Bonferroni correction for all comparisons (alpha level of .0125). Older adults in Experiment 2 had significantly fewer intrusion errors compared to Experiment 1, $t(58) = 2.95$, $p = .005$, whereas no significant difference was found for younger adults across experiments, $t(60) = 2.55$, $p = .013$. No difference in response latency was evident for either group across experiments, $p > .05$. In addition, older adults in Experiment 2 with environmental support performed similarly to young adults in Experiment 1 in terms of intrusion errors, $t(60) = .47$, $p = .64$, unlike the older group in Experiment 1 without environmental support (see Experiment 1 results). Therefore, across both chunking strategies (updated and full articulation), older adults benefited from enhanced environmental support, as shown by reduced intrusion errors in sequential performance.

Self-Inhibition

To examine Hypotheses 2 and 3 concerning self-inhibition and age differences therein, the proportion of Lag –1 errors within chunks was compared across articulation strategies for each group. It was expected that Lag –1 errors would be more suppressed within chunks in the updated than in the full articulation condition (see Figure 5). Contrary to expectation, more Lag –1 errors within chunks were found in the updated ($M = 0.02$, $SEM = 0.02$) than the full articulation strategy ($M = 0.005$, $SEM = 0.01$), $t(28) = 2.38$, $p = .024$, in the younger group, whereas no difference in Lag –1 errors within chunks was observed across articulation strategies in the older group (full: $M = 0.029$, $SEM = 0.01$; updated: $M = 0.029$, $SEM = 0.01$), $t(28) = .06$, $p = .952$. However, as predicted, no difference was found in Lag +1 errors within chunks in the updated as compared to the full articulation strategy in either groups, $p > .05$.

FIGURE 5. Experiment 2: Intrusion error rates as a function of age group, lag, and articulation strategy. Error bars represent one standard error of the mean.



An Age Group (younger, older) × Articulation Strategy (full, updated) × Negative Lag Errors (–4, –3, –2, –1) mixed factorial ANOVA was conducted to evaluate the negative effects of age on self-inhibition. A significant main effect of age group was observed, $F(1, 56) = 10.30$, $p = .002$, $\eta_p^2 = .16$, such that older adults ($M = 0.02$, $SEM = 0.002$) made more negative lag errors than younger adults ($M = 0.01$, $SEM = 0.002$). A significant main effect of negative lag errors was also observed, $F(3, 54) = 23.37$, $p < .001$, $\eta_p^2 = .57$, such that there were more Lag –1, –2, and –3 errors compared to Lag –4 errors and more Lag –1 and –2 errors compared to Lag –3 errors, $p < .001$. No other comparisons were significant, $p > .08$. Furthermore, a significant Age Group × Articulation interaction was found, $F(1, 56) = 4.17$, $p = .046$, $\eta_p^2 = .07$, such that older adults ($M = 0.02$, $SEM = 0.003$) made significantly more negative lag errors in the full articulation condition than younger ($M = 0.01$, $SEM = 0.01$), $t(28) = 3.67$, $p < .001$, whereas no difference in negative lag errors was observed between the groups in the updated condition ($M_O = 0.015$, $SEM_O = 0.01$; $M_Y = 0.01$, $SEM_Y = 0.01$), $t(28) = .84$, $p = .411$.

Similar to Experiment 1, a significant Age Group × Negative Lag interaction was observed, $F(3, 54) = 4.08$, $p = .01$, $\eta_p^2 = .19$. Bonferroni corrected *t*-tests (alpha level of .01) showed that younger adults had fewer Lag –1 errors compared to older adults, $t(58) = 3.46$, $p = .001$, but similar Lag –2, –3, and –4 errors, $p > .01$. Again, this result indicates that the immediate item (i.e., *n* –1) was suppressed to a greater extent in younger than older adults, with no difference for earlier items.

We further examined the time course of self-inhibition by analyzing Lag –1 errors as a function of distance from task completion (i.e., number of intervening distractors). Using a Distractor (0, 1) × Age Group (younger, older) × Articulation Strategy (full, updated) mixed factorial ANOVA, a main effect of distractor was observed, $F(1, 36) = 43.88$, $p < .001$, $\eta_p^2 = .55$, with more intrusions errors when there was a distractor between *n* –1 repeats ($M = 0.09$, $SEM = 0.01$) as opposed to none ($M = 0.01$, $SEM = 0.004$). No other effects or interactions were significant, $p > .05$. Notably the Age Group × Distraction interaction that was significant in Experiment 1 was nonsignificant in this study. We surmise that the practice of overt articulation enabled the older adults in the present experiment to avoid distraction more effectively than in the previous study.

Omission Errors

We analyzed omission error rates to check for age group differences in response bias using an Age Group (younger, older) × Articulation Strategy (full, updated) factorial ANOVA. This analysis revealed only a main effect of age group such that older adults ($M = 0.03$, $SEM = 0.004$) had more omission errors than younger adults ($M = 0.01$, $SEM = 0.004$), again ruling out the possibility that age differences in response bias were driving the intrusion error results.

Summary

The results of the current experiment replicate and extend those of Experiment 1. The environmental support provided by overt articulation benefited older adults more than young adults, as evidenced by reduced overall intrusion errors across both articulation strategies. Articulatory rehearsal of chunked elements led to a similar pattern of data as observed in Experiment 1: Odd serial positions had longer response latencies than even positions. Similar to Experiment 1, this scalloped pattern was more accentuated in the older participants, indicating that they were slower to retrieve chunks from long-term memory compared to young adults (Zacks et al., 2000); thus the marginal Age × Sequence position interaction in Experiment 1 was supported in this experiment.

In contrast to Experiment 1 however, the scalloping pattern of RTs emerged later in the sequence. It appears that despite the two-item verbalization instruction, younger participants may have initially loaded four items into working memory (Cowan, 2001), but then were unable to maintain this strategy and resorted to activating two-item chunks for the rest of the sequence. Older adults appear to have used a similar strategy in the early part of the sequence, at least up until the third item in the list. Testers anecdotally reported that participants began reciting the first chunk prior to the beginning of each trial. This behavior may account for the shorter Item 1 RTs observed in the present experiment. However it is not clear why a similar facilitatory effect was not present for older adults. We speculate that this age difference reflects an age-related reduction in working memory capacity (Zacks et al., 2000).

Contrary to our attempt to encourage self-inhibition by having participants drop rehearsal of items responded to in the updated condition as opposed to the full articulation condition, we observed more Lag –1 errors in the former than the latter condition, particularly for young adults. It appears that for young adults, instructions to drop recital of a previously relevant within-chunk item resulted in increased activation of that item. This pattern bears some similarity to the enhancement effect observed during studies of thought suppression (Wenzlaff & Wegner, 2000), in which a concept or target item is made more available to conscious awareness when participants are instructed to *not* think about it (Wegner, 1994; Wenzlaff & Wegner, 2000). It is plausible that the enhancement effect is responsible for increased activation of n –1 items in the updated articulation condition, at least for the younger group in this study. Further experimentation is needed to explore potential age differences in the enhancement effect (cf. Erskine, Kvavilashvili, & Kornbrot, 2007). Nevertheless, self-inhibition was weaker overall in older adults than younger adults, in accordance with our Experiment 1 findings. Taken together, the results of Experiment 2 resemble those of Experiment 1 and thus help validate the claim that chunking and self-inhibition occur spontaneously in the basic sequential performance paradigm.

GENERAL DISCUSSION

The present work extends previous research on sequential performance by exploring the interactions of age, mnemonic, and inhibitory processes. Our overall goal was to determine whether age differences in sequence representation, retrieval, or inhibition, contribute to age differences in sequential performance. The Experiment 1 results suggest that young and older adults represent sequence elements similarly, although the efficient retrieval of each chunk is compromised by aging. Further, we showed that self-inhibition contributes to sequential performance and is age-sensitive. The Experiment 2 results corroborate the role of chunking and self-inhibition and importantly, the utility of environmental support in serial performance. Together, the results suggest that although young and older adults exhibit spontaneous chunking and self-inhibition during sequential performance, older adults are less efficient in retrieval and inhibitory processes in this context. Instructing older adults to recite the chunk elements systematically in Experiment 2 provided effective environmental support and resulted in improved accuracy in sequential performance. The remaining discussion focuses on aging, sequence representation, self-inhibition, and the benefits of overt rehearsal.

Our current approach to studying sequential behavior has been to use experimental cognitive methods to mimic the requirements of a naturalistic action task and enable a more detailed analysis of response latencies and error types. By using an ordered but novel sequence, we reduced the probability of triggering a well-ingrained hierarchical representation (e.g., making coffee) but consequently, could not make strong predictions about the sequence structure. We therefore made links to recent behavioral work on task switching, executive control, and task span performance, with the assumption that the underlying cognitive processes in sequential performance can be conceptualized as a series of discrete tasks which may or may not be grouped together, or chunked, similar to naturalistic action sequences.

Using Logan's (2004) method of analysis, we found a uniform pattern of chunked sequence representation, in which subsets of sequence elements were retrieved (long RTs), held active in working memory (short RTs), and then inhibited (low lag –1 intrusions). We argue that this pattern is in line with hierarchical models of sequential action (e.g., Cooper & Shallice, 2000; Houghton & Tipper, 1996). The present findings are also consistent with models of memory that involve the activation or retrieval of information from long-term memory in chunks or subsets (e.g., Cowan, 1995; Ericsson &

Kintsch, 1995). Conceptually similar ideas have been proposed by Palmer and Pfordresher (2003) in their model of sequence production during musical performance. Our present results extend previous findings by showing that the efficiency of chunk retrieval is affected by aging, and that non-target stimuli associated with within-chunk elements are more likely to trigger intrusion errors than non-targets from outside the currently active chunk, which speaks to the activation strength of currently relevant chunks.

Chunk Size and Retrieval

In the present study and others, chunk size appears to be significantly influenced by stimulus characteristics such as sequence length and structure (Koch et al., 2006). For instance, Logan's (2004) 10-element sequences produced three-item chunks, which he attributed to the particular structure of his sequences where three tasks repeated in varying combinations. Our current findings suggest that the eight-element sequence was spontaneously broken up into two-item chunks (Experiment 1). Teaching participants to use two-item chunks led to the same general pattern (Experiment 2).

Closer inspection of the RT data in Experiments 1 and 2 also suggest the possibility of a 4-2-2 chunking strategy rather than a 2-2-2-2 pattern. While we did not have *a priori* expectations regarding chunk size, we reason that because four items are within the range of working memory capacity (Cowan, 2001), it is plausible that participants held one four-item chunk in mind initially, but then found the working memory load too demanding to sustain, reverting to a more economical two-item chunking structure for the remainder of the sequence. It may be that reduced cognitive effort is required to retrieve chunks with fewer items (i.e., less complex chunks), an idea consistent with findings from Schneider and Logan (2006, Experiment 2) in task switching. They observed reduced latency to retrieve less complex task sequences composed of a small number of task switches as opposed to complex ones with many task switches. It is also possible that the repeated suggestion of a 4-2-2 strategy may be a function of the eight-item list length used in our experiments; Logan (2004, Experiment 2) showed that manipulating list length affected chunk size within his task span procedure.

A strong assumption of hierarchical models of sequential behavior is that chunking is an inherent aspect of sequence representation (e.g., Schneider & Logan, 2006), and therefore should occur spontaneously (e.g., Miller, 1956; Tulving, 1962). Research on motor programming, task switching, and the present paradigm, reinforce the ubiquity of hierarchical organization in sequential performance (Rosenbaum, Carlson, & Gilmore, 2001; Schneider & Logan, 2006, 2007). For instance, hierarchical organization or representation has been demonstrated at the level of motor programming in tasks such as typing or tapping (Kornbrot, 1989; Povel & Collard, 1982). More recently, the influence of hierarchical representation has been demonstrated in task switching where shifting between task sequences influenced performance at the level of the task, leading to the absence of switch costs (Schneider & Logan, 2006).

Given the ubiquity of chunking/hierarchical organization of sequences, it may not be surprising that we did not observe age differences in sequence structure. This is in line with previous work by Allen and Coyne (1988, 1989), who reported age-invariance in the occurrence of spontaneous chunking and chunk size during serial recall (Allen & Crozier, 1992). Although sequence structure appeared to be comparable between age groups, the processes associated with sequence recognition (i.e., chunk retrieval, self-inhibition) seemed to be compromised in older adults. We found that older adults responded disproportionately more slowly to the lead item of each chunk than to subsequent within-chunk elements, suggesting an age-related decline in chunk retrieval efficiency. In a discussion of age effects in task set switching, Mayr (2001) proposed that older adults require more cognitive capacity to retrieve and maintain task set information, and that retrieval difficulty may be due to increased interference, or alternatively, to weaker memory traces. Given that participants overlearned the sequence order in our two experiments, we favor the interference interpretation.

Our findings are also relevant to the literature on age-related declines in associative memory (e.g., Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Naveh-Benjamin, Cowan, Kilb, & Chen, 2007). By this view, older adult should show evidence of (i) poorer chunk retrieval due to weaker binding between items within a chunk and (ii) smaller chunks due to reduced processing resources available for associative binding (Naveh-Benjamin et al., 2007). While our present results are compatible with the first prediction, they are incompatible with the second. While we did not make strong predictions regarding chunk size and aging, we speculate that the observed age-equivalence in chunk size may be due to the requirement of overlearning the same eight-item sequence throughout the experiment (see Naveh-Benjamin et al., 2007 for similar discussion).

A related question is whether young and older adults benefited differentially from the environmental support (Craik, 1986) offered by overt rehearsal (Kray et al., 2004) in Experiment 2. If older adults utilize more cognitive capacity when they chunk, they should have derived a greater benefit from overt articulation than young adults. In line with this, we did find reduced intrusion error rates for older adults in Experiment 2, across both articulation strategies, compared to Experiment 1. In addition, environmental support allows for older adults to perform similarly to young adults who are not given a strategy: As observed, older adults in Experiment 2 with environmental support had a similar proportion of intrusion errors as young adults in Experiment 1. This is likely due to a reduction of potential interference from between-chunk items with overt rehearsal (Bryck & Mayr, 2003).

Comparing overall performance across experiments, we found no between-experiment differences in overall RT for either age group. Furthermore, the chunking pattern (operationalized as odd–even differences in RT across serial positions) was similar across experiments (p = .32), which helps to validate our chunking interpretation of the Experiment 1 data.

Self-Inhibition

As operationalized in the present study, older adults exhibited less efficient self-inhibition than young adults, in line with our predictions and other results concerning deletion-type inhibition. However, the conceptually similar process of backward inhibition (Mayr & Keele, 2000) appears to be maintained in old age (Li & Dupuis, 2008; Mayr, 2001). While these findings appear to conflict, self-inhibition and backward inhibition are thought to have different triggering conditions: self-inhibition merely by above-threshold activation of item representation (Arbuthnott & Campbell, 2003) and backward inhibition by competition between a to-be-established task set and a prior one that is no longer relevant (Mayr & Keele, 2001).

The finding of age-related increases in perseverative errors is similar to what Humphreys and Forde (1998) reported with brain damaged patients with Action Disorganization Syndrome. This parallel is consistent with evidence of age-related loss in the integrity of prefrontal regions (Raz & Rodrigue, 2006), and links between decreasing dopamine neurotransmission and susceptibility to neural noise in old age (Bäckman, Nyberg, Lindenberger, Li, & Farde, 2006).

Our further examination of Lag –1 errors as a function of intervening distractors provides additional evidence that older and younger adults engaged self-inhibition processes most strongly immediately after task execution, but that self-inhibition dissipated over time. This result allows us to rule out the possibility that older adults have slower acting self-inhibition processes compared to young adults, a consideration raised by Maylor et al. (2005).

Conclusions and Outlook

Together, the present results address the question of which processes associated with sequential performance are age-sensitive and which are age-invariant. Our findings extend what is known about healthy aging and sequential performance by taking a cognitive behavioral approach to enable a more sensitive assessment of sequence representation and underlying processes. In both experiments, older adults exhibited less efficient retrieval and inhibitory processes. A potential underlying cause of these two findings is age-related decreases in the ability to handle interference or age-related increases in neural noise. These positions are not mutually exclusive, and are well-supported by previous findings (Bäckman et al., 2006; Rabbitt, 1965). It remains for future studies to examine whether manipulations that increase potential interference will affect both retrieval efficiency and self-inhibition, and whether the current test paradigm shows different chunk structures with everyday action sequences.

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