Evidence for age-related changes to temporal attention and memory from the choice time production task

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Abstract

The effect of aging on interval timing was examined using a choice time production task, which required participants to choose a key response based on the location of the stimulus, but to delay responding until after a learned time interval. Experiment 1 varied attentional demands of the response choice portion of the task by varying difficulty of stimulus-response mapping. Choice difficulty affected temporal accuracy equally in both age groups, but older participants' response latencies were more variable under more difficult response choice conditions. Experiment 2 tested the contribution of long-term memory to differences in choice time production between age groups over 3 days of testing. Direction of errors in time production between the two age groups diverged over the 3 sessions, but variability did not differ. Results from each experiment separately show age-related changes to attention and memory in temporal processing using different measures and manipulations in the same task.

Interval timing, the ability to distinguish quantities of time in the seconds to minutes range, is an underlying requirement for normal cognition. A sense of time that is both accurate and precise is also necessary for daily functioning: it is central to safely crossing a busy street, or preparing a hot meal. To prepare a breakfast in which everything arrives at the table hot, and at the same time, requires a number of timing-related skills. Even in the absence of a clock, we have a sense of how long an egg takes to cook, or how long a toaster takes to pop. Thus some of the same cognitive skills that underlie successful interval timing may also be those that are critical to daily functioning, which is compromised in many neurodegenerative diseases related to aging, for example, Alzheimer's disease (American Psychiatric Association, 2000).

Advancing age impacts a number of cognitive functions, including perception, attention, memory, processing speed, and motor control (for review, see Craik & Salthouse, 2000). Many of these functions are also thought to be components of the machinery supporting interval time production. Previous results of studies of the influence of aging upon our ability to time short intervals have pointed to differences in attention (e.g., Lustig & Meck, 2001; Vanneste & Pouthas, 1999), or memory (Perbal et al., 2005; Rakitin, Scarmeas, Li, Malapani, & Stern, 2006; Rakitin, Stern, & Malapani, 2005), and sometimes both (Baudouin, Vanneste, Isingrini, & Pouthas, 2006; Baudouin, Vanneste, Pouthas, & Isingrini, 2006), among other factors, as contributors to differences that have been found.

One reason for the lack of consensus on the basis for changes in temporal cognition with age is the diversity of experimental protocols used. Some experimental factors that can affect the conclusions drawn have included prospective versus retrospective timing, experimental task, and the measures that are submitted to analysis (Block, Zakay, & Hancock, 1998). Age differences in mean time judgments (Perbal, Droit-Volet, Isingrini, & Pouthas, 2002; Rakitin

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et al., 2006; Rakitin et al., 2005), or time judgment variability (e.g., Lustig & Meck, 2001; Wearden, Wearden, & Rabbitt, 1997), have been reported. The length of the interval to be timed may also be important: Rammsayer (2001) has found that older adults are less sensitive on a temporal discrimination task and make longer reproductions of a 1-second interval, but are not different in reproducing a longer interval (15 seconds). In contrast, other studies have found age differences when producing longer intervals (e.g., Rakitin et al., 2006). Differences in approaches among studies have led to difficulties in making generalizations regarding the effect of aging on timing abilities. The aim of the current set of experiments was to use a single experimental task, choice time production (Rakitin, 2005), to separately test the effects of manipulations to attention (Experiment 1) and memory (Experiment 2) upon interval timing in young and aged adults.

Perhaps the most influential model of interval timing is Scalar Expectancy Theory, or SET (Gibbon, 1977; Gibbon, Church, & Meck, 1984). In brief, the model consists of three stages: clock, memory, and decision. The clock stage includes a pacemaker, which generates an isochronic signal marking the passage of time, and an accumulator, which keeps track of how many signals have accrued since the stimulus to begin timing. The decision process performs a comparison between the current number of "ticks" in the accumulator (transferred to working memory) and the number that is stored in long-term memory (LTM) for previous examples of the same period of time. The working memory and LTM components make up the memory stage of the model. If the current accumulator value becomes salient (e.g., a reward is delivered at that time), this value is transferred to LTM. In order to account for systematic distortions in mean temporal estimates, the parameter K^* is included in the SET model (Gibbon et al., 1984). K^* is simply a multiplicative factor applied to the current accumulator value upon transfer to LTM. When K^* is greater than 1, estimates of time intervals are expected to be greater than the objective time. When it is less than 1, estimates of time intervals are expected to be less than the objective time.

Aging, Attention & Interval Timing

According to the SET model and its variants, declining attentional resources should cause predictable changes in timing abilities, preferentially influencing the clock stage, by means of a "switch" gating the passage of pacemaker pulses to the accumulator (Meck & Church, 1983; Rakitin, 2005; Zakay & Block, 1997). When a concurrent task draws attention away from timing, the switch opens, preventing pacemaker "ticks" from incrementing the accumulator, and thus making the perception of time shorter than it actually was. For this reason, adding a secondary, distracter task during the acquisition of temporal memory will lead to underestimation (Lejeune, 1999; Penney, 2003) of the learned time if the secondary task is removed during the testing phase, because the target number of signals will be reached earlier, absent "flickering" of the switch (Fortin & Breton, 1995; Rakitin, 2005). Conversely, adding a distracter task during the testing phase, after the veridical duration has already been learned, will lead to overestimation, because it will take longer to accumulate the same number of "ticks" (Lejeune, 1999; Penney, 2003).

Findings regarding the effect of aging on non-temporal dual-task performance show that greater demands on attention more significantly impact performance in the elderly, as compared to younger adults (e.g., Holtzer, Stern, & Rakitin, 2004, 2005; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). This extends to the realm of interval timing, such that dual-task paradigms that include an interval timing task and a distracter task produce greater increases in timing errors and variability in older individuals, consistent with the notion that attentional resources become more limited with age. For example, Pouthas and Perbal (2004) required both younger and older adult participants to engage in a concurrent reading task while encoding time intervals. Participants were then asked to reproduce the intervals without a secondary task. Both age

groups made shorter reproductions in the concurrent reading condition, as predicted by the SET model, and this effect is exacerbated in older adults, who therefore presumably have even fewer attentional resources (e.g., Craik & Salthouse, 2000; McDowd & Craik, 1988).

While the introduction of concurrent nontemporal tasks elicits predictable changes in the accuracy of interval timing, it has also been noted that inattention to time can cause changes in intraindividual variability of temporal responses (Block et al., 1998; Brown, 1997; Rakitin, 2005; Vanneste & Pouthas, 1999; Wearden et al., 1997). One characteristic of interval timing behavior in humans as well as animal models is its adherence to Weber's Law (Gibbon, 1977). Weber's Law as it relates to interval timing means that intraindividual variability increases in proportion to the average response latency. This phenomenon is also known as the scalar property of interval timing, and confers its name to the SET model. Adherence to Weber's Law is tested quantitatively by calculating the coefficient of variation (CV), or the standard deviation divided by the mean, for productions at various time intervals. If the standard deviation is a constant proportion of the mean time estimations made by an individual, CV will be equal for all target times tested. Scalar contributors to variability include pacemaker speed; rate of transfer to reference, or long-term, memory (K*), or decision threshold (the subjective time that is "close enough" to be deemed the same as the standard). Violations of the scalar property are thought to reflect disturbances of one or more of the non-scalar components of the SET information processing model (e.g., attention).

If in dual-task time production the attention-demanding nontemporal task that holds the switch open varies in duration from trial to trial, then the switch-open time will vary as well. This will lead to an increase in variability over and above the normal variability for the temporal component of the task. Indeed, Brown (1997) found increases in variability when time productions were made concurrently with motor (pursuit rotor tracking), perceptual (visual search), or cognitive (mental arithmetic) tasks. Further, older adults were found to produce a larger CV when given compound stimuli as opposed to single stimuli, while younger adults did not (Lustig & Meck, 2001).

Aging, Memory, and Interval Timing

Memory is crucial to a number of stages in the interval timing mechanism. The accumulator component of SET keeps track of how many pulses have accrued since the signal to begin timing. Thus, the accumulator has been defined as sensory or working memory for elapsing time intervals. Long-term memory (LTM), or reference memory, stores the values of previously rewarded times that will be compared with the current accumulator value. Both types of memory are important for accurate time production, and may be responsible for some of the differences in timing ability between older and younger adults (Pouthas & Perbal, 2004).

The decline of many forms of memory with age, including LTM, has been well-documented (Brickman & Stern, In press; Zacks, Hasher, & Li, 2000). Differences in long-term memory for short time intervals (e.g. 6 and 21 s) between younger and older adults have also been the subject of investigation (Malapani, Rakitin, Fairhurst, & Gibbon, 2002; Rakitin et al., 2006; Rakitin et al., 2005). For instance, older and younger adults learned to reproduce two separate time intervals (6 and 17 seconds) and then were tested on reproduction of each interval 24 hours later with no feedback. Both groups overproduced the shorter time interval on recall, but the older adults' errors were twice as large as those made by the younger adults (Rakitin et al., 2005). This finding has been replicated in subsequent studies (Rakitin & Malapani, 2008; Rakitin et al., 2006) and is illustrative of the form of age-related differences in interval timing evidenced in the peak-interval procedure.

Scalar Expectancy Theory predicts the form of systematic errors arising from storing or retrieving accumulator values. For example, increasing K*, the multiplicative factor applied to long-term memories described above, should lead to rightward-shifted (longer) reproductions, and should also increase variability in a scalar manner. The effect of over-production of both intervals, found in the majority of older subjects in the 2005 study, was attributed to a change in K*, because in the majority of older subjects the changes in accuracy were accompanied by adherence to the scalar property. This interpretation is clouded, however, by the fact that a minority of aged participants showed changes that were duration dependent, meaning that the direction of the shift in time productions differed for the two remembered intervals; and non-scalar. A later report replicated these duration-dependent errors with a 1 hour retention interval in the elderly (Rakitin et al., 2006), and manipulations of feedback contingencies (Rakitin & Malapani, 2008). Thus the possibility that factors other than K* play a part in time production errors after a delay could not be excluded, at least for a subset of the older group.

The Choice Time Production Task

The choice time production (choice TP) task combines time production with a spatial response choice task. In a previous study (Rakitin, 2005), the choice TP task was used to determine the effects of divided attention on time production. First, participants learned spatial response mappings in a choice reaction time (choice RT) task. For example, if the target appeared at a specific point on the screen (e.g., on the far left), participants responded with a specific key (e.g., "Z"). They next learned to make time estimates in a baseline time production (baseline TP[*]) task which required a simple response, pressing the spacebar, at the end of a learned target interval. Then, the two tasks were combined in the choice TP task, performing the spatial response-choice task while delaying the response until the previously-learned time interval had passed. There were three choice task conditions that varied in difficulty: simple (meaning no choice), compatible (responses that are mapped in a way that is spatially compatible with the signal, such as far right key in response to far right stimulus), or a spatially incompatible mapping. Differences in performance in the choice RT task as a function of increasing choice difficulty provides the direction and magnitude of expected differences in response latency for the choice time production task.

The serial "switch" model of attention's effect on timing as derived from SET assumes that the secondary task, in this case choice RT, is processed in series with timing. This would predict that choice time production response latency will be proportional to the sum of the baseline time production response latency plus the difference between simple reaction time and choice reaction time. In other words, choice time production would be proportional to baseline time production plus the amount of time required to perform the choice portion of the choice reaction time task.

Surprisingly, in the 2005 experiment, choice time production means did not change with spatial choice difficulty in the distracter task. However, CV was increased in difficult choice-response groups. As would be predicted by attentional switch models, the CV for the shorter target interval was greater than that for the longer target interval in the most difficult (incompatible) condition, presumably because non-scalar sources of variance (e.g. switch opening and closing) swamped scalar sources of variance, more so in the shorter intervals than the longer ones. Thus, the results on variability of responses did support the notion of an attentional switch, while response latency data did not. This contradiction was reconciled with the proposal of a model that assumed that timing and non-timing processes occur in series, but the duration of the

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[*]Called "simple time production" in Rakitin, 2005

interval timed is shortened by the duration of non-temporal processing – a process described as "temporal discounting".

The current set of experiments uses the choice time production task to determine the age-related changes to interval timing as they interact with increasing attention load (Experiment 1) and with long-term memory (Experiment 2). By varying attentional and long-term memory demands in separate experiments, and by using both accuracy and variability measures, we can achieve maximum sensitivity to memory and attentional effects using the same task.

Experiment 1: Choice time production in short-delayed free recall

The goal of Experiment 1 was to establish age differences in the generation of temporal estimates in the choice timing task. To this end, healthy young and older adults were run through a modified choice time production protocol (Rakitin, 2005), to examine age differences in performance. It was hypothesized that a more difficult response choice task would be more variable in duration to complete, causing more variable switch-open time for the timing component and thus producing greater non-scalar variability for both age groups. Thus, choice time production variability from both age groups in the incompatible choice condition should violate the scalar property, with CVs that are greater to the short target time than the long. This hypothesis was tested by comparing the effect of response choice difficulty group upon CV between the two target intervals. Further, previous results (Block et al., 1998; Lustig & Meck, 2001) suggest that non-scalar variability should increase more with increasing choice response task difficulty in the choice TP task in older adults as compared to younger adults, because they have fewer attentional resources and will be less able to control variability of switch opening and closing when coordinating the two tasks. This hypothesis was tested by comparing the effect of increasing nontemporal task difficulty on choice time production CV between older and younger adults.

These predictions depend upon the outcomes from the baseline tasks: the choice time production task is a combination of the baseline TP and choice RT tasks. According to the temporal discounting model (Rakitin, 2005), choice time production means should follow the pattern of baseline time production means, and variances should follow the pattern of choice reaction time variances. We expect greater variability in response times in the "incompatible" groups at both ages than the "simple" or "compatible" groups at comparable ages in the choice reaction time task, as has been demonstrated previously (Grosjean & Mordkoff, 2001; Rakitin, 2005). Previous research also suggests greater within-subject variability on choice reaction time tasks for older adults as compared to younger adults (Deary & Der, 2005; Der & Deary, 2006). These results on the choice reaction time task would lead to a similar pattern in the choice time production task.

We also wished to determine whether the duration-dependent effects found in previous studies (Rakitin et al., 2006; Rakitin et al., 2005) could be replicated in older individuals using the choice time production task. The present experiment is modeled on the earlier choice time production experiments (Rakitin, 2005).

Method

Participants—Forty-eight young adults and forty-eight elderly adults participated in this experiment. All participants were screened for past and current medical, neurological, and psychiatric disorders, were not currently being treated with psychiatric drugs, and achieved a Dementia Rating Scale (DRS, Mattis, 1988) score of greater than 125. All the participants provided informed consent, and all were compensated $10 for their participation. Young and older participants were assigned to one of three experimental groups: simple, compatible, or incompatible, at random, yielding six groups of 16 participants.

Neuropsychological tests were administered to characterize participants' general and specific cognitive functioning. These tests included the DRS, modified Mini-Mental Score (mMMS, Stern, Sano, Paulson, & Mayeux, 1987), and the National Adult Reading Test (NART, Nelson, 1982). Table 1 provides descriptive statistics for these individuals' age, education, gender, and some neuropsychological measures. No differences were found among groups for the NART (Mann-Whitney U(94) = 1072.5, ns). Dementia Rating Scale (Mann-Whitney U(95) = 495.0, $p < 0.05$) and mMMSE (Mann-Whitney U(96) = 395.5, $p < 0.05$) were higher for the younger group than the older group.

Procedure—An experimental session for 1 participant consisted of a sequence of five tasks. The tasks, in order of administration within a session, were (a) a baseline time production task, with one of the two target intervals (i.e., 4.5 or 7 s), (b) a baseline time production task using the other target interval, (c) a choice RT task, (d) a choice time production task using the first target interval from the baseline time production tasks, and (e) a choice time production task using the second target interval. The assignment of target interval for baseline and choice timing blocks was counterbalanced across participants.

Tasks—The three different tasks used in this experiment shared a common warning signal array and stimulus. The warning signal array consisted of a central fixation point (a "+") and four place markers (a "_ _ _ _"). The fixation point and place markers were on a horizontal axis in the middle of the screen. A stimulus (an "X") was superimposed on the warning signal array after 250 ms. The stimulus appeared just above one of the four lines in the warning signal display. Both the stimulus and the warning signal array persisted until a response was made or until the trial timed out.

Feedback messages were presented 250 ms after the clearing of the warning signal array and the stimulus. Messages were presented in the center of the screen for 1750 ms.

<u>Baseline time production task:</u> The baseline time production task began with 10 passive demonstration trials. The stimulus was presented in each demonstration trial in a random position for the duration of the target interval, either 4.5 or 7 s, depending on the task. The stimulus was cleared after the interval elapsed, and the message "Get ready for the next trial" was shown. Participants were instructed that the duration of the stimulus indicated the target interval and that no responses were to be made during the demonstration. All participants were given the same instructions.

Forty-four baseline time production trials followed the demonstration, the first 4 of which were considered practice and not included in the analyses. Participants were instructed to press the space bar when the elapsed time from the stimulus to begin timing matched the target interval shown during the demonstration. Stimulus location was determined at random and was irrelevant to the task. Following every trial, feedback indicated that the response was either "too early" (if the response latency was less than 90% of the target interval), "too late" (if the response latency was greater than 110% of the target interval), or "right on time" (if the response latency was between 90% and 110% of the target interval).

<u>Choice reaction time task:</u> In this task, participants selected the correct response by applying a rule relating the four screen positions to the response key or keys. Participants operated the "Z" key with their left middle finger, the "X" key with their left index finger, the "period" key with their right index finger, and the "slash" key with their right middle finger, and were instructed to respond as quickly as possible while still maintaining accuracy. Feedback messages indicated whether the response was correct or incorrect, and if incorrect, then what the correct response key was.

The rule used for selecting the response varied according to choice-difficulty group assignment. The compatible group was instructed to press the left-most ("Z") key when the imperative stimulus appeared in the left-most position, the middle-left ("X") key when the stimulus appeared in the middle-left position, and so on. Participants in the incompatible group were given the following mapping. The far-left screen position was assigned to the right-most ("slash") key, the middle-left position to the middle-right ("period") key, the middle-right position to the far-left ("Z") key, and the far-right position to the middle-left ("X") key. To provide comparable disruption in rehearsing the time intervals, participants in the "simple" choice-difficulty group for purposes of the choice time production trials were assigned incompatible-type mappings for the choice RT task.

The intertrial interval (ITI) was 1 s. Forty-eight trials were presented. The first 8 trials were practice, with 2 trials in a row in each of the four stimulus locations. These trials were not included in the data analysis.

Choice time production task: In this task, both the s-r mapping from the earlier choice RT and the target intervals from the baseline time production blocks were relevant. Participants were instructed to choose which key to press when the stimulus appeared, based on their group assignment, but to delay making the response until the end of the target interval. Along with compatible and incompatible task-difficulty conditions, a simple condition was also included that was identical to the baseline time production task described above. Feedback followed the first 8 trials of the task and indicated both whether the correct key was chosen (and the identity of the correct key if the wrong key was chosen) and whether the response was made too early, right on time, or too late, relative to the target interval. These practice trials were not included in the data analyses. Practice was followed by 40 test trials, none of which were followed by feedback.

Analysis—The intraindividual mean and CV of response latencies were computed for each of the five tasks. These variables were computed from correct responses only (where applicable) and excluded all response latencies that fell outside of 1.68 standard deviations from the mean, computed within participant and task. A minimum response time of 750 ms for time production tasks was also required.

Hypotheses were tested for each variable in each task using separate analyses of variance (ANOVAs). Task difficulty was a three-level (simple, compatible, incompatible) between-participants effect for the analyses of the mean and CV of response latencies. Age group was a two-level (older v. young) between participants effect for all models. Target duration was a two-level (4.5 or 7 s) within-participants factor in the analysis of all variables from the baseline and choice time production tasks. Paired samples t-tests were also were also performed as post-hoc analyses to determine whether CV of baseline TP task responses were different from CV of choice TP responses.

Planned contrasts were chosen based on previous results for the choice TP task (Rakitin, 2005). CV was expected to follow the trend previously found, namely that the incompatible group would have the highest values and the compatible group would have the lowest. As described in the introduction, no effect of choice difficulty upon mean latency was found in the previous set of experiments, and so none was expected here.

It was expected that there would be a linear effect of choice difficulty as it interacts with age group, again only for CV. A first-order Helmert contrast (i.e., an average of simple and incompatible, versus compatible) was also performed to compare the simple and incompatible groups with the compatible group on the choice RT task because the simple choice difficulty group performed the incompatible mapping for this task.

Results

Choice Reaction Time—Table 2 reports the response latency and CV data for Experiment 1. Task difficulty significantly affected the mean (F(2,90) = 46.9, p < 0.05). In order to prevent rehearsal of the time intervals during the choice reaction time task in the "simple" choice difficulty group, the group labeled "simple" in regard to choice conditions in the choice TP task was assigned the "incompatible" mapping for the choice RT task. The groups with the more complex conditions ("simple" and "incompatible") produced much longer reaction times than that with the compatible condition (first-order Helmert contrast t(94) = 6.7, p < 0.05). Age was also a significant factor (F(1,90) = 88.6, p < 0.05). Older adults were slower on average than young adults, and this effect was intensified when the task was more difficult, as evidenced in the interaction effect between age and choice difficulty group (F(1,90) = 9.2, p < 0.05).

Task difficulty affected reaction time CV (F(2,90) = 47.9, p < 0.05). CV was greater in the more difficult choice conditions (simple and incompatible group; first-order Helmert contrast t(94) = 9.2, p < 0.05). A significant age effect on CV (F(1,90) = 4.2, p < 0.05) indicated that older adults were generally more variable than younger adults. Task difficulty interacted with age to affect CV also (F(2,90) = 4.56, p < 0.05), such that older adults had greater variability than younger adults in the compatible condition, as opposed to the incompatible one in which both age groups showed high variability.

Baseline Time Production—The duration of the target interval (F(1,90) = 11602.5, p < 0.05) and age group (F(1,90) = 5.47, p < 0.05) significantly affected the mean response latency, such that production intervals for the 4.5 s interval were shorter than for the 7 s interval (i.e., participants more or less accurately reproduced the target intervals), and older individuals produced slightly longer estimates of the target intervals than younger participants on average (proportional errors of 0.042 and 0.026, respectively). There were no significant interactions with duration. Choice difficulty group did not significantly affect response latency (F(2,90) = 0.87, ns), as expected given that this task was the same for all three groups. The age x choice difficulty interaction was also not significant for response latencies in this task (F(2,90) = 0.73, ns).

CV was smaller for the long interval than for the short (F(1,90) = 18.2, p < 0.05), indicating that a significant contribution to the variance was non-scalar. Duration interacted with age and task difficulty condition in a complicated manner to affect CV in a very specific way (F(2,90) = 3.92, p < 0.05). In only the incompatible choice condition, for the longer duration only, young adults' and older adults' responses differed in variability (0.072 and 0.090, respectively). Non-significant effects on the CV included age (F(1,90) = 1.3, ns), choice difficulty group (F(2,90) = 1.4, ns), and the age x choice difficulty interaction (F(2,90) = 1.2, ns).

Choice Time Production—Figure 1, Panel A, provides a graphical representation of choice time production results. Target duration significantly affected the mean response latency (F(1,89) = 575.16, p < 0.05), indicating successful discrimination of the target intervals. Neither age (F(1,90) = 0.34, ns), nor task difficulty (F(2,90) = 2.81, ns), nor their interaction (F(2,90) = 2.11, ns), affected choice time production means. No interactions with target duration were significant (duration x age F(1,90) = 1.51, ns; duration x task difficulty F(2,90) = 0.8, ns; duration x age x task difficulty F(2,90) = 1.0, ns).

Target interval had a significant effect on CV (F(1,90) = 15.0, p < 0.05). As with baseline time production, the scalar property was violated: the CV for the short target time was greater than that for the long. CV was not affected by age (F(1,90) = 2.3, ns) or task difficulty (F(2,90) = 0.8, ns) alone. However, a significant age x choice difficulty group interaction on the CV (F(2,90) = 4.42, p < 0.05) indicated the pattern of results illustrated in Figure 1, Panel B, an effect which was absent in both baseline tasks, and this is likely attributable specifically to the effects

of dual-tasking. In the choice conditions, older participants' responses were more variable than those of younger participants. No significant interactions with target duration were found (duration x age $F(1,90) = 3.55$, ns; duration x task difficulty $F(2,90) = 0.9$, ns; duration x age x task difficulty $F(2,90) = 0.33$, ns).

Discussion

In Experiment 1, the choice time production task was used to determine age differences in temporal reproductions under a range of levels of attentional load. In the choice RT task, the baseline for the nontemporal portion of the choice TP task, intra-individual variability in the incompatible condition was greater than in the compatible condition for both young and older adults. In the choice TP task, older and younger participant groups in the incompatible response choice condition showed opposite effects: While older adults in this group were more variable in their responses, younger adults were less variable, compared to their age-matched counterparts in the other choice difficulty groups. The older groups followed a trend that matches what one might expect from the switch model given the choice RT results, i.e. that non-temporal tasks that are more variable to complete will lead to greater increases in variability in temporal estimations under dual-task conditions (although cf. Rakitin, 2005). Given the choice RT CV result, older adults followed the expected pattern for the choice TP task, but the younger groups did not. In fact, the opposite was found.

Two possibilities may explain the inability to reproduce the pattern of results in young participants here that are expected from the original switch model, or that were found in previous studies with young adults (Rakitin, 2005). Both explanations stem from the fact that the target intervals used in the current experiment are longer than those used in the earlier work, in order to give older adults enough time to accurately perform both tasks concurrently. The first possibility is that, at the time intervals used, the ratio between variability in timing processes and the increased variability due to non-timing processes was not large enough to generate a detectable effect in young adults. That is to say, at longer intervals, proportionately larger sources of timing variability swamp other sources of variability such as flicker of the attentional switch. This would explain the lack of increase in CV in the choice TP task with increasingly variable choice (from the choice RT task) conditions.

A second explanation may not only account for a lack of increase in variability in the younger incompatible group, but also explain the relative decrease in CV in this group. It is possible that the dual-task paradigm is less challenging overall for younger adults at the longer time intervals, and increasing choice difficulty only increases overall arousal, providing more attention for the time estimation task and thus reducing intraindividual response variability. It may be possible in future experiments to provide more practice trials to bring choice reaction time in the older subjects to a level at which they can perform choice timing with target intervals that are short enough to evidence the attention-related pattern of variability found in young participants.

In contrast to the variability results, both younger and older adults' mean response latencies in the choice TP task were modified by the added nontemporal task at each level of difficulty to a similar degree. This is despite the finding that choice RT latencies were influenced by task difficulty, age group, and their interaction. Such a result implies that the attentional switch closes the same amount of time in total when concurrently performing the choice component of the task for older and younger adults, or, alternatively, that temporal discounting is equally effective in both groups. Because there was a significant effect of age, and a significant age x choice difficulty interaction, in the baseline choice reaction time task, it seems unlikely that the former explanation holds. Rather, we suggest that older adults can shorten the interval timed in the choice time production task in the same way that younger adults can, in order to produce accurate response latencies even in the face of a more challenging secondary task.

Experiment 2: Choice time production in long-delayed free recall

Experiment 1 yielded no age-group difference in response latency in the choice timing task. This led us to question whether an added long-term memory component to the task could elicit the duration-dependent age-related accuracy changes in the choice TP task, given previous experiments that have demonstrated that aged individuals time inaccurately without feedback following a 24-hr delay (Rakitin et al., 2006; Rakitin et al., 2005). The current experiment tested whether this finding holds for a more attention-demanding task. Such a result would provide a demonstration of a shift in absolute time estimations in the same experimental procedure that produced an increase in inter-response variability in Experiment 1.

For this experiment, participants performed the baseline time production task, as well as the most difficult of the conditions for the choice reaction time and choice time production tasks (incompatible, see Experiment 1). We then re-assessed performance for the three tasks 24 hours and 48 hours after the original baseline training and testing, without any added training or feedback. The expectation was that, as in previous studies (Rakitin et al., 2006; Rakitin et al., 2005), older participants would overproduce the shorter interval, and, on average, accurately produce or slightly underproduce the long interval. Young participants were expected to show an attenuated version of the aging effect, as described previously (Rakitin et al., 2005).

Method

Participants—Nineteen older and fifteen younger adults participated in this study. Table 1 provides descriptive statistics for these individuals' age, education, gender, and some neuropsychological measures. No differences were found between age groups for the NART score (Mann-Whitney U(34) = 133.5; ns). However, mMMS was higher for the young group than for the older group (Mann-Whitney U(33) = 58; p < 0.05). Again, all participants provided informed consent and all were compensated $10 for their time.

Task—All participants were initially trained and tested with a procedure identical to that given to the incompatible choice difficulty group described in Experiment 1. Tests for all tasks were repeated 24 and 48 hours after initial training. In testing sessions on all 3 days no feedback on performance was provided. Forty trials were presented for each of the following tasks, on each subsequent day: 1) Baseline time production, the first interval, 2) baseline time production, the second interval, 3) choice reaction time, 4) choice time production, the first interval, and 5) choice time production, the second interval.

Analysis—As in Experiment 1, the intraindividual mean and CV of response latencies were computed for each of the five tasks, for each day of testing. Other aspects of the computation of variables were the same as in Experiment 1.

Hypotheses were tested for each variable in each task using separate ANOVAs, using models similar to those of Experiment 1, with one additional effect. All measures were taken over 3 testing sessions, so that testing day was a 3-level repeated-measures variable. First-order Helmert contrasts were planned to compare performance on the training session (day 1) to the successive testing sessions (days 2 and 3). Reported probability variables for the main effect of testing day were corrected for violations of the assumptions for repeated-measures ANOVA using the Huynh-Feldt epsilon (Huynh & Feldt, 1976).

Results

Means and variance for each task are summarized in Table 3. A description of the results of statistical tests follows.

Baseline Time Production—Baseline time production means for each age group on each testing day are displayed graphically in Figure 2, Panel A. A main effect of target interval on mean time production was observed ($F(1,32) = 302.1$, $p < 0.05$). Age was a significant factor, in that older participants' responses were generally shorter than those of younger participants ($F(1,32) = 13.2$, $p < 0.05$). There was no main effect for testing day ($F(2,64) = 0.8$, ns). However, testing day interacted with age group, such that young adults overproduced estimates in later testing sessions, while older adults underproduced them (session x group interaction $F(2,64) = 14.8$, $p < 0.05$; Helmert contrast, $F(1,32) = 18.0$, $p < 0.05$). There were no differential effects over the three testing days for the two target times (session x target interaction $F(2,64) = 1.00$, ns; target x age interaction $F(1,32) = 1.80$, ns; session x target x age interaction $F(2,64) = 2.42$, ns).

CV results are depicted graphically in Figure 2, Panel B. The lack of a significant main effect for duration indicates adherence to the scalar property ($F(1,32) = 1.9$, ns). This does not replicate results from Experiment 1, which showed CV for the longer interval to be smaller than that for the short. No significant main effects or interactions were found on variability as measured by CV for the simple time production task (group $F(1,32) = 0.37$, ns; session $F(2,64) = 1.3$, ns; session x group interaction $F(2,64)$ 1.1, ns; duration x group $F(1,33) = 0.005$, ns; session x duration $F(2,66) = 0.7$, ns; session x duration x group $F(2,66) = 0.16$, ns).

Choice Reaction Time—A significant main effect of session on choice RT mean ($F(2,64) = 23.30$, $p < 0.05$; Helmert contrast $F(1,32) = 29.94$, $p < 0.05$) indicated that, on average, participants' RT decreased on the choice reaction time task with each testing session (Day 1–3: 1604.0, 1396.3, 1263.8). Age was also a significant factor ($F(1,32) = 55.3$, $p < 0.05$): older participants were generally slower than younger adults on this task. However, there was no significant interaction between age group and session ($F(2,66) = 0.8$, ns), indicating that both groups improved at a comparable rate over the three testing days. CV was not systematically affected by any of the manipulations used, nor were any significant interactions found among the factors for this variable (group $F(1,32) = 0.1$, ns; session $F(2,64) = 1.35$, ns; session x group $F(2,64) = 2.13$, ns).

Choice Time Production—Choice time production task means paralleled the results for the baseline time production task, and are depicted graphically in Figure 2, Panel A. Results showed a main effect for target interval ($F(1,32) = 275.6$, $p < 0.05$). There was also a significant main effect for age ($F(1,32) = 5.97$, $p < 0.05$), with older participants generating shorter productions than younger participants. There was no significant main effect for session ($F(2,64) = 1.1$, ns). As in baseline time production, a significant session x age group interaction ($F(2,64) = 4.14$, $p < 0.05$; Helmert contrast $F(1,32) = 4.59$, $p < 0.05$) suggests that, over both time intervals, older participants overestimated time in later sessions, while young participants overestimated time. A marginal session x target interval x age interaction ($F(2,64) = 2.45$, $p = 0.087$) suggests a trend for the more inaccurate reproductions of the younger individuals for the 7-second interval, and older individuals for the 4.5-second interval, to become greater over the course of the 3 sessions.

No significant differences in variability between the two durations measured indicates adherence to the scalar property in timing ($F(1,33) = 1.5$, ns). This does not replicate results from Experiment 1, where replications of short duration were more variable than those of the long. There were no significant main effects or interactions for choice TP variability (group $F(1,32) = 1.34$, ns; session $F(2,64) = 1.5$, ns; session x group interaction $F(2,66)$ 1.1, ns; duration x group $F(1,33) = 0.07$, ns; session x duration $F(2,66) = 0.6$, ns; session x duration x group $F(2,66) = 0.11$, ns). CV results are depicted graphically in Figure 2, Panel B.

Between-task comparisons—Paired-sample t-tests were performed to compare the accuracy of responses in the baseline TP and choice TP tasks in all 3 sessions, for both target intervals. A significant effect of task was found only for the 7-second interval, during the last testing session (t(33) = 2.80, p = 0.008).

Discussion

Experiment 2 examined age-related changes in long-term memory for short time intervals, in attention-demanding conditions. In both the baseline and choice time production task, we found differences in the direction of errors in temporal estimates between the two age groups upon recall, but intraindividual response variability remained unchanged. This finding suggests that, in the both the baseline and choice time production tasks, differences in time production accuracy mark differences in LTM for interval time between groups.

The difference in time production errors between older and younger participants following the delay can be explained by an age-related change to K*, the multiplicative factor applied to temporal values before being stored in LTM described in the introduction. A few points support this conclusion: First, the effect is greater in later sessions, upon retrieval from LTM without the benefit of feedback, at 24 hours and 48 hours after initial encoding. It is possible that feedback provided to participants during the baseline time production task, and at the beginning of the choice timing task, on Day 1 prevents drift in productions on both the training (baseline TP) and testing (choice TP) tasks on that day, but not after a significant delay. Similar results obtained with the peak-interval (PI) procedure have shown that, in older adults, test trials with no feedback presented immediately after demonstration of a six-second interval did not result in significant errors in response latency (Rakitin & Malapani, 2008).

Second, there were no significant session effects on CV corresponding to those session effects on accuracy, indicating that variability changed proportionately with the change in temporal estimates with session. Drift in accuracy across time with proportional changes to variability, as evidenced by a lack of session effect on CV, is also predicted from changes to a multiplicative factor such as K*. Although the effects were marginal, the trend for temporal estimates to become more divergent between age groups for the longer interval as opposed to the shorter, over sessions, supports the notion of that K* takes different values for young (K* > 1) and older (K* <1) adults.

Practice effects on the choice component of the choice reaction time task cannot account for the difference in direction of timing errors between the two age groups over sessions. Although younger adults produce faster responses on the choice reaction time task, both age groups reduce reaction time with practice to the same extent. In contrast, choice time production becomes earlier with practice for older adults, but not for the young group. Indeed, choice timing errors mirror the trend for baseline time production over the three sessions, arguing against the notion of practice effects on the choice component driving the effects seen in the choice time production task. Instead it seems that the mechanism causing timing errors in baseline time production, perhaps an age difference in the value of the K* parameter, is the major source of accuracy errors for the choice timing task as well.

General Discussion

Age-related differences in the accuracy and variability of temporal estimates have been attributed, variously, to changes in processing speed (Craik & Hay, 1999), attention (Block et al., 1998; Lustig & Meck, 2001; Vanneste & Pouthas, 1999), or memory (Baudouin, Vanneste, Isingrini et al., 2006; Baudouin, Vanneste, Pouthas et al., 2006; Perbal et al., 2002; Rakitin et al., 2006; Rakitin et al., 2005). Because there is evidence that each of these is affected negatively by advancing age, it is possible that any or all of these effects may work alone or in combination

to affect timing accuracy and variability depending upon the specific task used to measure temporal estimation abilities. The choice time production task is relatively new, and it allows us to explicitly test the effects of memory and attention on time production in aging using a single task, by varying the procedure in which it is embedded, and task conditions, respectively. When memory and attention were manipulated separately, we were able to find evidence that aging affected both.

First, attention was manipulated in Experiment 1 by varying the difficulty of the concurrent nontemporal (choice response) portion of the task. Older adults, who presumably have fewer attentional resources at their disposal, were more variable in performance in the more difficult conditions, but accuracy did not differ between younger and older adults. Experiment 2 added a long-term retention factor using the most difficult of the three tasks used in Experiment 1. The results were complimentary to Experiment 1 in that older adults now differed in mean time production accuracy from younger adults, and scalar variability was the same between the two groups. These points together argue that choice time production variability is more sensitive to attentional manipulations, while accuracy of responses is more sensitive to long-term memory differences. This reflects previous claims that attentional challenges should increase timing variability (Rakitin, 2005), in older adults especially (Block et al., 1998; Lustig & Meck, 2001; Vanneste & Pouthas, 1999). Further, SET parameter effects upon memory such as K* predict that differences in memory encoding between these two groups would affect response latency, but not scalar variance. This is a demonstration of specific effects upon each measure of interval timing behavior in response to task modifications targeting two discrete components of the timing mechanism.

The finding that there was no age difference in mean response latencies in response to increasing choice difficulty shows that not all temporal cognition seems to differ with age. For example, "executive temporal discounting" is a putative ability to use a deliberate strategy of reducing the serial time required to complete both tasks simultaneously, by the (intra-subject average) amount of time it takes to complete the nontemporal task. Older adults may be unaffected in their ability to perform this type of discounting.

Another factor contributing to older adults' unaltered temporal accuracy performance in the choice TP task may be the novel use of an integrated signal that indicates both when to begin timing and which response to choose. It has been demonstrated that waiting for an expected interruption in timing can increase the timing mean, in a manner that increases with the delay between the onset of the timing signal and the beginning of the expected interruption (Fortin & Masse, 2000; Tremblay & Fortin, 2003). These effects are more pronounced in older adults (Bherer, Desjardins, & Fortin, 2007). In the choice TP task, increasing stimulus onset asynchrony (SOA) between the signal to begin timing and that to determine the response choice increases mean response latency in young adults (Rakitin, 2005). Previous studies of aging and increased concurrent attentional demands relied on methods that required an SOA, which may have contributed to the increase in mean latency along with increases in timing. In any case, the finding that increasing attentional demands in choice time production did not produce differences in mean response latency allowed us to demonstrate a dissociation between the effects of increasing attentional and memory demands in timing in older adults.

Neither Experiment 1 nor Experiment 2 produced evidence for the duration-dependent effects upon retrieval from long-term memory previously found in aged participants (Rakitin et al., 2006; Rakitin et al., 2005). It seems that three necessary components may be important to elicit the duration-dependent effects that have been found in aged subjects in the past. The first is the time and type of feedback provided to the participant. A recent set of experiments (Rakitin & Malapani, 2008) found that testing following a long-term delay is necessary to reproduce these effects in healthy, older adults, but also, either no feedback during the retest session or

feedback during that session that serves as a reminder for the interval being timed. It seems that feedback regarding the decision-threshold (of the same type that we used here, "too early" or "too late"), as opposed to a reminder of the absolute target time, after acquisition can provide assistance in compensating for errors that protects against errors that verge toward each other. In Experiment 1 and on Day 1 of Experiment 2, we can consider the decision threshold feedback that was provided at the beginning of the choice TP task, after acquisition in the baseline TP task, as feedback following a delay. This may help explain why duration-dependent effects were not found. This feedback following a delay, as provided in the current set of studies, could possibly help to solidify memory for time intervals to protect estimates from further distortion upon later testing.

Further, decision processes may be very different between the current tasks and the PI procedure used previously. In the PI procedure, participants are required to make 4 responses centered on the anticipated end of the target interval. The baseline time production task requires one response that must be as close as possible to the target. Thus, it is possible that the thresholds for responding in the PI procedure are different from those in the baseline TP task. Future experiments to directly compare the two types of tasks with the same participants, at the same target intervals, and with the same feedback, would help to determine the similarities and differences in measures of timing ability that can be captured by studies using each.

Choosing the proper target intervals may also be an important component to generate duration-dependent effects. The curvilinear accumulator model laid out to explain the Parkinson's disease migration effect (Rakitin & Malapani, 2008) that was later detailed by Shea-Brown and colleagues (2006) suggests that duration-dependent effects of dopamine depletion upon time estimates may require testing of specific target intervals: one interval must be before the crossing-point of the accumulator functions for the two intervals, and one must be after the crossing-point. Although a different pharmacological mechanism is likely responsible for the duration-dependent effects found in healthy older adults (Rakitin et al., 2006), the same general function may be in place for the two types of duration-dependent effects. If the duration-dependent effects reported previously, using the PI procedure, are to be elicited with the current baseline or choice timing procedure, it may be essential to test interval timing in older and younger participants at the longer target intervals (6 and 17 s) used in those studies.

Earlier results from the choice time production procedure in young adults (Rakitin, 2005) underscore the importance of measuring not only mean response latency, but also variability, in timing tasks. Although predictions regarding changes in mean latency of responses with increasing concurrent nontemporal task difficulty were not borne out, those regarding response variability were. Thus, a manipulation that could have been falsely interpreted as producing no change in time reproductions had only response latency been measured, was shown to in fact affect a change in variability. The same holds true in the current set of experiments: In Experiment 1, measuring mean response latency only would have led to the false conclusion that age did not modulate the effect of varying nontemporal task difficulty in this task; measuring only variability would have done the same in Experiment 2.

In summary, the current set of studies demonstrates the presence of both attentional and memory effects of aging on temporal reproduction abilities, using the same task. Thus differences in the accuracy and variability results in response to the two types of manipulations used in our two experiments cannot be attributed to inconsistencies in task parameters: the tasks were essentially the same in both experiments, with only changes designed to target specific components of the information-processing model. Many cognitive changes are known to occur with advancing age, and most of them are expected to impact our sense of time. The current set of studies constitutes a step toward determining which of these changes produce which specific effects.

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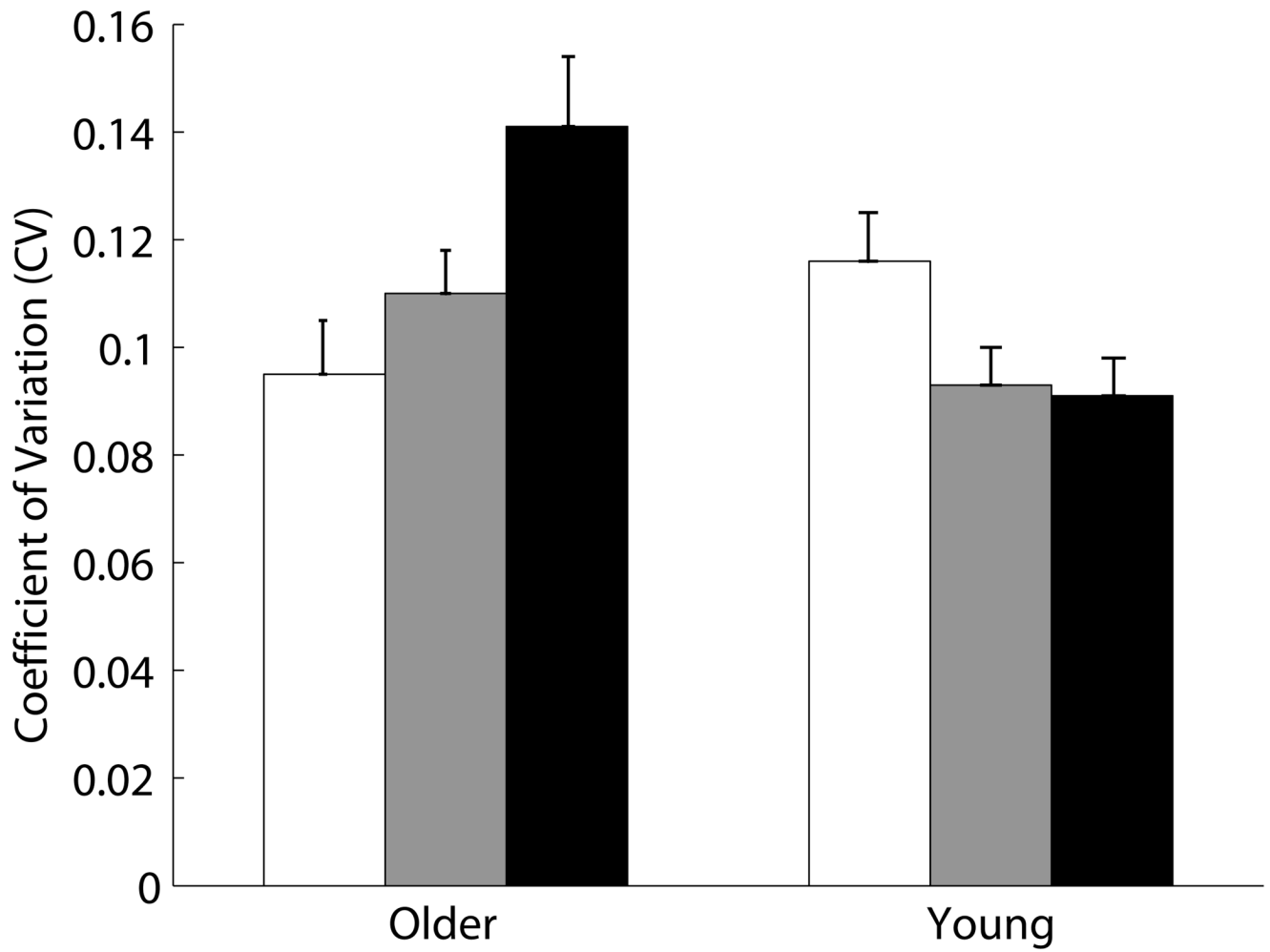## Acknowledgments
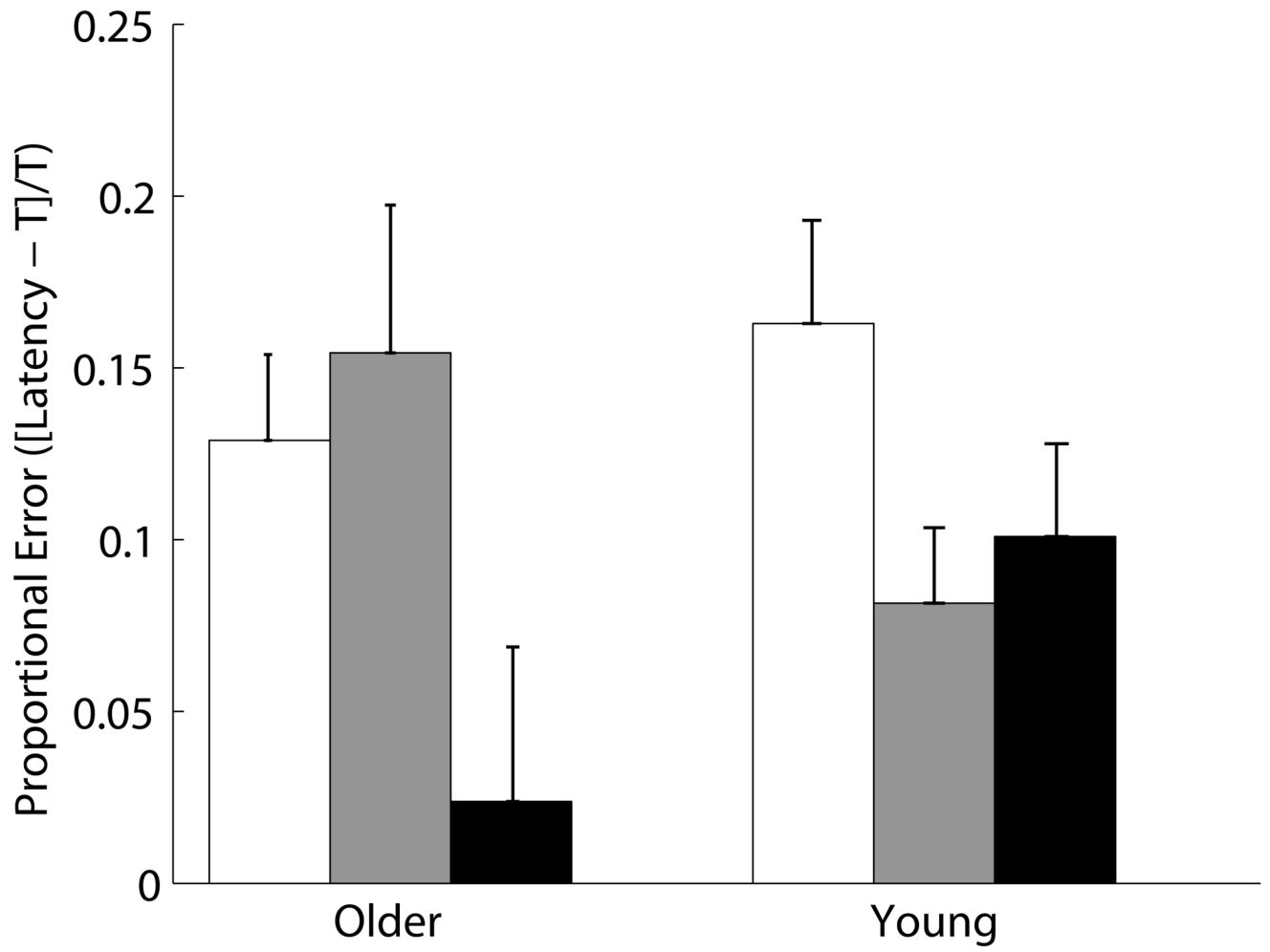
Figure 1.
Results of Experiment 1, choice time production task. Panel A shows the group-average proportional errors, computed as (latency – target) / target. The bars show averaged data for the simple (white), compatible (grey), and incompatible (black) choice groups for each age group. Panel B shows the group-average CVs, averaged over both target intervals, for older and younger adults in the choice time production task, coded in the same way as Panel A.
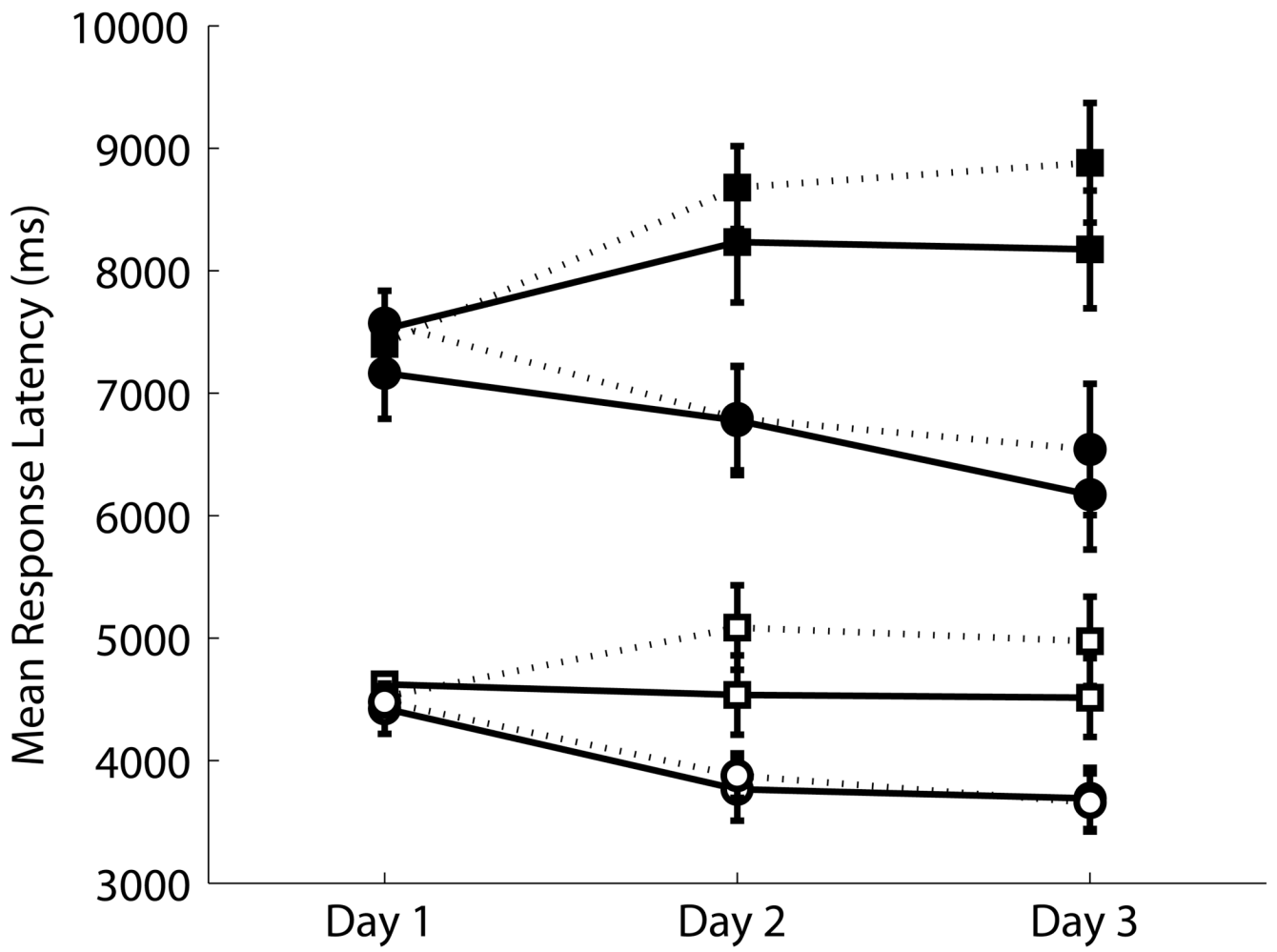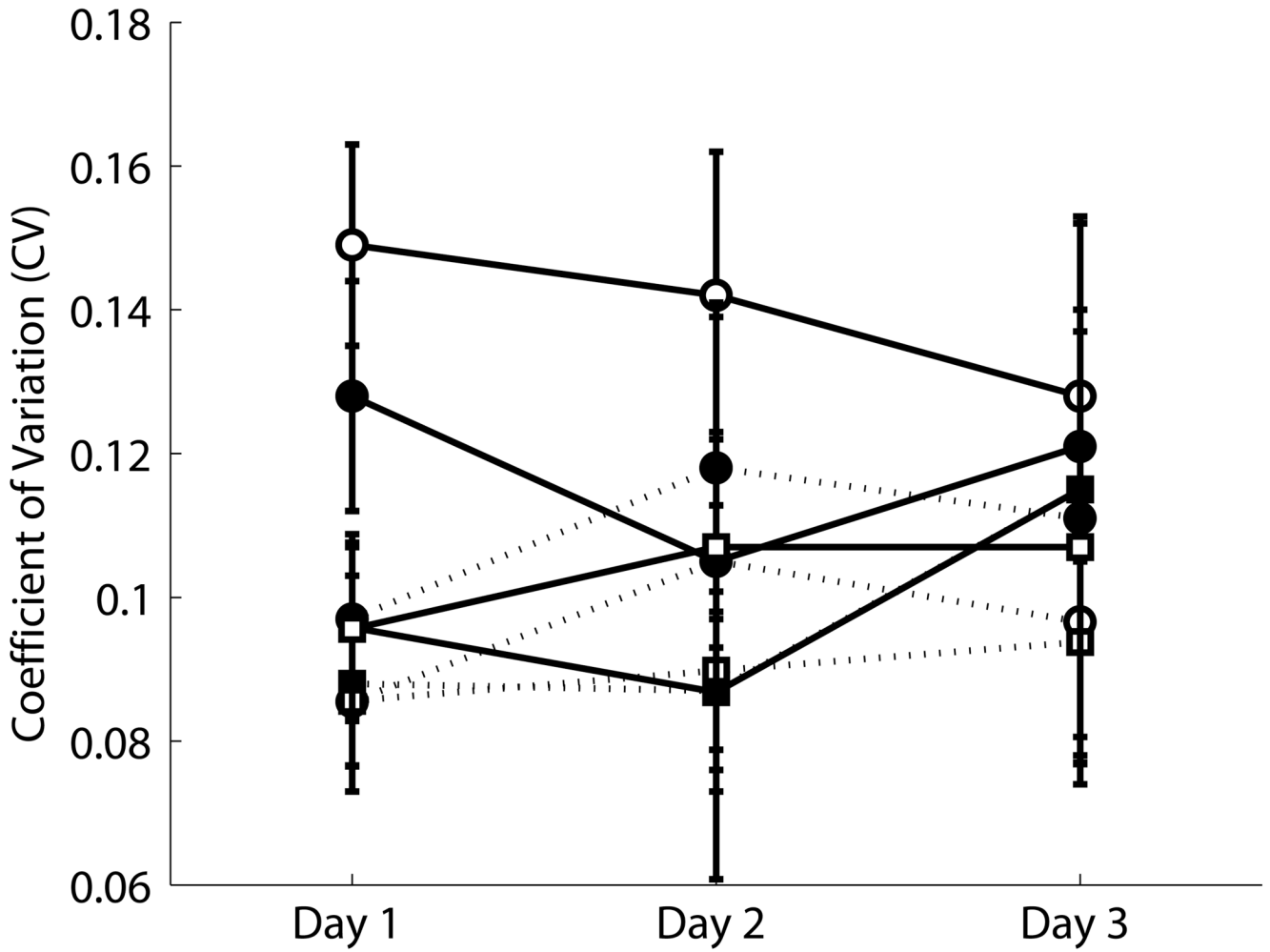
Figure 2.
Results of Experiment 2, baseline and choice time production tasks. Panel A shows the group-average response latency for the baseline (dashed lines) and choice (solid lines) time production task, young adult group (squares) and older adult group (circles), as measured over 3 sessions, 24 hours apart. Open markers show data for the 4500 ms target blocks, and filled markers show data for the 7000 ms target blocks. Panel B shows group-average coefficient of variation data, coded in the same way as Panel A.

Table 1

Demographic Information

Task Difficulty	Age Group	N	Age Range	Age	% Female	Education (years)	MMS	DRS	NART
					Experiment 1				
Simple	Older	16	61–85	74.9 ± 1.4	87.5	14.9 ± 0.66	52.3 ± 0.82	138.8 ± 0.91	117.5 ± 1.8
	Young	16	19–29	22.1 ± 0.7	68.7	15.8 ± 0.36	55.6 ± 0.42	142.3 ± 0.46	113.1 ± 1.7
Comp	Older	16	62–81	72.8 ± 1.6	62.5	14.4 ± 0.65	53.3 ± 1.05	140.2 ± 0.65	115.9 ± 2.0
	Young	16	19–29	22.6 ± 0.8	81.2	16.0 ± 0.53	56.0 ± 0.45	142.38 ± 0.51	116.4 ± 1.9
Incomp	Older	16	68–84	75.5 ± 1.3	75	13.4 ± 0.70	53.4 ± 0.59	139.1 ± 0.96	115.2 ± 2.4
	Young	16	18–30	22.6 ± 0.8	62.5	16.6 ± 0.60	55.9 ± 0.26	142.38 ± 0.35	119.3 ± 1.3
					Experiment 2				
Incomp	Older	19	60–90	75.4 ± 1.9	63.2	14.7 ± 0.62	52.4 ± 0.68	---	114.3 ± 2.23
	Young	15	21–35	26 ± 0.96	69.8	16.2 ± 0.46	55.1 ± 0.42	---	113.8 ± 1.57

Note: Values are Mean ± Standard Error of the Mean for Age, Education, mMMS, DRS, and NART.

Table 2

Experiment 1 Results

		Simple		Compatible		Incompatible	
		Young	**Older**	**Young**	**Older**	**Young**	**Older**
Choice Reaction Time[†]	M	949.1	2085.4	470.5	767.2	1037.6	2054.8
	SE	76.6	156.5	26.0	40.4	96.6	167.1
	CV	0.322	0.392	0.133	0.200	0.350	0.313
	SE	0.017	0.030	0.009	0.019	0.020	0.024
				Target = 4500 ms			
Baseline Time Production	M	4397.8	4549.6	4447.1	4567.3	4486.6	4503.0
	SE	51.8	43.3	61.5	37.4	41.6	30.8
	CV	0.096	0.097	0.091	0.116	0.083	0.089
	SE	0.008	0.006	0.007	0.009	0.007	0.006
Choice Time Production	M	5196.8	4964.1	4724.5	5279.0	4733.6	4693.2
	SE	189.8	159.2	144.5	393.0	159.9	327.7
	CV	0.122	0.104	0.097	0.124	0.093	0.154
	SE	0.013	0.017	0.011	0.011	0.009	0.019
				Target = 7000 ms			
Baseline Time Production	M	7496.7	7448.8	7457.6	7620.0	7412.2	7499.1
	SE	56.0	57.8	63.1	58.9	75.9	61.1
	CV	0.090	0.077	0.085	0.085	0.072	0.090
	SE	0.009	0.007	0.007	0.007	0.007	0.009
Choice Time Production	M	8196.4	8082.4	7844.8	7994.6	7748.6	7033.2
	SE	309.8	248.2	195.1	217.4	239.1	381.8
	CV	0.111	0.086	0.087	0.092	0.084	0.128
	SE	0.013	0.012	0.008	0.011	0.013	0.016

[†] Simple same as incompatible for this task

*
SE = Standard error of the mean

Table 3

Experiment 2 Results

		Day 1		Day 2		Day 3	
		Young	Older	Young	Older	Young	Older
Choice Reaction Time	M	1139.6	1970.7	871.5	1810.6	803.6	1627.2
	SE	90.7	102.8	68.2	98.2	57.7	98.2
	CV	0.31	0.29	0.31	0.35	0.33	0.30
	SE	0.02	0.019	0.016	0.025	0.022	0.017
Target = 4500 ms							
Baseline Time Production	M	4520.9	4479.9	5087.6	3877.3	4975.1	3658.7
	SE	40.5	65.9	345.6	181.7	364.4	237.5
	CV	0.086	0.086	0.090	0.11	0.094	0.099
	SE	0.009	0.009	0.011	0.018	0.017	0.016
Choice Time Production	M	4622.7	4424.8	4536.7	3767.2	4515.4	3690.8
	SE	87.8	205.4	323.7	256.6	321.4	250.0
	CV	0.096	0.149	0.107	0.143	0.107	0.128
	SE	0.013	0.014	0.034	0.020	0.033	0.012
Target = 7000 ms							
Baseline Time Production	M	7401.2	7571.7	8768.1	6792.8	8880.7	6540.2
	SE	98.3	74.6	338.4	422.9	488.3	535.8
	CV	0.088	0.097	0.087	0.117	0.115	0.111
	SE	0.015	0.104	0.011	0.021	0.038	0.181
Choice Time Production	M	7521.3	7164.5	8233.4	6776.3	8173.4	6171.0
	SE	315.1	374.2	492.1	445.4	480.2	448.5
	CV	0.096	0.128	0.096	0.105	0.100	0.121
	SE	0.013	0.016	0.026	0.012	0.037	0.016