Brain and Cognition **49,** 402–419 (2002)
doi:10.1006/brcg.2001.1507

Lapses of Intention and Performance Variability Reveal Age-Related Increases in Fluctuations of Executive Control

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We examine the hypothesis that the efficiency of executive control processes is less stable over time in older than younger adults. An age-related decrease in the efficiency of executive control should result in an increase in performance variability in task conditions requiring the recruitment of executive control processes and not in task conditions requiring minimal involvement of executive control. Performance variability was similar for younger and older adults in task conditions requiring minimal executive control and greater for older than younger adults in task conditions requiring executive control. These and other data are consistent with the proposal that aging is associated with a decrease in the stability of executive control over time.

Key Words: aging; executive control; performance variability; working memory; response time distribution.

The current work is founded on the proposal that executive control processes fluctuate in efficiency over time and that older adults are more susceptible to these fluctuations than are younger adults. This proposal leads to the prediction that lapses of intention (Craik & Kerr, 1996) should be more frequent and performance variability (Shammi, Bosman, & Stuss, 1998) greater for older adults than younger adults in tasks conditions requiring high levels of executive control. The goals of the present work are two-fold: (1) to review data from our recent studies examining the transient nature of lapses of intention and (2) to present data from a new study demonstrating that age-related increases in performance variability are greater in task conditions requiring the recruitment of executive control processes than in less demanding task conditions where executive control is less critical to efficient task performance.

The research described in the this article was funded by grants from the James S. McDonnell Foundation awarded to F. I. M. Craik (96-53) and D. T. Stuss and colleagues (98-31) and Grant AG13845-01 from the National Institute of Aging awarded to L. L. Jacoby and F. I. M. Craik. Preparation of the article was partially supported by funds from the American Foundation for Aging Research awarded to Robert West.

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0278-2626/02 $35.00

Lapses of Intention and Fluctuations of Executive Control

Lapses of intention reflect those curious and often frustrating occasions in daily life when our actions become dissociated from our intentions (Reason, 1979); for instance, failing to give an important message to a friend at the appropriate time (i.e., a lapse of intention) or putting salt instead of sugar into our morning coffee (i.e., an action slip). The effect of aging on the frequency of lapses of intention has recently been considered in studies of prospective memory (West & Craik, 1999) and selective attention (West, 1999a).

Laboratory-based prospective memory tasks often require the individual to make a select response to some particular prospective memory cue embedded in a more or less engaging ongoing activity. When the pattern of prospective memory failure has been examined the efficiency of prospective memory is dynamic in nature, with individuals often failing to respond to a prospective memory cue that has elicited a prospective response only a few minutes ago and responding to a prospective memory cue that failed to elicit a prospective response in the recent past. Maylor (1996) proposed that these characteristics of prospective memory can be quantified in indices of forgetting (the probability of failing to respond to a prospective memory cue given a correct response to the preceding prospective memory cue) and recovery (the probability of responding to a prospective memory cue given that the preceding prospective memory cue failed to elicit a prospective response). Using this analytic strategy one can differentiate instances where the intention is forgotten (i.e., estimates of recovery are zero) from lapses of intention, where the intention merely fails to guide behavior on a limited number of trials, resulting in estimates of forgetting that are less than 1 and estimates of recovery that are greater than zero. In Maylor's study, older adults were more likely than middle-aged adults to forget and less likely to recover. This finding suggests that age-related increases in prospective memory failure result not from having forgotten the intention but rather from moments where the intention failed to guide behavior (Craik & Kerr, 1996).

Lapses of intention can also be observed in the Stroop task, where individuals must inhibit a dominant response tendency (word reading) in order to make a correct response (color naming; Stroop, 1935; MacLeod, 1991), as in intrusion errors where the word is read instead of the color being named. In one study (West, 1999a), an age-related increase in the number of intrusion errors was observed across three experiments, while the number of nonspecific errors was similar in younger adults and older adults, consistent with the idea that there is an age-related increase in the frequency of lapses of intention. Examination of the intrusion error data from Experiment 1 of this study revealed that older adults were more likely than younger adults to experience pairs of intrusion errors on consecutive incongruent trials. This finding leads one to wonder whether lapses are actually more frequent in older adults (as would be expected if there is an age-related increase in the degree to which executive control processes fluctuate in efficiency over time) or whether lapses simply lasted longer in older adults than in younger adults. These alternatives were considered in Experiment 2 of this study, which included all incongruent trials and permitted the calculation of both the number of lapses and the duration of each lapse. This analysis revealed that the number of distinct lapses was greater for older adults than younger adults, suggesting that fluctuations in the efficiency of executive control were in fact more frequent for older than younger adults.

In Experiment 1 of West (1999a) there was also a significant decrease in the number of intrusion errors across the course of the task for older adults, a finding that is consistent with other data indicating that lapses of intention or goal neglect are most likely to occur when a task is relatively novel (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Reason, 1979). Based on these data one wonders whether the decrease in the number of intrusion errors over the course of task performance results from a decrease in the frequency or duration of lapses. To answer this question the number of lapses lasting a single trial or two or more trials in duration were examined across quarters of the task in Experiment 2 of West (1999a). The number of lapses lasting a single trial in duration did not decrease across the course of the task for younger adults or older adults. In contrast, the number of lapses lasting two or more trials in duration decreased from the first to third quarters of the task for both older adults and younger adults. Based on these data it seems that task experience leads to a decrease in the duration of lapses and has relatively little impact on the frequency of lapses. These findings led to the proposal that transient fluctuations in efficiency are an intrinsic property of executive control processes and are relatively immune to the influence of task experience or fatigue (West, 1999a).

Other data consistent with the idea that lapses result from transient fluctuations in the efficiency of executive control emerged from a consideration of the response time data for trials preceding the commission of an intrusion error in West (1999a). In Experiment 2 of this study there was a systematic slowing of response latency on trials leading up to an intrusion error relative to trials in the experiment that were temporally distant from intrusion errors (West, 1999a). This slowing may be thought to result from a gradual waning in the efficiency of executive control processes giving rise to intrusion errors once the system crosses some critical boundary required to maintain goal-directed action.

Fluctuations of Executive Control and Performance Variability

In addition to the well-documented age-related increase in mean response time there is a common assumption that later adulthood is also accompanied by an increase in performance variability (Hale, Myerson, Smith, & Poon, 1988; Morse, 1993; Shammi, Bosman, & Stuss, 1998). Performance variability can be defined in at least three different ways: (1) diversity, or between-individual variability; (2) dispersion, or within-individual variability; and (3) consistency of performance, or stability of task performance over multiple testing sessions (Stuss, Pogue, Buckle, & Bondar, 1994).

Age-related increases in diversity have been examined by a number of researchers using both meta-analytic and experimental methods. Morse (1993) examined age-related increases in diversity for both response time and accuracy measures within the domains of memory and intelligence. In this study, diversity was greater in older adults than younger adults for response time, memory, and fluid intelligence, while age-related differences in diversity were nonsignificant for crystallized intelligence. The findings of this meta-analytic study have been replicated in a study, including a large sample of older adults, where diversity increased with age to a greater degree for measures of fluid intelligence and memory than for measures of crystallized intelligence (Christensen et al., 1994). Consistent with these data, age-related increases in diversity have also been observed in finger tapping and time estimation tasks (Shammi et al., 1998). These findings indicate that age-related increases in diversity are observed in tasks that may require the recruitment of executive control processes in support of task performance; while levels of diversity between younger and older adults are similar in tasks that are less demanding of executive control processes, such as those dependent on crystallized intelligence. However, there are other data indicating that diversity remains relatively stable with advancing age (Lindenberger & Baltes, 1997) and that age-related differences in diversity are no longer significant when age-associated slowing of mean response time is controlled (Hale et al., 1988; Shammi et al., 1998, for choice RT).

Possible age-related increases in dispersion or within-individual variability have been addressed in relatively few studies. Salthouse (1993) reported an age-related increase in dispersion that was consistent across four separate studies, including 100 to 200 individuals for a digit copy task and a digit substitution task, and in this study there were small but reliable unique influences of age on dispersion when variance shared with mean response time was controlled in two of the four samples for both the digit copy task and digit substitution task. However, these effects were somewhat inconsistent within a given study. In the two studies where the unique influence of age on dispersion was significant for the digit copy task the effect was not significant for the digit substitution task; and in the two studies where the unique influence of age on dispersion was significant for the digit substitution task the effect was not significant for the digit copy task. Consistent with the finding that age-related differences in dispersion are not robust against statistical control of mean response time, Shammi et al. (1998) reported that the effect of age on dispersion in a choice reaction time task was no longer significant after controlling for differences in mean response time. Also, Lindenberger and Baltes (1997) report that dispersion remains stable or actually decreases in later adulthood in psychometric measures of intelligence, depending on ability level of the individual.

Age-related declines in consistency of performance over relatively short intervals have probably received the least consideration in the empirical literature. Shammi et al. (1998) reported that age-related decreases in consistency over 2 days of testing were observed only in a time estimation task with filled intervals (i.e., when a reading task was performed during the estimation interval), while levels of consistency were similar for older adults and younger adults for a blank interval (i.e., only the estimation task was performed) in a time estimation task. A second study including 13 measurements over a 6-month period found a significant correlation between age and consistency for episodic memory, but not sensorimotor performance (Li & Lindenberger, 1999). These findings provide initial evidence that aging leads to a decrease in consistency of performance in task conditions that may require the recruitment of executive control processes.

Executive Control and the Ex-Gaussian Distribution

In recent years there has been a growing interest in moving away from analyses of response time data based solely on measures of central tendency such as the mean or median to analytic strategies that allow the investigator to more fully characterize the entire shape of the response time distribution (Miller, 1988; Heathcote, Popiel, & Mewhort, 1991). One such approach is to fit the ex-Gaussian function to the response time distribution. The ex-Gaussian function represents the convolution of an exponential and Gaussian (normal) distribution characterized in a three-parameter model (μ, σ, τ). Mu and σ represent the mean and standard deviation of the leading edge of the response time distribution that typically has a Gaussian distribution. Tau represents the mean and standard deviation of the exponentially distributed tail of the distribution that is generally positively skewed. By considering conditional and group differences in the three parameters of the ex-Gaussian function one can gain insight into the degree to which conditional and group differences are pervasive in nature, operating across the entire range of the response latency distribution (i.e., are observed in μ, σ, and τ), or are more localized in nature influencing one and not the other parameters.

The ex-Gaussian analysis has been used to explore the nature of age-related declines of executive control processes in the areas of selective attention and working memory. In one study, Spieler, Balota, and Faust (1996) found that the magnitude of the Stroop interference effect was similar in younger adults and young-old adults for the μ parameter, while the magnitude of the interference effect was greater for older adults than younger adults in the τ parameter. Based on these findings one could suggest that the operational efficiency of executive control processes supporting performance of the Stroop task was similar for older adults and younger adults on those trials primarily contributing to estimates of the μ parameter and that fluctuations in the efficiency of these executive control processes, that primarily contribute to estimates of the τ parameter, have a more profound impact on the performance of older adults than that of younger adults (for an alternative view see Spieler, 2001).

The ex-Gaussian analysis has also been used to explore the nature of age-related differences in response time observed in a continuous working memory task (i.e., 1-back; West, 1999b). In this study, younger and older adults performed a task where they were required to identify in which of four spatial locations a stimulus appeared (immediate condition) or to identify the spatial location of the stimulus presented in the previous display (1-back condition). As might be expected, mean response time was greater for older than younger adults and this difference was greater in the 1-back condition than the immediate response condition. Decomposition of these data using the ex-Gaussian analysis revealed that for younger adults the response time costs associated with the 1-back condition were essentially limited to the τ parameter, suggesting that transient fluctuations of executive control processes supporting working memory may have contributed to the increased response time observed in this condition. For older adults the response time costs associated with the 1-back condition for the τ parameter were greater than for the younger adults, consistent with the idea that transient fluctuations in the efficiency of executive control processes are more detrimental to the performance of older adults than to that of younger adults. There were also substantial response time costs associated with the 1-back conditions for older adults in the μ parameter, possibly indicating that in addition to the increased susceptibility to fluctuations in the efficiency of executive control processes older adults also experienced a pervasive decline in the ability to manage the demands of the 1-back condition.

Performance Variability, Executive Control Processes, and Aging

In the current study we sought to examine the effects of age on diversity, dispersion, and consistency using an experimental design that would allow us to vary the demands placed upon executive control processes within a single task. For the study, individuals completed a choice response time task requiring the identification of one of four digits presented in the current display (immediate response–nonexecutive) or in the previous display (1-back–executive). This design should circumvent potential problems faced in interpreting the results of earlier work where demands placed on executive control processes varied across structurally diverse tasks in experimental (Shammi et al., 1998) and meta-analytic (Morse, 1993) studies. Individuals were tested on 4 consecutive days (twice in the morning and twice in the evening), permitting the examination of possible interactions between variations in the efficiency of executive control processes, age, and task experience. Given the proposal that aging leads to an increase in the tendency for executive control processes to fluctuate in efficiency over time, we predicted that age-related increases in performance variability would be greater in task conditions eliciting the recruitment of executive control processes than in task conditions placing few demands on executive control processes. Time of testing was alternated between morning and evening sessions in light of recent evidence that time of day may have a differential influence on the cognitive efficiency of younger and older adults (May & Hasher, 1998; May, Stoltzfus, & Hasher, 1993). In an initial series of analyses the main effects of time of day and the age by time of day interactions were not significant. Given these negative findings these results are discussed no further.

METHODS

Participants

Twenty younger adults ($M = 23.91$, range 19–29 years of age) and 20 older adults ($M = 73.80$, range 65–83 years of age) participated in the study. The younger adults ($M = 16.45$) and older adults ($M = 16.90$) had attained similar levels of formal education [$t(38) = .59$, $p > .550$]. The older adults ($M = 34.95$) scored higher on the WAIS-R vocabulary subtest than the younger adults [$M = 30.85$; $t(38) = 2.37$, $p < .020$], while the younger adults ($M = 64.15$) scored higher on the digit copy test than the older adults [$M = 50.56$; $t(38) = 3.86$, $p < .001$].

Design

A 2 age group (younger vs older) × 2 (morning vs evening start) × 4 (day of testing) design was used, with age group and morning vs evening start as between-subject factors and day of testing as a within-subject factor. Half of the participants began testing in the morning (i.e., 09:00) and half in the evening (i.e., 17:00). Individuals alternated between morning and evening sessions across the 4 days of testing, being tested twice in the morning and twice in the evening. This design allowed us to assess performance variability in younger and older adults across multiple testing sessions and to examine interactions between age, task conditions, and task experience. The data reported are from a larger battery of tasks measuring various aspects of memory and attention function. The battery was administered in a fixed order across days of testing so that the influence of one task on another was relatively consistent over the 4 days of testing.

Materials and Procedures

Digit immediate response: 1-back task. Four conditions were represented in the task. In the *target isolated immediate response* condition a target (i.e., digits 1, 2, 3, 4) appeared in the center of the computer monitor and the individual was instructed to press a button on a response box mapped to the digit as quickly and accurately as possible. In the *target+distractor immediate response* condition the target digit was presented adjacent to a distractor (i.e., letters A, B, C, D). For this condition the individual was instructed to ignore the distractor and respond by pressing the button mapped to the digit. The letters and digits were presented in yellow on a black background and the display measured 20 mm × 15 mm. Individuals were allowed to adjust viewing distance to achieve optimal resolution. The numeric sequence of the digit and the alphabetic sequence of the letter were always incompatible (e.g., 1B could be a stimulus, while 1A could not). In the *target isolated 1-back* condition a target appeared and the individual was instructed to remember the identity of the current target and respond with the identity of the target from the previous display. Finally, in the *target+distractor 1-back* condition a target and distractor were presented and the individual was instructed to remember the identity of the current target, ignore the distractor, and respond with the identity of the target from the previous display.

These four conditions were presented in a constant order of increasing difficulty for all subjects in four blocks of trials (target isolated immediate response, target+distractor immediate response, target isolated 1-back, and target+distractor 1-back). Each block consisted of 50 trials presented in a quasi-random order where targets and distractors were not repeated across consecutive displays. Targets and distractors were presented side by side on the computer screen and appeared equally often in the left and right positions. In the 1-back conditions the initial target or target and distractor were presented for 2 s and no response was required in order to establish a previous target upon which to base a response when the second display was presented. Before beginning each block of trials the individual received eight practice trials with the stimulus display and task requirements for that block. During practice a tone was presented signaling the occurrence of an error. Following each response the current target or target and distractor were replaced by a blank screen for 200 ms before the next stimulus was presented.

Measurement of Variability

Diversity—between-individual variability—was measured using the Brown and Forsythe (1974) procedure. This index represents the absolute deviation of the individual conditional mean from the group conditional median and was calculated as a function of an immediate or 1-back response, the presence or absence of a distractor, and across the 4 days of testing. Dispersion—within-individual variability—was measured as the individual's conditional standard deviation of mean response latency with separate estimates being obtained as a function of an immediate or 1-back response, the presence or absence of a distractor, and across the 4 days of testing. Consistency—variability in performance across days of testing—was measured as the sum of the absolute deviations from the individuals conditional grand mean across days of testing.

RESULTS

For the digit task the mean response latency data were analyzed in a 2 (age) × 2 (distractor: target isolated or distractor) × 2 (1-back: immediate or 1-back response) × 4 (day of testing) ANOVA (see Table 1). In this analysis older adults ($M = 1198$ ms) responded more slowly than younger adults [$M = 838$ ms; $F(1, 38) = 18.76$, $p < .001$], individuals responded more slowly in the 1-back condition ($M = 1315$ ms) than in the immediate response condition [$M = 720$ ms; $F(1, 38) = 96.34$, $p < .001$], and response latency decreased across days of testing [day 1 $M = 1170$ ms, day 2 $M = 1034$ ms, day 3 $M = 962$ ms, day 4 $M = 905$ ms, $F(1, 38) = 54.78$, $p < .001$]. Three of the two-way interactions were also significant; response slowing resulting from the requirement to respond 1-back was greater for older than younger adults [$F(1, 38) = 7.55$, $p < .009$], response latency was relatively stable in the immediate response condition across days of testing and decreased across days of testing in the 1-back condition [$F(3, 114) = 35.59$, $p < .001$], and the effect of the distractor was significant in the immediate, but not 1-back, condition [$F(1, 38) = 10.16$, $p < .006$]. Finally, the age × 1-back × day of testing interaction was significant [$F(3, 114) = 2.90$, $p < .038$], with the effect of age being stable across days in the immediate response condition [$F(3, 114) = 1.27$, $p > .25$] and decreasing across days of testing in the 1-back condition [$F(3, 114) = 2.91$, $p < .04$].

TABLE 1
Mean Response Latency for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1–4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	662	639	599	598
SD	27	28	26	24
1-Back				
M	1258	1080	956	916
SD	131	104	99	83
Older adults				
Immediate				
M	857	811	815	786
SD	27	28	26	24
1-Back				
M	1904	1609	1479	1322
SD	131	104	99	83

The level of diversity was greater in the 1-back condition ($M = 348$ ms) than in the immediate response condition [$M = 91$ ms; $F(1, 38) = 38.24$, $p < .001$] and decreased across days of testing [$M = 271$ ms, $M = 219$ ms, $M = 205$ ms, $M = 182$ ms; $F(3, 114) = 11.26$, $p < .001$]. The effects of age [age × day; $F(3, 114) = 3.25$, $p < .024$] and 1-back [1-back × day, $F(3, 114) = 8.36$, $p < .001$] interacted with day of testing. Also, the age × 1-back × day of testing interaction was significant [see Table 2; $F(3, 114) = 3.88$, $p < .011$] with the degree of diversity being similar for older and younger adults in the immediate response condition across days of testing ($F < 1$) and age-related differences in the 1-back condition decreasing over the 4 days of testing [$F(3, 114) = 3.86$, $p < .05$].

For the analysis of the standard deviation data, dispersion was greater for older adults ($M = 503$ ms) than for younger adults [$M = 377$ ms; $F(1, 38) = 6.70$, $p < .014$], was greater in the 1-back condition ($M = 667$ ms) than in the immediate response condition [$M = 213$ ms; $F(1, 38) = 165.79$, $p < .001$], and decreased across days of testing [day 1 $M = 505$ ms, day 2 $M = 438$ ms, day 3 $M = 420$ ms, day 4 $M = 395$ ms; $F(3, 114) = 9.51$, $p < .001$]. The effect of age was greater in the 1-back condition than in the immediate response condition [age × 1-back; $F(1, 38) = 7.33$, $p < .010$] and decreased across days of testing [age × day; $F(3, 114) = 3.95$, $p < .010$]. Also, the effects of age, 1-back, and day of testing interacted [see Table 3; $F(1, 38) = 4.03$, $p < .009$]. In the immediate response condition the degree of dispersion was fairly stable across days of testing and similar for younger and older adults ($F < 1$), while in the 1-back condition age-related differences in dispersion diminished over days of testing [$F(3, 114) = 4.90$, $p < .01$].

The results of the analysis for the mean and standard deviation data reveal that in all conditions older adults were slower than younger adults and that this slowing was magnified in the more demanding 1-back conditions. In contrast, the degree of dispersion was similar for younger and older adults in the immediate response condition and greater for older adults in the 1-back condition. Together these findings may indicate that different factors contribute to age-related differences in central tendency and within-subject variability. A question that arises from this observation is whether the increase in dispersion observed in older adults for the 1-back condition results

TABLE 2
Diversity for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	102	93	90	86
SD	17	19	15	15
1-Back				
M	325	293	270	259
SD	78	71	66	56
Older adults				
Immediate				
M	88	92	94	80
SD	17	19	15	15
1-Back				
M	569	398	368	302
SD	78	71	66	56

TABLE 3

Dispersion (Standard Deviation) for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	197	189	205	201
SD	20	23	27	22
1-Back				
M	607	570	517	531
SD	72	66	67	53
Older adults				
Immediate				
M	237	233	237	207
SD	21	23	27	22
1-Back				
M	982	762	722	645
SD	72	66	67	53

from a pervasive increase in variability that influences the entire response time distribution or whether the increase in dispersion results from the presence of a limited number of trials that elicit very slow responses leading to a greater degree of positive skewing of the response time distribution in older adults. To address this question we estimated the three parameters of the ex-Gaussian distribution (μ, σ, τ) for individuals on each of the 4 days of testing in the immediate response and 1-back conditions, collapsing across the presence or absence of a distractor to obtain sufficient numbers of trials. Inspection of the fit statistics (i.e., log likelihood) for the ex-Gaussian function reveals that the fits were generally uniform across younger and older adults in the immediate and 1-back conditions and across the 4 days of testing (see Table 4).

TABLE 4

Fit (Log Likelihood) for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	695	702	698	690
SD	61	79	48	56
1-Back				
M	725	752	747	729
SD	117	85	71	88
Older adults				
Immediate				
M	725	700	702	703
SD	46	85	49	48
1-Back				
M	710	758	725	719
SD	85	81	99	81

TABLE 5

Estimates of μ for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	482	468	437	418
SD	15	16	18	16
1-Back				
M	720	566	530	439
SD	76	71	59	52
Older adults				
Immediate				
M	647	613	621	608
SD	15	16	17	16
1-Back				
M	1004	888	826	724
SD	74	69	57	50

A 2 (age) × 2 (1-back) × 4 (day) ANOVA performed on the fits revealed only a significant main effect of 1-back [$F(1, 36) = 10.81$, $p < .002$], indicating that the fit was slightly better in the immediate response conditions ($M = 701$) than in the 1-back condition ($M = 732$). In the analysis of the ex-Gaussian parameters when significant main effects and interactions were observed a second analysis was undertaken where performance on the digit transfer test served as a covariate in an effort to statistically control for the influence of general slowing.[1] When there was a discrepancy between the results of these analyses (i.e., an effect was no longer significant after controlling for processing speed) the ANOVA results are reported followed by the ANCOVA results.

Analysis of the μ parameter revealed larger parameter estimates for older adults ($M = 741$ ms) than for younger adults [$M = 507$ ms; $F(1, 35) = 24.15$, $p < .001$; see Table 5], larger parameter estimates in the 1-back condition ($M = 712$ ms) than in the immediate response condition [$M = 536$ ms; $F(1, 35) = 25.49$, $p < .001$],

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[1] While the covariation approach has been used extensively in the cognitive aging literature as a method of adjusting for the influence of general slowing, it has recently come under some criticism (Lindenberger & Pöetter, 1998). So as an alternative approach we also examined the effects of age on dispersion using a percentile method where response latency is capture for the 10th, 25th, 50th, 75th, and 90th percentiles (Salthouse, 1993). Using this method one would expect that the effect of age would be greater at the highest percentiles than at the lowest percentiles if the degree of dispersion increased across the response latency distribution. Furthermore, if this effect is somewhat independent of the influence of general slowing one would be expect that the greater effect of age at higher than lower percentiles would persist when the data are normalized (i.e., zero centered based on the group grand mean). To address this hypothesis two analyses were performed, one on the raw percentile data and one on the normalized percentile data. For both of these analyses the age × 1-back × percentile interaction was significant [raw data $F(4, 148) = 6.52$, $p < .001$; normalized $F(4, 148) = 6.34$, $p < .001$], indicating that age-related differences between the immediate response and 1-back conditions increased from the lowest to the highest percentiles. Also, the 1-back × day × percentile interaction was significant in both analyses [raw data $F(12, 444) = 19.43$, $p < .001$; normalized $F(12, 444) = 19.46$, $p < .001$], indicating that differences between the 1-back and immediate response conditions from the lowest to the highest percentiles decreased across days of testing. The age × 1-back × day × percentile interaction was nonsignificant in either analysis [raw data $F(12, 444) = 1.05$, $p > .40$; normalized $F(4, 444) = 1.35$, $p > .18$].

and a decrease in parameter estimates across days of testing [$M = 713$ ms, $M = 633$ ms, $M = 603$ ms, $M = 547$ ms; $F(3, 105) = 28.87$, $p < .001$]. The decrease in μ across days of testing was greater in the 1-back than in the immediate response condition [1-back × day; $F(3, 105) = 16.19$, $p < .001$; $F(3, 102) = 1.53$, $p > .20$]. Interestingly, the effect of age did not interact with day of testing or the requirement to respond with the location of the previous stimulus [age × 1-back, $F(1, 35) = 3.28$, $p > .078$, observed power = .42; age × day, $F < 1$, observed power = .06; and age × 1-back × day $F < 1$, observed power = .15], indicating that age-related differences in μ were not significantly influenced by task demands or task experience.

Analysis of the σ parameter revealed somewhat similar results as for the μ data. Estimates of σ were greater in the 1-back condition ($M = 167$ ms) than in the immediate response condition before but not after controlling for processing speed [$M = 52$ ms; $F(1, 35) = 70.77$, $p < .001$; $F < 1$; see Table 6] and decreased across days of testing [day $M = 135$ ms, day $M = 108$ ms, day $M = 106$ ms, day $M = 90$ ms; $F(3, 105) = 3.83$, $p < .012$]. Estimates of σ did not differ between younger adults (M = 99.29 ms) and older adults [M = 121.35 ms; $F(1, 35) = 1.78$, $p < .191$, observed power = .25] and the age did not interact with the factors 1-back [age × 1-back; $F(1, 35) = 2.96$, $p > .093$, observed power = .39) or day of testing [age × day; $F(1, 35) = 1.34$, $p > .266$, observed power = .35]. These findings indicate that there was a positive shift in the leading edge of the distribution for older adults relative to younger adults that was similar for the 1-back and immediate response conditions (μ parameter), while the degree of variability in the leading edge of the distribution was similar for younger and older adults (σ parameter; see Fig. 1).

Analysis of the τ parameter revealed a greater degree of positive skew in the tail of the response latency distribution for older adults ($M = 456$ ms) than for younger adults that was only marginally significant after controlling for processing speed [$M = 328$ ms; $F(1, 35) = 6.26$, $p < .017$; $F(1, 34) = 3.61$, $p < .07$; see Table 7]. Tau was also greater in the 1-back condition ($M = 609$ ms) than in the immediate response condition before but not after controlling for processing speed [$M = 175$ ms; $F(1, 35) = 134.19$, $p < .001$; $F(1, 34) = 1.23$, p > .25]; also, the degree of positive skew decreased across days of testing [day 1 $M = 463$ ms, day 2 $M = 393$

TABLE 6

Estimates of σ for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	47	51	55	61
SD	5	6	7	8
1-Back				
M	174	157	130	109
SD	34	31	27	30
Older adults				
Immediate				
M	64	49	52	43
SD	5	6	7	8
1-Back				
M	256	166	190	150
SD	33	30	26	29

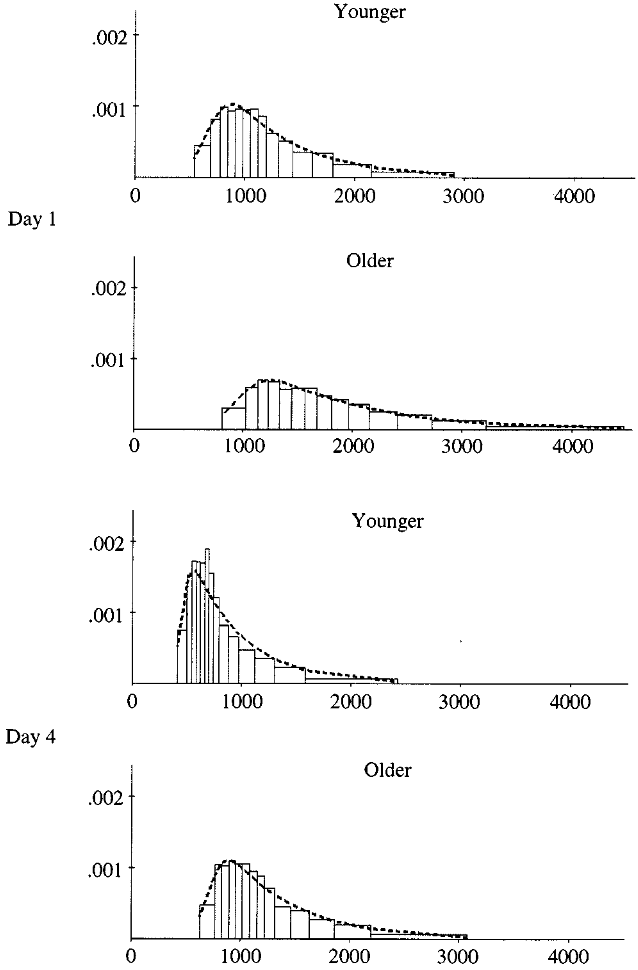

FIG. 1. Probability density and fitted ex-Gaussian function for younger and older adults in the 1-back condition on days 1 and 4 of testing. Note the reduction in the degree of positive skew for younger and older adults from day 1 to day 4 of testing, while the leading edge of the distribution is relatively stable over this same period. The *x* axis shows response time and *y* axis shows the probability density.

ms, day 3 $M = 356$ ms, day 4 $M = 356$ ms; $F(3, 105) = 18.08$, $p < .001$]. The effect of age [age × day; $F(3, 105) = 4.10$, $p < .009$] and the requirement to respond with the location of the previous target [1-back × day; $F(3, 105) = 18.48$, $p < .001$] interacted with day of testing, decreasing from the first to the fourth sessions. The effect of age also interacted with 1-back [$F(1, 35) = 9.35$, $p < .004$], and this interaction was qualified by an interaction of age, 1-back, and day [$F(3, 105) = 2.89$, $p < .039$] with age-related differences in the degree of positive skew in the 1-back condition being reduced across days of testing. These findings together with those for the σ parameter indicate that the increased dispersion observed for older adults in the 1-back condition resulted from an increase in the degree of positive skew in the tail of the distribution and not a pervasive increase in variability for this condition.

The results of the analyses for the ex-Gaussian parameters revealed that the variables age and 1-back only interacted for the τ parameter, consistent with the idea that age-related increases in performance variability primarily result from changes in the degree of positive skew of the response time distribution and not a pervasive increase in variability across the entire distribution. A slightly different way to ad-

TABLE 7
Estimates of τ for Younger and Older Adults in the Immediate Response and 1-Back Conditions on Days 1 to 4 of Testing

	Day			
	1	2	3	4
Young adults				
Immediate				
M	168	167	168	174
SD	17	18	17	18
1-Back				
M	569	502	417	465
SD	80	66	64	61
Older adults				
Immediate				
M	192	181	184	173
SD	17	18	16	17
1-Back				
M	926	725	656	614
SD	78	64	62	59

dress the issue is to ask the question of whether the same factors are needed to transform the response time distribution of the immediate condition into the response time distribution of the 1-back condition and, further, whether these factors differ for younger and older adults. In order to consider this hypothesis one first needs to establish the transformation required to transform the ex-Gaussian parameters of the immediate condition into those of the 1-back condition (e.g., $\mu_{\text{1-back}}/\mu_{\text{immediate}}$) and then to establish whether this transformation is constant for younger and older adults by examining the odds ratios for the younger and older adults across the ex-Gaussian parameters (e.g., old$\mu_{\text{transform}}$/young$\mu_{\text{transform}}$). If the old/young ratios are close to unity this can be taken as evidence that the parameters required to transform the immediate distribution into the 1-back distribution are similar for younger and older adult; in contrast, if the ratios are greater than unity this can be taken as evidence that different transformations are required for younger and older adults. The old/young odds ratios for μ, σ, and τ across the 4 days of testing are presented in Table 8. In these data the odds ratios for μ and τ are relatively stable across days of testing, while for σ there is a substantial increase from day 1 to day 4 of testing. The increase in the odds ratios for the σ parameter across days of testing results from a greater reduction in the 1-back/immediate ratio for younger than for older adults across days of testing, giving rise to the increasing old/young odds ratios.

A formal test of the hypothesis that the 1-back/immediate transformations are dif-

TABLE 8
Old/Young Odds Ratios for the Ex-Gaussian Parameters as a Function of Day of Testing

	Day			
Parameter	1	2	3	4
Mu	1.04	1.20	1.10	1.13
Sigma	1.08	1.10	1.55	1.95
Tau	1.42	1.33	1.44	1.33

ferent across parameters and across younger and older adults can be obtained by analyzing the log transformed ex-Gaussian parameters in a 3 (parameter) × 2 (age) × 2 (1-back) × 4 (day) ANOVA. In this analysis the parameter × 1-back interaction was significant [$F(2, 70) = 62.96$, $p < .001$], indicating that different transformations were required for the individual ex-Gaussian parameters. However, the critical parameter × age × 1-back interaction was not significant ($F < 1$), leading to the suggestion that the transformation required to change the immediate response time distribution into the 1-back response time distribution is similar for younger and older adults. This finding is inconsistent with the expectation that age-related increases in performance variability would primarily influence the τ parameter, resulting in a different transformations being required across the ex-Gaussian parameters. To further explore this hypothesis we performed three additional ANOVAs, one for each ex-Gaussian parameter independently. For the μ and σ parameters the age × 1-back interactions were nonsignificant [$\mu F(1, 35) = 1.24$, $p > .25$; $\sigma F(1, 35) = 1.07$, $p > .30$]. For the τ parameter the age × 1-back interaction was significant [$F(1, 35) = 4.38$, $p < .05$], consistent with the idea that age-related increases in performance variability would primarily influence the degree of positive skewing of the response time distribution.

The consistency data were considered in a 2 (age) × 2 (distractor) × 2 (1-back) ANOVA. In this analysis individuals were less consistent in the 1-back ($M = 567$ ms) than immediate response condition [$M = 360$ ms; $F(1, 38) = 96.16$, $p < .001$] and older adults ($M = 567$ ms) were less consistent than younger adults [$M = 360$ ms; $F(1, 38) = 12.46$, $p < .001$]. The interaction of age × 1-back was significant [$F(1, 38) = 8.21$, $p < .007$], with the degree of consistency being similar in the immediate response condition for older adults ($M = 187$ ms) and younger adults [$M = 152$ ms; $F(1, 38) = 1.35$, $p > .25$] and greater for older adults ($M = 948$ ms) than younger adults [$M = 568$ ms; $F(1, 38) = 10.91$, $p < .01$] in the 1-back condition. These findings indicate that older adults were only less consistent in their performance than younger adults across days of testing in the more demanding 1-back condition.

DISCUSSION

Aging and Performance Variability

Consistent with our predictions age-related increases in performance variability were limited almost exclusively to task conditions requiring the active recruitment of executive control processes. Levels of diversity, dispersion, and consistency were similar for younger and older adults in the immediate response condition across the 4 days of testing, while robust age-related differences in response time were observed in this condition across all 4 days of testing. This finding could be taken to suggest some degree of independence between those factors that give rise to age-related slowing of response time and age-related increases in performance variability. In contrast to the immediate response condition, age-related increases in performance variability were consistently observed in the 1-back condition. For diversity, the effect of age in the 1-back condition was only significant on the first day of testing, while the effect of age on dispersion in the 1-back condition remained significant across the 4 days of testing even when numerous measures were taken to control for the influence of general slowing. These findings indicate that task experience or practice may have served to quickly normalize the performance of a relatively limited number of older adults contributing to the elimination of age-related differences in diversity after the first day of testing. In contrast, age-related differences in dispersion in the

1-back condition remained significant on the fourth day of testing, indicating that within-subject variability was somewhat more resistant to the influence of task experience than between-subject variability. However, the nature of this possible difference is not apparent from the results of the present study. Age-related increases in dispersion were accompanied by age-related decreases in consistency of performance, consistent with recent work indicating that within-session variability can be a good predictor of variability in performance over an extended period of time (Rabbitt, 2000).

In an effort to examine the nature of age-related increases in dispersion in the 1-back condition the ex-Gaussian distribution was fitted to the response time distribution. This analysis revealed that age-related increases in dispersion resulted primarily from an increase in the degree of positive skewing of the distribution reflected in the τ parameter, while age-related differences in the σ parameter were small and only observed on the first day of testing. The age-related increase in the τ parameter was slightly reduced, but remained significant, when variance shared with processing speed was controlled. This finding indicates that the increased positive skewing of the response time distribution observed for older adults was somewhat independent of general slowing. Also, there was some support for a greater effect of age on the degree of positive skewing of the distribution relative to the central tendency of the distribution in the odds ratio data. These findings can be taken to indicate that age-related increases in dispersion result not from a pervasive increase in variability over the course of task performance, but instead result from relatively transient periods where executive control processes are operating at less than optimal efficiency. This proposal is consistent with the findings of Rabbitt and Goward (1994) demonstrating that individuals low in intellectual ability typically exhibit greater degrees of positive skew of the response latency distribution than individuals higher in intellectual ability.

Rabbitt and Goward (1994) also suggested that there were age and intellectual differences in the ability to benefit from practice that served to reduce the degree of positive skew of the response time distribution, with younger adults and individuals of higher intelligence improving more with practice than older adults and individuals of lower intelligence. The odds ratio data from the current study are somewhat inconsistent with this proposal. In these data there was an increase in the old/young ratios for the σ parameter across days of testing that resulted from greater decreases in the 1-back/immediate ratios for younger than older adults with task experience, while the old/young ratios were relatively stable across days of testing for the μ and τ parameters. This finding indicates that the effect of experience was similar for older and younger adults for these parameters. These data lead to the suggestion that practice resulted in a greater reduction in the degree of variability in the leading edge of the distribution for younger than older adults instead of the positively skewed tail of the distribution as proposed by Rabbitt and Goward (1994).

During the review process an anonymous reviewer suggested that the greater τ observed for older adults in the 1-back condition could have resulted from age-related differences in the trial-to-trial demands placed on individuals in the 1-back condition relative to the immediate condition. Specifically, this reviewer suggested that the use of a short response to stimulus interval (i.e., 200 ms) may have not allowed older adults enough time to recover from the processing demands of the previous trial when faced with the current trial. While this proposal presents an interesting alternative account of the observed data, one would still need to posit a model where age-related differences in the ability to recover from a previous trial contributed to performance on some trials more than others, as would be necessary to produce the greater effect on τ than μ or σ instead of having a more pervasive effect that would produce age-related differences in each of the ex-Gaussian parameters. In other words one would have to predict that the efficiency of those cognitive processes supporting recovery fluctuate over the course of task performance and that these fluctuations are greater or more frequent for older than younger adults, leading the individual to be less prepared on some trials than on others. This prediction seems qualitatively similar to our position that executive control processes fluctuate in efficiency over time and that these fluctuations contribute to increased performance variability in demanding task conditions. The primary difference, then, between our position and the recovery hypothesis would be one of specificity, where we are advocating that fluctuations are an intrinsic quality of cognitive processes supporting executive control in general and the recovery hypothesis specifies a particular process that is susceptible to these fluctuations.

Prefrontal Cortex, Fluctuations of Executive Control, and Aging

The data from two recent studies using event-related brain potentials indicate that the neural mechanisms supporting executive control in the Stroop task are dynamic in nature and tend to fluctuate in efficiency over the course of task performance (West & Alain, 2000a; West & Alain, 2000b). In one study a frontal-polar slow wave was identified associated with lapses of intention, reflecting differential neural activity when a goal-directed response was made relative to when an error was made. The inversion plane of this modulation is consistent with the activity of a neural generator that lies within the polar or lateral prefrontal cortical regions, supporting a role of the prefrontal cortex in maintaining optimal levels of executive control. The role of the prefrontal cortex in maintaining the optimal efficiency of executive control processes has also been demonstrated in a number of other studies. For instance, individuals who have sustained focal damage to the prefrontal cortex demonstrate increased performance variability relative to matched controls and individuals with posterior lesions (Stuss, Murphy, & Binns, 1998). Also, studies of individuals sustaining a traumatic brain injury (TBI)—often resulting in damage to the prefrontal cortex—demonstrate increased performance variability both within and between testing sessions relative to matched controls (Stuss et al., 1989; Stuss et al., 1994). TBI has also been associated with an increased susceptibility to goal neglect (Duncan et al., 1996), a decreased ability to maintain a high level of sustained attention (Robertson, Manly, Andrade, & Yiend, 1997), and an increased susceptibility to prospective memory failure (Shum, Valentine, & Cutmore, 1999).

There is mounting evidence indicating that the prefrontal cortex is more susceptible to the effect of the aging process than some other cortical and subcortical neural structures (see Albert & Kaplain, 1980; Phillips & Della Sala, 1999; West, 1996), although this position is not universally accepted (Greenwood, 2000). Age-related declines in the integrity of the prefrontal cortex have been revealed in studies reporting declines in frontal gray matter in older adults (Raz et al., 1997), declines in resting levels of cerebral blood flow and irregularities in patterns of blood flow in cognitive activation studies using PET (for a review see Cabeza, 2001), and age-related declines in performance on a variety of neuropsychological tasks sensitive to damage of the prefrontal cortex (Albert & Kaplain, 1980). Given these data, it seems reasonable to suggest that the age-related increase in the tendency for executive control processes to fluctuate in efficiency over time demonstrated by the increased number of intrusion errors in the Stroop task (West, 1999b), the greater positive skew of the response time distribution for older adults in task conditions requiring the recruitment of executive control processes (West, 1999a), and increased performance variability result from an age-related decline in the functional integrity of the prefrontal cortex.

CONCLUSIONS

The present work was motivated by the hypothesis that the efficiency of executive control processes fluctuates over time and that older adults are more susceptible to fluctuations in the efficiency of executive control processes than are younger adults. Consistent with this hypothesis, lapses of intention are more frequent in older adults than in younger adults and occur during periods of slowed responding, which may reflect the waning of executive control processes that serve to maintain a course of goal-directed action. Here we provide data from a new study of age-related differences in performance variability demonstrating that aging was accompanied by an increase in both diversity and dispersion and a decrease in consistency in task conditions requiring the recruitment of executive control processes. Age-related increases in diversity were reduced to nonsignificant levels with minimal practice, while age-related increases in dispersion remained significant across the 4 days of testing and primarily resulted from an increase in the degree of positive skewing of the response latency distribution.

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