Original Research Report

Staying on Task: Age-Related Changes in the Relationship Between Executive Functioning and Response Time Consistency

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Received May 21, 2014; Accepted August 25, 2014

Decision Editor: Bob G. Knight, PhD

Abstract

Objective: Little is known about the relationship of executive functioning with age-related increases in response time (RT) distribution indices (intraindividual standard deviation [ISD], and ex-Gaussian parameters mu, sigma, tau). The goals of this study were to (a) replicate findings of age-related changes in response time distribution indices during an engaging touch-screen RT task and (b) investigate age-related changes in the relationship between executive functioning and RT distribution indices.

Method: Healthy adults (24 young [aged 18–30], 24 young-old [aged 65–74], and 24 old-old [aged 75–85]) completed a touch-screen attention task and a battery of neuropsychological tests. The relationships between RT performance and executive functions were examined with structural equation modeling (SEM).

Results: ISD, mu, and tau, but not sigma, increased with age. SEM revealed tau as the most salient RT index associated with neuropsychological measures of executive functioning. Further analysis demonstrated that correlations between tau and a weighted executive function composite were significant only in the old-old group.

Discussion: Our results replicate findings of greater RT inconsistency in older adults and reveal that executive functioning is related to tau in adults aged 75–85. These results support literature identifying tau as a marker of cognitive control, which deteriorates in old age.

Key Words: Aging—Ex-Gaussian—Executive functions—Intraindividual variability—Sustained attention

Inconsistency, or intraindividual variability in response time (RT IIV), is increasingly being recognized as an important marker of central nervous system integrity and is thought to be a useful measure of neurocognitive function. The measure is typically expressed either as the standard deviation calculated within each participant’s response time data set (intraindividual standard deviation; ISD), or as a coefficient of variation (ISD/mean RT). Research employing a variety of experimental tasks (e.g., simple RT, choice RT, lexical decision, and semantic decision) has shown that response time IIV is greater in healthy older adults compared with younger adults (Hultsch, MacDonald, & Dixon, 2002; Hultsch, Strauss, Hunter, & MacDonald, 2008; Williams, Hultsch, Strauss, Hunter, & Tannock, 2005). Age stratification within older adult groups (e.g., young-old, mid-old, and old-old) reveals that inconsistency continues to increases with age, even in the later part of life (Hultsch et al., 2002). The evidence from more extensive cross-sectional lifespan research further supports the idea that aging is accompanied by a linear increase of within-person RT variability from the mid 20s to mid 80s at least (Williams et al., 2005).
One approach that researchers have taken to understand the source of elevated variability with age is to fit individuals’ data to an ex-Gaussian distribution, which permits the analysis of specific distribution components (West, Murphy, Armilio, Craik, & Stuss, 2002). An ex-Gaussian distribution is the convolution of a normal (Gaussian) function and an exponential function. The distribution is specified by three parameters: mu and sigma representing the mean and standard deviation of the Gaussian component respectively, and tau representing the right tail of the distribution, with a larger tau value indicating greater positive skew. Larger tau has been interpreted as an indicator of brief attention lapses (West et al., 2002).

A potential contributing factor to age-related increases in RT IIV and tau is the age-related deterioration of the frontal lobes (Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003), responsible for the top-down influence that enables sustained attention (i.e., cognitive control). Support for this connection comes from research on brain damaged individuals, neuroimaging research on healthy individuals, and research on older adults. First, the literature has shown that focal lesions to the frontal lobes impairs stability of cognitive performance (Stuss, Murphy, & Binns, 1999; Stuss, Murphy, Binns, & Alexander, 2003). Second, evidence from functional neuroimaging has confirmed an association between RT IIV and activation of brain regions involved in sustained attention, including the frontal lobes (Bellgrove, Hester, & Garavan, 2004). Third, and most relevant to the current investigation, studies have shown that older adults have higher tau values (Spieler, Balota, & Faust, 1996; West et al., 2002), and adult age differences in inconsistency have been reported to be primarily due to attention lapses, detected by changes in the slow end of the RT distribution (Anderson, 1999; Williams et al., 2005).

Another approach to understanding the source of age-related increases in variability is to relate observed differences in IIV and/or ex-Gaussian parameters with executive functions. However, studies that have explored this relationship have been limited by the measures used, or by conceptualization of executive function. One study examined how the influence of age on variability was modulated by varying demands on executive control processes (West et al., 2002). The rationale was that if aging results in greater fluctuations in executive control efficiency, then age-related increases in IIV would be more pronounced in tasks with higher executive control requirements. Indeed, their results showed that RT variability was greater in older adults in high executive control demand conditions, but similar to younger adults in conditions requiring minimal executive control. Their study used a choice response time task involving the identification of one of four digits in a current display (non-executive), contrasted with a condition requiring identification for the previous display (1-back executive). Although this manipulation elicited RT differences in relation to executive demand, it did not include assessment of a wider range of cognitive processes that constitute executive functioning. It is possible that individual differences in discrete executive abilities (e.g., flexibility, inhibition, and working memory) could differentially be related to variability in performance. Lastly, it is unclear whether the effects found were indeed due to increased executive demand, or simply a result of differences in task difficulty between choice RT and 1-back conditions. More recently, intervals on a continuous tapping task were manipulated to differentially engage attentional control systems (Bangert & Balota, 2012). The authors found that healthy older adults sped up their tapping at the slowest target rate compared to younger adults, which they reasoned was due to a breakdown in attentional control affecting the ability to maintain a synchronous response pattern independent of an auditory pacer.

A study combining both experimental and clinical tests showed that tau, computed from a composite of Stroop, Simon, and switching tasks, significantly correlated with several neuropsychological measures of cognition in a healthy older adult sample (Tse, Balota, Yap, Duchek, & McCabe, 2010). The relationships existed across several domains examined, but the strongest associations were with those tasks tapping speed of processing and executive/working memory abilities. In contrast, mu and sigma displayed fewer and weaker correlations with cognitive test performance, with no link to executive/working memory ability. Another study found that inconsistency in RT was associated with poorer everyday problem-solving abilities (Burton, Strauss, Hultsch, & Hunter, 2009). The authors demonstrated that this remained true after accounting for age, education, and mean level of performance. The problem-solving abilities studied in this research were instrumental activities of daily living (IADLs), and we know that these activities have a strong executive requirement, with established associations between certain neuropsychological tests of executive functioning and IADL measures (Bell-McGinty, Podell, Franzan, Baird, & Williams, 2002; Cahn-Weiner, Boyle, & Malloy, 2002; Jefferson, Paul, Ozonoff, & Cohen, 2006; Tomaszewski Farias et al., 2009). Together, this literature indicates a connection between executive functions and increased variability. However, neither of these two studies included a younger adult sample, and so they could not evaluate whether the relationship between intraindividual variability and executive functioning differs between old and young.

The goals of this study were (a) to replicate the findings of age-related differences in mean RT, target misses, RT ISD, and ex-Gaussian parameters during an engaging touch-screen attention task, in young, young-old, and old-old samples and (b) to investigate age-related changes in the relationship between performance on neuropsychological tests of executive functioning and RT distribution indices (ISD, mu, sigma, and tau). There is only one known study that previously examined the relationship between individual differences in various aspects of executive functioning...
and ex-Gaussian parameter estimates in older adults (Tse et al., 2010). However, their investigation focused on pathological differences, including both healthy older adults and those with mild cognitive impairment, rather than the healthy aging process. Additionally, Tse et al. (2010) did not contrast ex-Gaussian distribution parameters with an established measure of intraindividual variability (i.e., ISD).

We developed a task in which stimuli scroll continuously across a touch screen, with the goal being to tap a specified target as quickly as possible. The rationale was to have a task that was more engaging and relatable to the real world than typical RT tasks, which is a direction that has recently been taken in RT IV studies by employing driving and flight simulators (see Bunce, Young, Blane, & Khugputh, 2012; Kennedy et al., 2013). The recording of response time data from each tap allowed us to calculate ISD and estimate ex-Gaussian parameters. The recording of on-screen tap location also enabled the analysis of strategic differences. Here, an example of a strategy that would produce more consistent performance would be to position one's hand over a specific section of the screen and tap each time a target passed beneath. This is in contrast to a strategy that may produce greater variability where the participant's hand is not fixed over a certain section of the screen, promoting tapping to various locations. This analysis involved computing an x-coordinate ISD (i.e., variability in the location at which participants tapped). X-coordinate ISD is invariably linked to RT as touching a card further along the x-axis leads to a greater amount of time elapsed, but still provides separate information on response style. No prior study has explored whether strategy differences contribute to age-related increases in IV. Potentially, the greater IV observed in older adults could be partially explained by age differences in strategic approaches to tasks, a possibility that is supported by research demonstrating that older adults use different strategies compared to young adults (Brebinon, Smith, & Ehrlich, 1997; Touron & Hertzog, 2004; Velanova, Lustig, Jacoby, & Buckner, 2007).

We anticipated an age-related increase in response variability (ISD, sigma, tau) from young to young-old to old-old (Hultsch et al., 2002; Hultsch et al., 2008; West et al., 2002). We hypothesized that there would be no difference in strategy application between the groups as the literature has converged on attentional changes being the primary source of RT variability differences between young and old. Lastly, we expected that poorer performance on executive measures would be related to greater ISD and tau, reflecting the impact of decreased cognitive control on tests of executive functioning.

**Method**

**Participants**

We recruited 24 healthy young adults (aged 18–30 years; \( M = 24.4, SD = 3.1; 3 \) males) and 48 healthy older adults (aged 65–85 years; \( M = 74.4, SD = 6.1; 13 \) males) from the Rotman Research Institute participant database. The older adult group was recruited to comprise two subgroups with 24 participants each: Young-old (aged 65–74; \( M = 69.1, SD = 3.2; 6 \) males) and old-old (aged 75–85; \( M = 79.7, SD = 2.6; 7 \) males). Participants were excluded on the basis of the following criteria: A history of head injury resulting in a loss of consciousness, neurological impairment, or other major medical illnesses (e.g., stroke, dementia, and heart disease), radiation to the head, drug abuse, current use of psychiatric medication, or a lack of fluency in English. Older adults also had to achieve a score greater than 30 points on the modified Telephone Inventory of Cognitive Status (Welsh, Breitner, & Magruder-Habib, 1993) to be eligible to participate. Written informed consent was obtained from all volunteers, and monetary compensation was provided for participating in the study. This research was approved by Baycrest’s Research Ethics Board.

**Procedures**

After informed consent, a selected neuropsychological battery was administered to each participant. At the approximate midway point of the battery, participants completed the computerized attention task. Following the attention task, they resumed neuropsychological testing. The entire session lasted approximately 2 hr.

**Attention Task**

This task was designed to be more ecologically valid than more commonly used experimentally based simple and choice response time tasks by incorporating dynamic movement and a feature identification requirement. Our task borrowed from naturalistic activities requiring the maintenance of selective attention over a prolonged period of time, such as observing items moving along a conveyor belt and identifying specific targets. On a production line these targets might be defective products, whereas at airport security targets would be restricted or dangerous articles.

The task involved images of playing cards scrolling continuously from left to right or from right to left (depending on the participant’s dominant hand) on a touch screen, with the goal being to tap the target (8 of spades) as quickly as possible using a stylus. The program was run on a Hewlett Packard Touchsmart-tm2 tablet PC with 13-inch screen (resolution 1280×800) placed face up on a table, slightly angled towards the participant to reduce screen glare. Before the participant began the task they watched the experimenter demonstrate what was required with five target cards. The experimenter then handed the stylus to the participant for practice interacting with the touch screen. Successfully registered touches were indicated when the stimulus turned gray. Once the participant touched 10 targets, the practice ended. The task took approximately 20 min with three evenly placed breaks dividing the task.
into four blocks. Breaks were very short intermissions, only given for participants to rest their eyes briefly. Both response time and position (in pixel x-y coordinates) were recorded.

The attention task consisted of 1,728 images of playing cards, 144 of which were the target 8 of spades. The remaining cards included numbers 5 through 9 in each of the four suits (spades, hearts, clubs, and diamonds). For each participant, the program first constructed four blocks of 432 cards. The cards within each block were ordered into 108 sets of four cards each, with the target present in 36 sets per block (33%). Selection of the non-target cards was controlled, such that cards within a set shared a certain number of attributes (color, suit, number) in common with the target. Specifically, the non-target sets contained two 2-feature, one 1-feature, and one 0-feature overlap non-target cards (Figure 1) (Note that playing cards do not permit full factorial combinations of feature overlap with the target [i.e., the 1-feature overlap cards shared the number only, or the color only, but could not share the suit]). Target sets contained one 2-feature overlap non-target card, one 1-feature overlap non-target card, and one 0-feature overlap non-target card (Figure 1). Within each block, the sets were randomly ordered with the restriction that no more than three sets containing targets occurred consecutively. Once the trial set generation was completed, which only took a few seconds, the program began. It is important to note that although the cards were grouped into sets for the purpose of stimulus order selection, this grouping was not apparent to the participant while the program was running. All cards were evenly spaced, thus eliminating the appearance of preconceived organization.

Cards were presented on a white background. They moved from left to right for right-handed participants and in the opposite direction for left-handed participants. The cards moved at a speed of 714.3 pixels/s (or 0.146 m/s), which resulted in them being on the screen for approximately 1.79 s. The card images were 200×250 pixels in size, subtending visual angles of 5.8×7.3 degrees at an approximate viewing distance of 40 cm. At this speed and size, with preset spacing between cards, no more than four cards were visible on the screen at a given time.

### Data Preparation

Mean response time and IIV were calculated only from “hit” responses, excluding false alarms. Hit responses for the first target in each block were excluded from all analyses to accommodate task “warm-up” effects. Instances of unusually quick responses (faster than possible to carry out decision and motor action components) were unlikely to occur because the task demanded more thoughtful responding, compared to a simple button press. Accidental screen taps were rare, and typically represented false alarms (a frequency of .001%). Upper value outliers representing extremely slow responses were not possible because cards moved off the screen in 1.79 s, making that the upper limit for a response. If the participant was too slow to respond in that time, it was counted as a miss. Values for missing data points were not imputed.

### Estimating Intraindividual Variability and Ex-Gaussian Distribution Parameters

There are different indices of intraindividual variability and some researchers have chosen to use the intraindividual coefficient of variation (ICV) to control for systematic group differences in mean performance. However, this method combines effects of the ISD and mean performance, as well as their cross-product, which can lead to ambiguity in results (Hultsch et al., 2008). Thus, we employed the intraindividual standard deviation (ISD) with preceding data “purification” steps as a measure of IIV based on consensus from the field (Hultsch et al., 2008). This method ensures that systematic trends in performance (practice effects, fatigue, etc.), as well as other deterministic variations in mean performance are eliminated before calculation of ISD. First, the data were checked for linear, quadratic, and cubic trends, which revealed a small but significant negative linear slope. Next, individual trial RTs were regressed on trial number for each participant and residuals saved. Lastly, intraindividual standard deviations were calculated from the unstandardized residuals. We did not include block in the regression as preliminary analyses did not reveal differences across blocks.

Ex-Gaussian parameters were computed separately for each individual using a MATLAB toolkit (Lacouture & Cousineau, 2008). The MATLAB script estimated mu, sigma, and tau parameters for each participant.

### Neuropsychological Battery

The following tests were administered to each participant: Mini Mental State Examination (MMSE), Shipley’s...
Institute of Living Scale, The Boston Naming Test (30-item form), Wechsler Memory Scale III (WMS-III) Logical Memory I and II, WMS-III Digit Span forwards and backwards, Wechsler Adult Intelligence Scale III (WAIS-III) Digit Symbol Coding, and the Wisconsin Card Sorting Test (WCST). In addition, Trail Making, Color-Word Interference, and Fluency subtests from the Delis Kaplan Executive Function System (DKEFS) were administered. Of note, one of the five Trail Making subtests, number-letter switching, is analogous to the traditional timed Trail Making test part B, except that it is spread across a sheet of paper measuring 11 × 17 inches. Similarly, Color-Word Interference inhibition subtest is analogous to a timed version of the Stroop test—inhibition, and DKEFS Fluency consists of phonemic (FAS), semantic (animals and boys names), and switching (fruits/furniture) subtests.

Results
Demographics and Neuropsychological Functioning
Demographic information on the sample (i.e., age and education), as well as neuropsychological test scores, are summarized in Table 1. Inspection of the three age groups (young, young-old, and old-old) revealed similar levels of education, and general functioning as measured by the MMSE. Consistent with much prior research, younger adults performed slightly worse on the vocabulary subtest of Shipley’s Institute of Living Scale compared to both older participant groups. Although not present for every test, there was a tendency for younger adults to outperform young-old, who in turn outperformed old-old on cognitive measures.

Attention Task Performance
An age-regressed correlation matrix of attention task measures can be found in Table 2. Mean RT was significantly correlated with mu and sigma, which is not surprising given that the two parameters reflect the mean and standard deviation of the Gaussian distribution component. Mean RT also significantly correlated with x-coordinate ISD, and misses, but not RT ISD or tau. A significant association was found between RT ISD and the following measures: Tau, x-coordinate ISD, misses, and false alarms. Tau was significantly correlated with all measures except mean RT, with the strongest relationship being with RT ISD ($r = .786, p < .001$).

In order to confirm the effect of decreasing attention abilities with age, mean response time, target misses, RT ISD, ex-Gaussian parameters (mu, sigma, tau), and x-coordinate ISD were analyzed in separate one-way linear contrast ANOVAs with age group (young, young-old, old-old) as the between-subject independent variable.

Mean response time
There was a significant linear effect of age group on mean RT, $F(1, 69) = 13.16, p = .001, \eta^2 = .16$ ($B = 90.93$, standard error = 25.07). Younger adults were fastest ($M[SD] = 1,004.24[207.28]$), followed by the young-old ($M[SD] = 69.13[3.15]$) and old-old ($M[SD] = 79.67[2.65]$) groups. The $t$-tests between groups showed that younger adults were faster than both older groups ($p < .05$).
group (1,143.25[145.52]), and then the old-old group (1,186.11[162.26]).

Target misses
The contrast ANOVA revealed a significant linear effect of age group on target misses, $F(1, 69) = 25.42, p < .001, \eta^2 = .27$ ($B = 4.40$, standard error = .87). Younger adults missed the fewest number of targets ($M[SD] = 1.33[1.63]$), followed by the young-old group (4.67[3.88]), who missed fewer than the old-old group (10.13[9.58]). It should be noted, that the number of target misses was low, and not substantial enough to affect the RT distribution analyses.

False alarms
The contrast ANOVA revealed a significant linear effect of age group on false alarms, $F(1, 69) = 11.63, p = .001, \eta^2 = .14$ ($B = 1.90$, standard error = .55). Younger adults had the fewest number of false alarms ($M[SD] = 0.71[.91]$), followed by the young-old group (1.96[4.29]), and then the old-old group (4.50[5.03]).

Intraindividual variability
The analysis of ISD revealed a significant linear effect of age group on RT ISD (see Figure 2), $F(1, 69) = 6.18, p = .015, \eta^2 = .08$ ($B = 16.71$, standard error = 6.72). Younger adults were the most consistent with the lowest ISD ($M[SD] = 129.66[48.75]$), followed by the young-old group with greater ISD (141.24[43.85]), and then the old-old with the highest ISD (163.07[46.89]).

Ex-Gaussian parameters
A linear effect of age group was observed for mu, $F(1, 69) = 6.00, p = .017, \eta^2 = .08$ ($B = 67.32$).
standard error = 27.61). Younger adults had the lowest mu (M[SD] = 905.57[231.29]), followed by the young-old and old-old groups with higher mu respectively (1,034.99[167.29] and 1,040.21[165.03]). Tau demonstrated a significant linear effect of age group, F(1, 69) = 6.672, p = .012, η² = .09 (B = 23.61, standard error = 9.13). Younger adults had the lowest tau (M[SD] = 98.69[52.30]), followed by the young-old group with greater tau (108.05[63.54]), and then the old-old with the highest tau (145.90[72.49]). The effect for sigma was not significant, F(1, 69) = 2.844, p = .096.

**Tap X-coordinate IV**

A strategy one could employ to improve speed and reduce variability on our task is to keep the stylus near the edge at which the cards first appeared, tapping the target as early as possible. Using a touch screen enabled the recording of positional data of where participants touched the screen to make their response. We computed ISDs for the x-coordinates (based on pixels) using the same method as outlined above for response time. The effect of age group on x-coordinate ISD was not significant, F(2, 69) = 1.26, p = .290, η² = .03. We did not examine y-coordinates because all cards scrolled across the same vertical plane.

**Relationships Among IV, Ex-Gaussian Parameters, and Executive Functioning**

Because we know that age is related to executive function ability, IV, and ex-Gaussian parameters, any correlations between these variables could reflect simply aging, and not a true relationship between these measures. Therefore, in order to examine the relationship between executive functioning and RT distribution indices, we first regressed out age from all measures of interest—purified RT ISD, mu, sigma, tau, and selected tests of executive functioning, and then saved the standardized residuals using the complete sample of younger and older adults. We chose to include five executive function measures that are commonly used in neuropsychological research and clinical practice: WCST percent perseverative errors, DKEFS Trail Making number-letter switching (time to complete), DKEFS Color-Word Interference inhibition (time to complete), DKEFS Verbal Fluency (total words generated; FAS), and Digit Span (total span). These tests cover a range of executive abilities such as problem solving, switching, inhibition, fluency, and working memory.

Next, we constructed a structural equation model (SEM) of the executive function measures and RT distribution parameters. The model was composed of the four RT distribution indices, all leading to a single component, which then predicted each of the five executive function measures. Covariance between variables was established according to modification indices in the SEM output to achieve good model fit, based on CFI > .95, TLI >.90, and RMSEA < .08, and the chi-square (p > .05). After modification of the model guided by covariance and regression weight recommendations, the present model demonstrated a good fit to the data, CFI = .961, TLI = .918, RMSEA = .087, chi-square = 26.173, p = .071 (Figure 3). Inspection of the model indicates that the age-residualised ex-Gaussian variability parameters (sigma and tau) account for much more of the relationship with aspects of executive functioning than ISD or mu. The combined effect of all RT indices is related to WCST percent perseverative errors, Trail Making number-letter switching, and Color-Word Interference inhibition, with less weight to Verbal Fluency and Digit Span.

As a final step, we investigated age-related differences in the relationship between the most prominent RT parameter (tau) and executive functions. We used the regression weights from the SEM to construct executive function factor scores by multiplying the standardized regression weights by the raw neuropsychological scores (for a similar procedure see Souchay, Isgrinrini, & Espagnet, 2000; Taconnat et al., 2006). An executive function composite score was then created by adding these weighted scores together. Note that the standardized regression coefficients for this composite score were first multiplied by −1 to convert the latent variable from an executive dysfunction representation to that of an executive functioning characterization. The composite scores were also re-scaled to present all values with positive valence. Bivariate correlations were then calculated, separately for each age group, between our executive function composite score and tau. The results yielded a significant relationship only for the old-old group, r = −.543, p = .006, but not for the young, r = .044, p = .839, or young-old, r = .131, p = .543 (Figure 4);(The correlation between the EF composite and the other ex-Gaussian parameters was not significant at any age group independently. Only when the whole sample was combined did the association between the EF composite and mu and tau reach statistical significance.).

**Discussion**

**Aging Effects**

In the present study, we replicated prior findings of age-related declines in sustained selective attention using measures of mean response time, accuracy, and response time IV. Our data showed age-related differences in RT, target misses, and in false alarms, which are in line with prior research on attention declines in healthy aging (Giambra, 1993; Parasuraman & Davies, 1977; West et al., 2002). We found a significant aging effect, with greater RT ISD in each successive age group from the young through the young-old, to the old-old group with the highest RT ISD. This is in agreement with the literature on aging and within-person variability (Hultsch et al., 2002; Hultsch et al., 2008). Several studies have reported greater within-person variability with age across a multitude of attention tasks, including finger tapping, simple RT, choice RT, and choice one-back (Bielak, Hultsch, Strauss, MacDonald, &
More relevant to the present study is that research involving vigilance tasks has also confirmed the variability and aging effect (Bunce, 2001; MacDonald, Hultsch, & Bunce, 2006; O’Halloran, Finucane, Savva, Robertson, & Kenny, 2014). Similar to the observed effects on mean RT and ISD, significant linear age differences were found for the ex-Gaussian parameters mu and tau, but not sigma. Again, this is consistent with the literature demonstrating elevated mu and tau in older adults compared to younger adults (West et al., 2002).

We inferred that strategy differences in tapping the cards could be detected by examining x-coordinate ISD. By this logic, a low x-coordinate ISD could represent a response profile of locking one’s hand over a specific region of the screen and tapping a similar location each time a card passed beneath. No significant aging effect was found for x-coordinate ISD. This finding suggests that young adults were no more likely to employ such a strategy than were older adults. As far as we are aware, this is the first attempt to examine whether strategy differences account for age-related increases in IIV. Our data do not suggest that group strategy preferences in completing the present attention task play a role in age-related differences in RT IIV.

Executive Functions and Response Time Distribution Indices

The structural equation model indicates that combined RT distribution indices (RT-ISD, mu, sigma, and tau) contribute distinct associations with neuropsychological measures of executive functioning. The SEM shown in Figure 3 reveals that the ex-Gaussian parameters tau and sigma are most strongly associated with poor performance on WCST PPE, Trail Making number-letter switching, and Color-Word Interference inhibition. The present findings reveal a significant association between RT-ISD/tau and aspects of executive functioning individually. However, the inclusion of all
four distribution indices into the SEM led to a small contribution of RT-ISD to executive functioning. Tau emerged more prominently as an explanatory variable associated with cognitive performance. This finding is supported by research suggesting that the driving force of RT-ISD as a measure of interest is derived from the tau distribution component (Williams et al., 2005). These results indicate that ex-Gaussian variability (sigma and tau), and particularly those slow RTs at the tail of the distribution, is linked to aspects of executive functioning, such that greater variability is associated with higher perseverative tendencies, lower switching efficiency, and inferior inhibition ability.

Our results are broadly similar to Tse et al. (2010) who also reported an SEM and correlations between tau and neuropsychological tests. First, in terms of their SEM, Tse and colleagues used working memory capacity exclusively as their cognitive measure, which was evaluated through reading span, letter span, and computation span tasks. Our data replicated their finding of a stronger SEM regression weight for tau, compared to sigma and mu. Moreover, the present findings extend this greater tau relationship to a broader range of executive function abilities, beyond just working memory. Second, in terms of correlations, Tse et al. (2010) detected significant associations of tau with Digit Span, Word Fluency, and Trail Making Test part B. Comparatively, the present analysis revealed a significant correlation between tau and our executive function composite score, but only in the oldest age group. The examined relationship differs in that our weighted executive function composite contained measures from the WCST and Color-Word Interference test, which were not tested by Tse et al. Furthermore, Digit Span and Verbal Fluency in our composite were included with relatively weak contributions to the final score. It should be noted that disparity in the range of executive scores between the age groups could have contributed to the correlation differences observed.

In both the SEM and the correlations presented by Tse et al. (2010), their analyses suggest a stronger association between tau and working memory measures than in the present study. A first plausible explanation for this discrepancy is that complex span tasks, such as those used by Tse et al. (2010), are more sensitive measures of working memory than Digit Span. Secondly, in the creation of our SEM, we removed the effects of age prior to establishing the relationships between variables. Thus, it is possible that the outcome would have been different had a sample composed strictly of older adults been used. Lastly, their study had greater power to detect significant effects, with a sample size of over 200 in their healthy older adult group. Regardless, we have shown that the relationship between RT distribution parameters and cognition extends beyond just working memory to include other aspects of executive functioning. Future research may benefit from the inclusion of both experimental measures of cognition, along with traditional neuropsychological tests in evaluating the correspondence between the variables discussed.

It is worth considering how the effects we found in healthy older adults might compare to those in seniors with brain pathology. Presumably our findings would be strengthened with such a participant group. In fact, Tse et al. (2010) found stronger relationships between tau and most neuropsychological measures in their cognitively impaired group compared to healthy older adults. Another study on mild cognitive impairment found that participants with multiple domains of impairment were more variable in their RT performance compared with those who were deficient in only a single domain (Strauss, Bielak, Bunce, Hunter, & Hultsch, 2007). For older adults with difficulties in two or more non-memory domains, increased variability was most evident on the more cognitively demanding tasks requiring executive ability. These tasks required

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**Figure 4.** Correlation between tau and executive function composite score by age group.
manipulation of information, switching cognitive set, or inhibiting automatic responses. The same authors reported a modest correlation between executive measures (reasoning and fluency) and response time inconsistency in their group of non-memory multiple domain impaired participants. Moving along a range from healthy to significant cognitive impairment may be accompanied by increases in response time IV, more specifically in tau. Future research is required to explore this hypothesis.

Frontal lobe integrity may be an important link between executive functions and tau. Not only is the literature in agreement that the prefrontal cortex endures atrophy through the normal aging process (Fjell et al., 2009; Meguro et al., 2001; Resnick et al., 2003; Tisserand et al., 2002), but there is also considerable evidence of a brain-behavior relationship between the prefrontal lobes and executive function decrements in the ageing literature. In the context of age-related brain changes, aspects of executive functioning have been linked to prefrontal cortex atrophy (Gunning-Dixon & Raz, 2003; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998), volume of prefrontal white matter hyperintensities (Gunning-Dixon et al., 2003; Van Petten et al., 2004), and prefrontal fractional anisotropy (a measure of white matter integrity) (Grieve, Williams, Paul, Clark, & Gordon, 2007).

Even more convincing is that recent research has shown that greater white matter volume was associated with less IV and smaller tau, especially in frontal and default network regions (Jackson, Balota, Duchek, & Head, 2012).

Ratcliff’s diffusion model for one-choice RT tasks may also provide unique insights into the present data set (Ratcliff & Van Dongen, 2011). According to this diffusion model, response time is composed of encoding time, decision time, and response execution time. When engaging in a one-choice RT task, evidence is accumulated in the decision process, from a starting point to a decision criterion, prior to making a response. The rate of accumulation of evidence is termed the drift rate, which varies across trial. Applying a computational cognitive process model such as this one may allow for the separation of these different processing aspects and account for both response time measures and accuracy in performance. This alternate approach could provide additional insights into differences between how older and younger adults process information in an attentionally demanding RT task.

Conclusions
This study confirmed age-related elevations in RT ISD as well as in ex-Gaussian parameters (mu and tau). The motivation behind designing the present task was to achieve a greater level of ecological validity in measuring cognitive control. Our findings are suggestive of real world consequences to heightened variability in older adults, but we do not yet have the data to confirm this. Ongoing research in our lab includes measures of predictive validity. Importantly, the present results showed that aspects of executive functions are most strongly associated with RT distribution indices sigma and tau, after controlling for the effects of age. However, when the relationships were examined between age groups, tau and executive functioning demonstrated a significant correspondence only in older adults between 75 and 85 years. We suggest that those neural processes involved in the cognitive control of attention, leading to greater rightward skew, overlap with those responsible for at least a subset of executive mechanisms. Research has demonstrated the utility of IV in discriminating healthy aging from cognitive impairment as in early Alzheimer’s disease (Duchek et al., 2009). The present results more specifically could have important clinical significance in terms of diagnosing executive impairment based on RT inconsistency in addition to classical neuropsychological measures.

Funding
B. Vasquez and this research was supported by scholarships from the Heart and Stroke Foundation Canadian Partnership for Stroke Recovery, the Natural Sciences and Engineering Research Council of Canada, as well as by the Ontario Research Coalition.

Acknowledgments
We would like to thank C. Morris for programming the attention task and M. Simone for her help with data collection.

References


