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Comparing Individual Differences in Inconsistency and Plasticity as Predictors of Cognitive Function in Older Adults

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Abstract

Introduction—Recent theorizing differentiates key constraints on cognition, including one's current range of processing efficiency (i.e., flexibility or inconsistency) as well as the capacity to expand flexibility over time (i.e., plasticity). The present study uses intensive assessment of response time data to examine the interplay between markers of intraindividual variability (inconsistency) and gains across biweekly retest sessions (plasticity) in relation to age-related cognitive function.

Method—Participants included 304 adults (aged 64 to 92 years: M=74.02, SD=5.95) from Project MIND, a longitudinal burst design study assessing performance across micro and macro intervals (response latency trials, weekly bursts, annual retests). For two reaction time measures (choice RT and one-back choice RT), baseline measures of response time (RT) inconsistency (intraindividual standard deviation (ISD) across-trials at the first testing session) and plasticity (within-person performance gains in average RT across the 5 biweekly burst sessions) were computed, and then employed in linear mixed models as predictors of individual differences in cognitive function and longitudinal (6 year) rates of cognitive change.

Results—Independent of chronological age and years of education, higher RT inconsistency was associated uniformly with poorer cognitive function at baseline and with increased cognitive decline for measures of episodic memory and crystallized verbal ability. In contrast, predictive associations for plasticity were more modest for baseline cognitive function and were absent for 6-year cognitive change.

Conclusions—These findings underscore the potential utility of response times for articulating inconsistency and plasticity as dynamic predictors of cognitive function in older adults.

Keywords

inconsistency; flexibility; variability; plasticity; aging; cognition; cross-sectional; longitudinal; linear mixed models

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Traditionally, studies of human development have assumed that outcome measures represent enduring, stable characteristics of an individual (e.g., intellectual abilities, personality traits). Consequently, mean levels of performance or single sample measurements have been used almost exclusively as primary outcomes of interest (Williams et al., 2005). This general stability perspective assumes within-person variation in level of performance to represent intrinsic testing error, and should be interpreted as experimental ‘noise’. Nesselroade (1991) proposed an alternate model of development characterized by the interplay between intraindividual change (e.g., year-to-year changes in ability), and intraindividual variability (e.g., moment-to-moment variations in performance). Building upon this seminal differentiation of enduring change vs. more labile variability, numerous recent studies have linked increased variability (e.g., across RT trials for various cognitive tasks – termed RT inconsistency) to both normative and pathological age-related cognitive decline (see MacDonald & Stawski, 2015). Through this accumulation of evidence on RT inconsistency as a potential proxy for cognitive process or central nervous system (CNS) function, we have come to appreciate that an exclusive emphasis on central tendency may represent an oversimplification of performance patterns (e.g., Nesselroade, 1991). As within-person variability increases (e.g., inconsistent responses across RT trials), single-trial assessments or mean-level differences in performance may be insufficient for accurately characterizing behaviour (e.g., Hultsch, Strauss, Hunter, & MacDonald, 2008; MacDonald, Li, & Bäckman, 2009). Although the stability perspective remains the dominant one, a clear momentum toward examining variability as forethought rather than afterthought for the study of adult development and aging is evident (cf., Diehl, Hooker, & Sliwinski, 2015).

Li and colleagues (2004) proposed a taxonomy in which several subtypes of variability are associated with different stages of skill acquisition. These stages follow a continuum from initial learning to acquired functioning. In general, as expertise increases, variability in performance decreases. This model implies that variability associated with the early acquisition of a skill is potentially quite different than the variability observed about the average performance once asymptote of the skill has been reached (e.g., Siegler, 1994). Therefore, there are likely different types of intraindividual variation associated with different phases of learning. For example, greater fluctuations during the acquisition phase may reflect diversity processes (e.g., novel exploratory behaviour and strategy use), adaptive shifts in performance (e.g., reactive shifts in response to external stimuli or internal states), or functional plasticity (e.g., training gains). In contrast, persistent fluctuations despite experience with a task are hypothesized to reflect a lack of processing robustness and maladaptive functioning. Recent studies have demonstrated that RT inconsistency (intraindividual variability across response latency trials of cognitive tasks) is significant in magnitude (relative to interindividual differences), is a relatively stable trait-like characteristic, and may function as a predictor of longitudinal rates of change (e.g., Bielak, Cherubin, Bunce, & Anstey, 2013; Hultsch et al., 2000, 2008; MacDonald et al., 2012; Nesselroade & Salthouse, 2004; Rabbitt, Osman, Moore, & Stollery, 2001).

Epidemiological and population-based studies of adulthood and aging have demonstrated individual differences in levels of performance for cross-sectional studies across a range of cognitive abilities (e.g., Rönnlund & Nilsson, 2006; Rönnlund, Nyberg, Bäckman, &

Nilsson, 2005), as well as variability in rates of change in longitudinal studies (e.g., DeFrias, Lövdén, Lindenberger, & Nilsson, 2007; Lindenberger & Ghisletta, 2009). Various factors have been proposed to exert beneficial influences on cognitive functioning in older adults, including physical activity, social engagement, and cognitively stimulating lifestyles (Bäckman, Small, Wahlin, & Larsson, 2000; Hertzog, Kramer, Wilson, & Lindenberger, 2009; Hultsch, Hertzog, Small, & Dixon, 1999; Kramer, Beher, Colcombe, Dong, & Greenough, 2004). However, the underlying mechanisms through which these factors influence cognitive aging remain to be fully characterized. To address these questions, various studies have investigated the mechanisms by which plasticity shapes development at behavioural and neural levels of functioning (Baltes & Singer, 2001; Li, 2003; Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; MacDonald, Nyberg, & Bäckman, 2006; MacDonald et al., 2012). Baltes & Willis (1982), for example, defined cognitive plasticity as the extent to which an individual's task performance is altered pursuant to training or exposure to performance-optimizing conditions. More recently, Park & Reuter-Lorenz (2009) proposed the Scaffolding Theory of Aging (STAC), which suggests that the brain responds to age-associated neural insults by engaging in continuous functional reorganization (plasticity), resulting in self-generated support of cognitive functions. STAC places neurocognitive aging within the context of both plasticity and environmental challenges, providing a broad integrative framework for understanding the relationship between structural and functional changes in the brain (Park & Reuter-Lorenz, 2009).

Lövdén and colleagues (2010) recently proposed a theoretical framework whereby plasticity is driven by a prolonged mismatch between an individual's existing functional supply and environmental demands. In this model, plasticity is conceptualized as the capacity for reactive change within one's current range of functioning (i.e., the capacity for change in flexibility). The related term *flexibility* is used to emphasize the inherently variable nature of cognitive and brain functioning, as well as a range of possible adaptations to environmental demands. Both flexibility and plasticity are assessed within-persons, but are indexed across distinct temporal spans. Similar to Nesselroade's (1991) notion of intraindividual variability, flexibility reflects current function and is thus best indexed across short-term (e.g., trial-to-trial) assessments (cf., RT inconsistency or processing robustness; Li et al., 2004; MacDonald & Stawski, 2015). In contrast, plasticity reflects an ability to benefit from previous exposure or training and is consequently best measured across a longer follow-up period (e.g., weeks, months). Using cognitive function as an example, increased task demands may differentiate performance on measures of executive function for less vs. more flexible individuals, with diminished flexibility characterized by less existing functional supply and less functional adaptability across states. These patterns, along with Lövdén and colleagues (2010) synonyms for flexibility (e.g., functional capacity, brain functioning), parallel explanations offered for the study of brain signal variability (e.g., Garrett, Kovacevic, McIntosh, & Grady, 2013) as well as greater RT inconsistency across response latency trials reflecting a maladaptive process (cf., Li et al., 2004; West et al., 2002). According to Lövdén's mismatch model, functional supply initially responds to increased environmental demands, but later, when supply meets the demands, further impetus for plastic change is lost. From this perspective, stable levels of cognitive performance over defined periods of time can be interpreted as dynamic equilibrium states of reactive change within an individual’s system. A key proposition within the framework is that some unknown duration of the supply-demand mismatch must be reached in order to drive the system away from its current equilibrium state (Bäckman & Dixon, 1992). Although the model does not stipulate the amount of time or training required to elicit plasticity, it does state that the phase of development of a plastic response must be longer than the time it takes to induce the initial and primary plasticity-inducing change. For these reasons, multi-trial, repeated measures designs of cognitive performance have the greatest likelihood of capturing an individual’s range of flexibility and potential plasticity.

In the present study, we operationalized behavioral performance markers of flexibility and plasticity and employed them as predictors of cognitive function for a sample of community-based older adults. Using two reaction time measures (choice RT and one-back choice RT), we computed estimates of RT inconsistency (intraindividual standard deviations across RT trials of the first burst assessment) to index *current* flexibility (higher RT inconsistency reflects diminished flexibility), with within-person slopes of performance gains across the 5 biweekly sessions computed to index plasticity (the capacity for change within one’s current flexibility or range of function). There are several key research objectives. The first involves examining the association between indices of baseline inconsistency and plasticity. Previous taxonomies of intraindividual dynamics (cf., Li et al., 2004) have emphasized the potential importance of both variability and plasticity (e.g., as predictors of cognitive function), but to date, no empirical studies have examined the two classes of predictors concurrently. Performance on a task that is amenable to improvement pursuant to practice may reflect an adaptive form of variability -- functional plasticity (e.g., learning-related gains). Mirroring a basic premise in plasticity research dating back over 100 years (e.g., Baldwin, 1901), we indexed whether performance was altered pursuant to repeated exposure, and moreover whether individuals who exhibited greater plasticity (i.e., showed larger gains across the same period of time) exhibited better cognitive performance and less age-related cognitive decline. In contrast, among examples of maladaptive dimensions of variability, the observation of increased performance fluctuations (variously referred to as RT inconsistency, lability, processing robustness, etc.), particularly for basic cognitive tasks (similar to those employed in the present study), may reflect diminished processing capacity. In the present study, the expectation is that RT inconsistency and plasticity, with higher and lower values respectively linked to deleterious age-related outcomes, will be negatively correlated.

The second research objective will examine RT inconsistency and plasticity as predictors of individual differences in cognitive function at year 6. Although the association between short-term variability and subsequent long-term cognitive change seems intuitive, few studies have examined this link. The question of how short-term variability processes map onto long-term developmental change remains an important and largely undocumented focus in the literature (e.g., Lindenberger & von Oertzen, 2006; MacDonald & Stawski, 2015). A further strength concerns the direct comparison of two competing markers of intraindividual variability: RT inconsistency indexed across RT trials of the first burst assessment to index current flexibility (higher RT inconsistency reflects diminished flexibility) vs. within-person slopes of performance gains across the 5 biweekly sessions computed to index plasticity (the capacity for change within one’s current flexibility or range of function). Further, we expect that observed associations between long-term cognitive change and the predictors of inconsistency and plasticity will vary as a function of task complexity, with larger associations observed for the one-back choice RT task, which requires greater executive control processes (e.g., West et al., 2002).

A final research objective will examine RT inconsistency and plasticity as predictors of 6-year cognitive change. Notably, advantages of the measurement burst design (Nesselroade, 1991; Sliwinski & Mogle, 2008) employed in the present study permit us to examine the potential influences of micro-level processes (e.g., RT inconsistency) on macro-level change (6-year change in neuropsychological function). We expect that increased year 1 RT inconsistency as well as diminished plasticity, both maladaptive manifestations of intraindividual dynamics (Li, Huxhold, & Schmiedek, 2004), will be negatively associated with 6-year cognitive change.

Method

Sample

We analyzed data from a total of 304 community-dwelling older adults (208 females, 96 males), who were between the ages of 64 to 92 years (*M* age = 74.02, *SD* = 5.95) at baseline. All participants resided in the region of Victoria, British Columbia, Canada, and were recruited through advertisements in local media requesting healthy volunteers concerned about their mental functioning. Exclusionary criteria included a diagnosis of dementia by a physician, a Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) score < 24, a history of significant head injury (i.e., loss of consciousness > 5 minutes), other neurological or major medical illness (e.g., Parkinson’s disease, heart disease, cancer), severe sensory impairment (visual, auditory), drug or alcohol abuse, a current psychiatric diagnosis, psychotropic drug use, and lack of fluency in English.

Participants provided demographic and self-reported health information during an initial intake interview. In addition to the MMSE, several benchmark cognitive measures were administered, including the Wechsler Adult Intelligence Scale-III (WAIS-III; Wechsler, 1997) Block Design (M=12.19, SD=2.83) and Vocabulary (M=14.61, SD=2.59) subtests, and the North American Adult Reading Test (NAART; M=14.53, SD=8.65; Blair & Spreen, 1989). Estimates of full scale IQ (FSIQ; M=119.63, SD=6.74) were computed based on age-adjusted Block Design and Vocabulary subtests (Sattler & Ryan, 1999), while premorbid IQ (M=119.63, SD=12.59) was based on NAART performance (Blair & Spreen, 1989). Overall, the participants were well educated (*M* = 15.16, *SD* = 3.14), ranging from 7 to 24 years of education, with only 10.2% (*n* = 31) having less than 12 years of formal education. The participants were relatively healthy, with 65.5% (*n* = 199) having 3 or fewer chronic health conditions. The participants’ global cognitive functioning was quite high (MMSE; *M* = 28.74, *SD* = 1.23), but consistent with an independent sample (Victoria Longitudinal Study (VLS)) of older adults recruited from the same geographic population (Dixon et al., 2007). Limited sample attrition was observed, with 84.5% (*n* = 257) of the original sample completing years 2 and 3, 79.6% (*n* = 242) completing years 4 and 5, and 71.4% (*n* = 217) completing year 6.

To examine the impact of attrition, we compared performance at baseline for background characteristics and outcomes measures between individuals who completed the study (n=217) vs. those who attrited (n=87). In terms of demographics, individuals who remained in the study for the entire 6-year period were younger (73.47 vs. 75.40 years, $p < .05$) and had fewer chronic (e.g., heart disease, hypertension, etc) conditions (2.74 vs. 3.39, $p < .01$). No significant group differences were observed as a function of sex or years of education. As expected, those who remained in the study also exhibited superior baseline cognitive performance across the neuropsychological measures (described below, all p's > .01), as well as less inconsistency across RT trials ($p < .001$); groups differences in plasticity were comparable.

Procedure

Potential participants were initially screened for inclusion and exclusion criteria by telephone interview. The study measures were administered across seven sessions (1 group, 6 individual), scheduled over approximately 3 months. The complete test battery was repeated annually, for a total of six waves of data. For each annual wave, the first two sessions were used to obtain demographic and health information, and to administer cognitive measures. Participants then completed a *burst* evaluation, consisting of five individual testing sessions, each scheduled approximately two weeks apart (for waves 2 through 4, only four individual biweekly testing sessions were conducted). During each of the sessions, participants completed a battery of reaction time (RT) tasks, designed to assess short-term fluctuations in response speed. For each annual burst (wave), the RT measures were identical and the order of presentation was invariant across participants.

Cognitive Tasks

Cognitive ability was based on performance on a series of tests assessing different cognitive domains. The battery was administered once per testing wave, using standardized group procedures.

Processing speed—Perceptual processing speed was assessed with the WAIS-Revised Digit Symbol Substitution task (Wechsler, 1981). Participants were presented with a coding key pairing nine numbers (1 through 9), with nine corresponding symbols. The task requires participants to transcribe as many symbols as possible into rows of randomly ordered numbers with empty boxes, in 90 seconds. The number of correctly completed items represented the outcome measure.

Fluid reasoning—Participants' fluid reasoning was assessed with the Letter Series Test (Thurstone, 1962). In this test, participants were presented with sets of letter strings that formed a distinct pattern. The task required participants to inductively decipher the pattern and to generate the next letter in the string that was congruent with the pattern. The number of correct responses generated in 6 minutes from a total of 20 strings of letters was the outcome measure.

Episodic memory—Episodic memory was assessed using a word recall task consisting of immediate free recall of 30 English words (Hultsch, Hertzog, & Dixon, 1990). The word list consisted of 6 words from 5 taxonomic categories (e.g., birds, flowers), presented on a single page in unblocked order. Participants were given 2 minutes to study the list and 5 minutes to write their recall of as many words as possible. The number of correctly recalled words was used as the outcome measure.

Verbal fluency—Participants' verbal fluency was assessed using the Controlled Associations Test (Ekstrom, French, Harman, & Dermen, 1976). Participants were given 6 minutes to generate as many synonyms as possible in response to a set of four target words. Total number of correct synonyms was the outcome measure.

Crystallized ability—Crystallized ability was assessed using a 36-item multiple-choice recognition vocabulary test (Ekstrom et al., 1976). Participants were instructed to select the correct definition of a target word from five possible definitions. Participants were given 10 minutes to complete the test. The total number of correct items was the outcome measure.

Global cognitive functioning—The Mini-Mental State Examination (MMSE; (Folstein et al., 1975) was administered as a measure of global cognitive functioning. Participants responded to a series of basic questions related to orientation (time and place), memory, attention and concentration, language functioning, arithmetic calculations, and visuospatial processing. A total score out of 30 was the outcome measure.

Reaction Time Tasks

Intraindividual variability and plasticity were calculated from response latencies for two multi-trial computer-based RT tasks. The RT tasks varied in complexity and were presented on a laptop with 14″ color screen, interfaced with an external response box. Participants were instructed to emphasize speed in responding to stimuli, while minimizing errors to the best of their ability. Participants' reaction times were recorded to the nearest millisecond (ms). The following RT tasks were administered on 5 occasions at biweekly retest intervals during the year 1 assessment.

Choice RT (CRT) task—Participants were presented with a horizontal row of four plus (+) signs, with a matching arrangement of keys on an external response box. Following a 1000ms delay, one plus sign changed into a box, and the participant was required to press the key corresponding to its location as quickly as possible. The location of the box was randomly equalized across trials. Practice trials ($n = 10$) were administered first, followed by 60 test trials. The latencies and percent correct for the test trials were recorded.

One-back choice RT (BRT) task—The BRT task used the same display, response box, and stimulus presentation design as the CRT task. However, participants were instructed to press the key corresponding to the location of the box on the previous trial as quickly as possible. A total of 10 practice trials and 61 test trials were administered. Because participants made no response on Trial 1, the latencies and percent correct of the remaining 60 test trials were assessed.

Data Preparation

Outliers & missing values—The complete RT data set was examined for outliers by evaluating the distributions of raw latency scores at the level of individual trials. Extremely fast or slow responses likely represent sources of measurement error (e.g., accidental key press), and prior research has suggested valid lower bounds for responses (150 ms; Hultsch et al., 2002). Upper bounds were identified by computing intraindividual means and standard deviations for each task and occasion of measurement. For each individual, any trials that exceeded the mean by three or more standard deviations were removed. A total of 91,200 trials were possible across individual assessments (60 trials per administration of each RT task), sessions (5 biweekly retests), and persons (n=304); 60*5*304 = 91,200) at year 1 for each of the CRT and BRT tasks. For the CRT task, 0.13% of trials were excluded due to missing values, 1.43% due to incorrect responses, and 1.78% due to trimming outliers, leaving 96.65% useable trials. For the BRT task, 0.20% of trials were excluded due to missing values, 10.46% due to incorrect responses, and 2.42% due to trimming outliers, leaving 86.93% useable trials. By applying these data preparation procedures for eliminating outliers, within-subject variation is reduced, thus representing a conservative approach to examining intraindividual variability and cognitive plasticity in RT performance.

Computation of intraindividual variability—A general index of each individual's performance distribution was computed as the across-trial within-person individual standard deviation (ISD) about each individual's mean RT (Hultsch et al., 2008). In order to disentangle systematic from unsystematic sources of variance that may confound interpretations of intraindividual variability, our estimates of RT inconsistency control for a number of key confounds (e.g., polynomial trends for trial-to-trial learning, fatigue, differences in mean RT). Using a multilevel model, total variation for a given RT task was decomposed into between-subject (systematic and unsystematic) and within-subject (systematic and unsystematic) variability, with the index of variability (RT inconsistency) computed as the intraindividual standard deviation of the within-subject unsystematic portion (Hultsch, Strauss, Hunter, & MacDonald, 2008).

$$\mathrm{Y} = a + b(\mathrm{Age\,Group}) + c(\mathrm{Trial}) + d(\mathrm{Age\,Group} \times \mathrm{Trial}) + e.$$

To facilitate comparisons across tasks, the residual scores were converted to standardized T-scores ($M = 50$, $SD \approx 10$). ISD values were then individually averaged across the burst sessions (5 session at baseline, 4 sessions for Waves 2–4) for each RT task, producing one ISD score per task per wave for each individual.

Computation of cognitive plasticity—In accord with the mismatch model (Lövdén et al., 2010), cognitive plasticity was operationalized as within-person RT performance gains across the 5 biweekly sessions for the first year of measurement. Specifically, cognitive plasticity was indexed as individual slopes of cognitive change for the CRT and BRT tasks, derived from 2-level multilevel models of cognitive change (mean response latency for weekly burst assessments nested within individuals). Response latencies (in milliseconds) were analyzed from all correct-response trials.

Statistical Analyses

To investigate the relationship between baseline RT inconsistency and plasticity as predictors of subsequent (year 6) cognitive function, six unique hierarchical multiple regression models, varying in sequential blocked entry, were generated for each of the five cognitive outcome measures (Letter Series, Digit Symbol, Word Recall, Verbal Fluency, Vocabulary). The relative contributions of specific demographic variables (chronological age, years of education), intraindividual variability (CRT ISD, BRT ISD), and plasticity (CRT plasticity, BRT plasticity) were assessed by adding each of the variables into the models as univariate or multivariate predictors of cognitive function.

Multilevel modeling (MLM) was used to evaluate 6-year rates of cognitive change. The focus of MLM is on change at the individual level, which allows for two separate change questions to be asked. First, how does each person change over time at a micro-level (*Level 1; within-individual differences in change*). Second, which variables differentiate individual patterns of change at a macro-level (*Level 2; inter-individual differences in within-individual change over time*). A typical Level 1 model is described by the following equation:

$$\mathbf{Level\ 1}\text{:Cognitive Performance}_{ij}=\beta_{0i}+\beta_{1i}\left(\text{Time in Study}_{ij}\right)+\text{e}_{ij} \quad (1)$$

In this equation, cognitive performance (on a specific measure) for a given individual (*i*) at a given time or measurement occasion (*j*) is a function of that individual's initial level of performance at baseline assessment (the intercept: β_{0i}), and the individual's linear rate of change across number of years in the study (the slope; β_{1i}), plus a residual (e_{ij}). At Level-1, each person's rate of change is represented by a unique individual trajectory (β_{0i}; intercept, β_{1i}; slope).

For Level 2 models, the Level 1 parameters become outcomes that depend on stable between-person sources of variation. Specifically, a typical Level 2 model using age (centered at 75 years), education (categorized,0 or 1, as ≤ or > 12 years of education, respectively), and CRT inconsistency as between-person predictors is represented by the following equations:

$$\mathbf{Level-2}\text{:}\beta_{0i}=\gamma_{00}+\gamma_{01}(\text{Age75})+\gamma_{02}(\text{Education})+\gamma_{03}(\text{CRT ISD})+\text{u}_{0i} \quad (2)$$

$$\beta_{1i}=\gamma_{10}+\gamma_{11}(\text{Age75})+\gamma_{12}(\text{Education})+\gamma_{13}(\text{CRT ISD})+\text{u}_{1i} \quad (3)$$

In equation (2), each individual's intercept (β_{0i}; Initial Status) is modeled as a function of the starting point for the average 75 year-old with ≤ 12 years of education (γ_{00}), plus the average difference for a 1-unit increase in age (in years; γ_{01}) or education (i.e., average difference between ≤ 12 and > 12 years of education; γ_{02}), plus a 1-unit increase in CRT ISD (γ_{03}), plus a random effect (error) reflecting between-individual differences in intercept (u_{0i}). In equation (3), each individual's linear average rate of change in cognitive performance (β_{1i}; slope) is modeled as a function of the average change for a 1-unit increase in time in study for a prototypical 75 year-old with ≤ 12 years of education (γ_{10}), plus the average difference in slope associated with a 1-unit increase in time in study with a corresponding 1-unit increase in age above 75 years (γ_{11}), plus a 1-unit increase in time in study with a corresponding 1-unit increase in education (> 12 years of education) (γ_{12}), plus a 1-unit increase in CRT ISD (γ_{13}), plus a random effect (u_{1i}) that reflects between-person differences in rates of change. To minimize the impact of attrition on our multilevel models, we employed HLM Version 6.08 software and full-information maximum likelihood (FIML) estimation to derive population-based estimates. FIML can efficiently handle missing data by dropping only those specific observations and retaining a participant's remaining data in the analytic model, as opposed to dropping an entire participant's data (i.e., listwise deletion). Thus, analyses reported in our study are based upon all available data from the full sample ($n = 304$).

Results

Associations between Inconsistency & Plasticity

To address the first research objective, correlations between indices of RT inconsistency and cognitive plasticity were computed (see Table 1). Consistent with previous factor analytic work (Bielak et al., 2010; Strauss et al., 2007), we observed strong associations among inconsistency indicators from the CRT and BRT tasks, $r(302) = .68$, $p<.05$, as well as between BRT variability and plasticity, $r(302) = -.61$, $p<.05$. A more modest association was observed among corresponding indicators of plasticity, $r(302) = .21$, $p<.05$.

Inconsistency & Plasticity as Predictors of Individual Differences in Cognition

The second research objective examined the utility of baseline indices of RT inconsistency and plasticity as predictors of individual differences in cognitive function at the last time of testing (i.e., at year 6). To examine the relative contributions of inconsistency and plasticity as predictors, a series of hierarchical regression analyses were conducted employing a sequential blocked order of predictor entry. Demographic variables (age in years, total years of education) were consistently entered in block 1, with blocks 2 and 3 alternating the order of entry for RT inconsistency and plasticity to ascertain whether one (e.g., CRT inconsistency) yielded a unique predictive influence independent of the other (e.g., CRT plasticity) on year 6 cognitive function for the five outcome measures (letter series, digit symbol, word recall, verbal fluency, vocabulary).

Table 2 displays the predictive influence of RT inconsistency indices at baseline on year 6 cognitive function. Block 1 variables (age and education) accounted for the largest proportion of variance for each of the five cognitive outcomes measures (digit symbol = 24.5%, letter series = 26.8%, word recall = 13.6%, verbal fluency = 10.7%, vocabulary = 6.4%). Age uniquely contributed to digit symbol ($\beta = -.497$, $p<.001$) and word recall (age: $\beta = -.343$, $p<.001$), Education uniquely contributed to vocabulary ($\beta = .234$, $p<.01$), while both age and education each contributed significantly to performance on letter series (age: $\beta = -.409$, $p<.001$; education: $\beta = .232$, $p<.001$), and verbal fluency (age: $\beta = -.197$, $p<.01$; education: $\beta = .220$, $p<.01$). When subsequently entered in block 2, both CRT ISD (see

Table 2, model 1) and BRT ISD (see Table 2, model 3) inconsistency were significantly predictive of year 6 cognitive performance for each of the five outcome measures. The reported regression coefficients were uniformly negative, indicating that as year 1 inconsistency values increased, participants' subsequent cognitive performance decreased. Across the five cognitive outcomes and independent of age and education, inconsistency in CRT accounted for 2.4 to 7.6% of the variance, with BRT ISD inconsistency accounting for between 4.4 to 14.4% of the variance. Even when the CRT and BRT inconsistency predictors were entered in the last block (block 3 – see Table 2, models 2 and 4), increased inconsistency remained a uniformly significant predictor of individual differences in year 6 cognitive function independent of age, education (block 1), and plasticity (block 2). Regardless of order of entry, RT inconsistency accounted for additional variance, above and beyond that which can be explained by the effects of age, education, and plasticity.

To facilitate direct comparison, Table 3 displays the corresponding predictive influence of CRT and BRT plasticity indices, computed across the year 1 biweekly retest assessments, on year 6 cognitive function. Although cognitive plasticity emerged as a predictor of individual differences in year 6 cognitive function, its effects were limited and selective relative to the inconsistency indices. For example, as shown in Table 3 (model 1), CRT plasticity did not account for unique variance independent of the block 1 demographic variables. In contrast, when entered in block 2 (see Table 3, model 3) the more cognitively demanding BRT plasticity index accounted for a significant proportion of additional explained variance for four out of five cognitive measures (2.7% for digit symbol, 10.7% for letter series, 2.7% for word recall, and 1.6% for vocabulary). Notably, the uniformly positive regression coefficients reported in Table 3 indicate that higher levels of year 1 plasticity were associated with higher levels of cognitive functioning at year 6. This unique prediction of BRT plasticity was further moderated by the order of entry into the models, accounting for a greater proportion of variance when entered prior to the BRT ISD predictors (i.e., in block 2 vs. block 3). With the exception of word recall (Table 3, model 2) and letter series (Table 3, model 4), neither CRT nor BRT plasticity accounted for unique variance above and beyond age, education, and inconsistency. Overall, the hierarchical regression findings indicate that individuals who exhibited greater inconsistency and, to a lesser extent, lower plasticity at baseline were more likely to exhibit poorer cognitive function 6 years later.

Inconsistency as a Predictor of 6 Year Cognitive Change

Table 4 shows results for two models, CRT ISD and BRT ISD inconsistency indices, as predictors of cognitive change. At baseline, Age (γ_{01}) exhibited select effects on cognitive performance independent of all other predictors in the model. Education (γ_{02}) exhibited uniform effects for all cognitive measures, with >12 years of education conferring higher baseline cognitive performance. Greater inconsistency at baseline was also associated with poorer cognitive performance at the initial year of assessment. For example, per each 1-unit increase in BRT ISD, the average 75 year-old recalled 0.44 fewer words on the word recall task at baseline (γ_{03}).

No evidence for significant change in cognitive function across the 6 year period was observed for any of the five cognitive outcome measures, likely reflecting both the select nature of the sample as well as the influence of practice effects common in measurement burst designs. However, despite the absence of significant average change, corresponding level 2 random effects for slope (u_{1i}) were significant for all outcomes except letter series, suggesting heterogeneity in variance (i.e., significant individual differences in rates of change). Accordingly, we explored predictors for both CRT ISD and BRT ISD models (see Table 4). Select effects were observed for age and inconsistency as predictors of 6-year rates of cognitive change. For each additional year in study and each additional year older than 75 years of age (γ_{11}), age significantly and negatively moderated rates of change for letter series, word recall, and verbal fluency. CRT ISD inconsistency (γ_{13}) selectively moderated individual rates of cognitive change for word recall and vocabulary, while BRT ISD (γ_{13}) only moderated change for word recall. For example, with each additional year in study and a corresponding 1-unit increase in CRT inconsistency, the average 75 year old's slope decreased by 0.06 units ($p_{\text{diff}} < .01$) on word recall (i.e., increased inconsistency was associated with declining cognitive function). There were no significant effects of education (γ_{12}) on rates of change for any of the cognitive tasks.

Cognitive Plasticity as a Predictor of 6 Year Cognitive Change

To assess whether indices of plasticity predicted 6 year cognitive change, additional multilevel models were computed (see Table 5) that substituted level-2 predictors for CRT plasticity and BRT plasticity. Consistent with patterns and interpretations discussed for the previous models, significant differences in baseline age (γ_{01}) and education (γ_{02}) were observed (see Table 5). Further, significant positive differences were found for baseline indices of plasticity for all cognitive measures except vocabulary. For example, per each 1-unit increase in CRT plasticity, the average 75 year-old transcribed 0.16 more symbols on digit symbol. Limited effects on rates of change (β_{1i}) were found, with age emerging as the sole significant predictor. Neither CRT plasticity nor BRT plasticity predictors exerted significant moderating effects on rates of 6 year cognitive change, independent of chronological age or years of education. Significant random effects indicated that individual differences remained to be explained for both intercepts (u_{0i}) and rates of cognitive change (u_{1i}) for all measures except letter series.

Discussion

Our purpose in the present study was to explore the relationship between inconsistency and plasticity in older adulthood and to extend current knowledge of the longitudinal nature of these phenomena. Specifically, we investigated (i) the association between indices of inconsistency and cognitive plasticity, (ii) whether baseline inconsistency and plasticity predicted cognitive function after 6 years, and (iii) whether baseline inconsistency and plasticity predicted longitudinal rates of cognitive change across 6 years.

Associations among Indices of Inconsistency and Plasticity

Consistent with expectations, strong associations among inconsistency indicators were found. These results corroborate previous research showing significant moment-to-moment intraindividual fluctuations in cognitive performance on psychomotor reaction time tasks (Bielak et al., 2010; Hultsch et al., 2000; MacDonald et al., 2003; Nesselroade & Salthouse, 2004; Rabbitt, Osman, Moore, & Stollery, 2001). Strong links between indices of inconsistency and plasticity were also found for the more complex one-back choice RT task (i.e., BRT), suggesting unique but related relationships exist between these constructs. It is likely that the increased cognitive demands on the BRT task, including greater working memory, attention, and inhibitory control, highlighted individual differences in flexibility and plasticity to a greater extent than the more basic CRT condition. The modest links found between markers of plasticity may reflect restriction of range effects for the CRT task in particular (i.e., the simple cognitive demands of the basic choice RT task may have lacked the requisite supply-demand mismatch to induce plasticity). According to the mismatch model (Lövdén et al., 2010), this would suggest that the study participants' functional supply exceeded the environmental demands of the task. With an insufficient supply-demand mismatch, the impetus to push a system away from its dynamic equilibrium is lost, thus limiting the potential for structural and functional changes from occurring.

Inconsistency & Plasticity as Predictors of Year 6 Cognitive Function

Individuals' initial level of RT inconsistency significantly predicted cognitive function 6 years later across each of the five cognitive outcome measures. This trend was generally observed for both CRT and BRT indices of inconsistency (i.e. regardless of cognitive load), and ISD significantly accounted for additional variance despite order of entry into the hierarchical models. These results support previous longitudinal research using a similar community-based sample of older adults, showing significant prediction over 6 years (MacDonald et al., 2003). Consistent with expectations, the pattern of prediction in the current study exhibited an inverse relationship, with increased baseline inconsistency associated with poorer cognitive performance 6 years later. Further, there was some evidence that the predictive relationship for inconsistency was of larger magnitude for measures reflecting the fluid mechanics (e.g., digit symbol, letter series; see Baltes, Lindenberger, & Staudinger, 2006) rather than the crystallized pragmatics (e.g., vocabulary) of cognition, with larger effects observed for the BRT task. Tasks such as processing speed or reasoning that differentially reflect cognitive mechanics more heavily tax basic information processing abilities that are neurophysiologically mediated, whereas tasks reflecting the pragmatics of cognition (e.g., vocabulary) draw more heavily upon the accrual of acculturated knowledge. Baseline cognitive plasticity also emerged as a predictor of cognitive function 6 years later, although its effects were more limited and selective. With the exception of Word Recall, CRT plasticity did not significantly account for unique variance above and beyond demographic variables (age, education) and intraindividual variability (CRT ISD) as a predictor. In contrast, the more cognitively demanding BRT plasticity index (i.e., increased attention, working memory, and attentional control demands), accounted for a significant proportion of additional variance for each of the cognitive measures, with the exception of Verbal Fluency. This unique prediction of BRT plasticity was further moderated by the order of entry into the models, with greater predictive power when added prior to the inconsistency predictors. In sum, individuals who are more variable or less plastic at baseline are more likely to exhibit poorer cognitive function 6 years later. Direct comparison of baseline inconsistency and plasticity indicators suggest that the former accounts for more variance in individual differences in year 6 cognitive function.

Inconsistency and Plasticity as Predictors of Cognitive Change

Baseline inconsistency and plasticity were also examined as predictors of longitudinal rates of cognitive change. Five unique two-level multilevel models were developed to investigate mean intraindividual change, as well as interindividual differences in intraindividual change on each of the five cognitive outcome measures. Small, non-significant rates of change were observed for each of the cognitive tasks, indicating relatively stable cognitive function across 6 years for the study sample as a whole. Notably, however, significant random effects were observed both within person and between individuals over time for all outcomes except letter series, suggesting significant heterogeneity in rates of 6 year cognitive change. Further, there were significant age-related differences in average rates of change. With each additional year in study and each additional year older beyond 75 years, the average participant's rate of change significantly decreased on each of the five cognitive tasks. These findings suggest that the initial positive slopes observed on tasks reflecting the mechanics of cognition (e.g., digit symbol, letter series, word recall) gave way to declines in cognitive performance with increasing age. There were no significant effects of education as a moderator on any of the cognitive tasks. Significant between-person differences in rates of intraindividual change were found for all tasks, except letter series. This finding may reflect the more fluid nature of the letter series task and its considerable cognitive difficulty. Inconsistency was found to selectively moderate rates of cognitive change, independent of all other predictors in the model, for word recall and vocabulary. Neither CRT plasticity nor BRT plasticity were found to significantly predict 6 year rates of cognitive change for any of the outcome measures.

The findings from the present study lend support for previous longitudinal research demonstrating considerable inter- and intra-individual heterogeneity in trajectories of cognitive and functional change across the adult lifespan. Inconsistency was found to be a robust predictor of individual differences and rates of change in cognition across a range of domains. These findings are consistent with previous research demonstrating that inconsistency in performance is a stable, endogenous characteristic, associated with the aging process, and predictive of longitudinal cognitive, behavioural, and neurological functioning (Bielak et al., 2010; Burton et al., 2006; Dixon et al., 2007; Hultsch et al., 2000, 2002; MacDonald et al., 2003, 2006, 2008). Similarly, evidence for the stability of inconsistency has shown that the amount of fluctuation in performance on a particular task at one point in time is positively correlated with the amount of inconsistency on that task at a later point in time (Allaire & Marsiske, 2005; Fuentes et al., 2001; Hultsch et al., 2000, 2002; Rabbitt et al., 2001). Additionally, individuals who are more inconsistent across trials on one RT task, are more inconsistent trial-to-trial on other RT tasks, lending support for intraindividual variability as an endogenous mechanism (Fuentes et al., 2001; Hultsch et al., 2000, 2002).

In contrast, measures of plasticity selectively predicted long term cognitive function, but not trajectories of cognitive change. A key proposition within the framework of the mismatch model is that some unknown duration of the supply-demand mismatch must be reached for a system to abandon its current dynamic equilibrium and adopt a state of plastic change. This "sluggish" capacity for reactive change requires prolonged exposure, and/or sufficient repetition, in order to achieve the required mismatch and initiate the adaptive change. Furthermore, if a system can effortlessly respond to challenges with existing resources it will not experience the required supply-demand mismatch. In the current study, it is possible that the RT tasks did not induce a sufficient mismatch to elicit strong predictive associations for the high-functioning, well-educated, participants. Moreover, the number of RT trials at each testing session ($n = 60$) may not have been adequate to induce the primary plasticity-inducing changes. Even with these experimental constraints, BRT plasticity emerged as a unique predictor of long-term cognitive function for a range of domains including perceptual speed, fluid reasoning, episodic memory, and crystallized verbal knowledge.

Inconsistency, Plasticity, and the Cognitive Load Hypothesis

In the current study, we expected that the degree of task complexity, or cognitive load, would increase the strength of the relationship between indices of inconsistency and plasticity with measures of long term cognitive function. Specifically, it was predicted that the one-back choice RT task, which requires greater executive control processes (i.e., monitoring, updating, inhibiting), would be associated with greater plasticity and inconsistency (Shammi et al., 1998; Stuss et al., 2003; West et al., 2002). Only the more challenging BRT index of plasticity emerged as a significant predictor of 6 year cognitive function. In contrast, both indices of inconsistency were found to predict 6 year cognitive function, but rates of cognitive change were only associated with measures of episodic memory (word recall) and verbal knowledge (vocabulary). A number of explanations may account for these select findings of increased cognitive load and its predictive relationship to cognitive function. West and colleagues (2001; 2002) proposed the frontal lobe hypothesis of cognitive aging, and suggested that age-related deficits in the functioning of the prefrontal cortex results in decreased stability of executive control and increases the potential for variability in performance (see also Stuss et al., 2003). Further, reduced executive control is associated with increased lapses of “intention.” These lapses result in prolonged latencies, resulting in much greater positively skewed RT distributions (compared to younger adults), and increasing an individual’s overall level of performance inconsistency. A similar explanation by Bunce and colleagues (1993) suggested that aging is associated with an increase in attentional blocks. These blocks result in extended RTs, more positively skewed distributions, and greater performance inconsistency. In addition, recent findings clearly link increasing RT inconsistency for an interference (but not control) condition of an executive task to positron emission tomography (PET) derived estimates of dopamine (DA) binding. Specifically, increasing age and ISDs on the interference condition of the multi-source interference task (MSIT) were linked to diminished DA D_1 binding potential in several brain regions (anterior cingulate gyrus, dorsolateral prefrontal cortex, and parietal cortex) that comprise the cingulo-fronto-parietal dorsal attention network (MacDonald, Karlsson, Rieckmann, Nyberg, & Bäckman, 2012). These findings suggest that dysfunctional DA modulation may contribute to increased age-related variability in cognitive performance. Notably, age-related increases in variability were confined to the interference trials of the MSIT with no complementary patterns observed for mean RTs, supporting claims that the executive demands of a cognitive task modulate the presence of age-related differences in inconsistency (West et al., 2002). In sum, this evidence suggests that within-task inconsistency may reflect a breakdown in executive and attentional control systems that are necessary to maintain goal-directed behaviour and regulate competing cognitive processes.

Limitations and Conclusions

Although the present results are novel and among a small number of studies to demonstrate the relationship between plasticity, inconsistency, and longitudinal cognitive function, they are not without limitations. First, despite the large number of community-based study participants, the sample was composed of a relatively homogenous population of healthy, highly educated individuals. This, coupled with positive selectivity due to attrition as well as generalized practice effects, may account for the modest individual differences in variance of change over 6 years. Use of cognitive ability measures that were designed to be psychometrically stable, and generalized practice effects may also account for observed individual differences at year 6, as well as limited declines in performance over time, with the study participants benefitting from the 1 year retest interval and burst testing sessions. Finding significant results with a well-educated and healthy sample bolsters the present results and suggests replication attempts in more diverse and less healthy samples (including those characterized by even greater levels of attrition) potentially would show even stronger effects. Although some theorists attempt to statistically control for practice effects, we side with theorists who criticize such attempts, underscoring that development and retest effects are perfectly confounded and thus cannot be easily disentangled through statistical modeling (cf., Sliwinski & Mogle, 2008). Next, there were only two indicators of inconsistency and plasticity, both derived from psychomotor tasks. Analyses using higher order or more executive-based RT tasks (e.g., a switching RT task) may demonstrate a different pattern of change. Additionally, the one-back manipulation may not have been sufficient to yield a supply-demand mismatch and assessment of plasticity according to the model proposed by Lövdén and colleagues (2010), and use of n-back variants placing greater demands on cognitive resources could provide a more sensitive examination of the effects of plasticity (e.g., Verhaeghen, Cerella & Basak, 2004). However, given past findings regarding task complexity (Bielak et al., 2010; Bunce et al., 2004; West et al., 2002), the pattern using such tasks is predicted to be even stronger, with more pronounced individual differences. It is also possible that a portion of changes in inconsistency and plasticity could be due to individual differences in strategic response behaviour (Ratcliff & McKoon, 2008), or differences in personality traits and motivational factors (Duchek, Balota, Storandt, & Larsen, 2007). Future research should strive to identify potential mechanisms (e.g., cognitive processes such as the setting of a response criterion) that underlie observed patterns of inconsistency and plasticity; experimental manipulation of such mechanisms can be achieved through use of diffusion models (Ratcliff & McKoon, 2008).

The present study aimed to fill a gap in the knowledge base on how inconsistency and plasticity predict longitudinal change in cognitive function in older adulthood. Independent of chronological age and years of education, higher inconsistency was associated uniformly with poorer cognitive function at baseline and increased cognitive decline for measures of episodic memory and crystallized verbal ability. Predictive associations for plasticity were more modest for baseline cognitive function, and absent for 6 year cognitive change. These findings establish a meaningful relationship between inconsistency, plasticity, and cognitive performance and trajectories of aging-related cognitive change. A shift toward greater characterization of these dynamic factors is warranted, and their utility as proxies of neurological integrity and potential preclinical markers of underlying pathologies (e.g., dementia) represents an important area for future research.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Intercorrelations between Intraindividual Variability (ISD) and Plasticity for Reaction Time (RT) tasks

Variable	**1.**	**2.**	**3.**	**4.**
1. CRT ISD	1			
2. BRT ISD	.675**	1		
3. BRT plasticity	−.385**	−.611**	1	
4. CRT plasticity	−.307**	−.284**	.211**	1

**$p<0.01$;

ISD = intraindividual standard deviation; CRT = choice RT; BRT = one-back choice RT

Table 2

Year 1 RT inconsistency indices predicting year 6 cognitive performance.

		Cognitive Test														
Order of Entry	**Variability Index**	***Digit Symbol***			***Letter Series***			***Word Recall***			***Verbal Fluency***			***Vocabulary***		
		F	$R^2\Delta$	β	***F***	$R^2\Delta$	β	***F***	$R^2\Delta$	β	***F***	$R^2\Delta$	β	***F***	$R^2\Delta$	β
Univariate																
Model 1: **Block 2**	CRT ISD	23.55***	.076	−0.31	16.19***	.052	−0.26	16.78***	.064	−0.28	5.79*	.024	−0.17	13.70***	0.57	−0.27
Model 2: **Block 3**	CRT ISD	21.39***	.069	−0.31	13.61***	.044	−0.25	20.59***	.077	−0.33	7.61*	.031	−0.21	13.00***	.054	−0.27
Model 3: **Block 2**	BRT ISD	32.96***	.102	−0.39	52.12***	.144	−0.47	20.10***	.075	−0.34	10.95***	.044	−0.26	14.64***	.060	−0.30
Model 4: **Block 3**	BRT ISD	24.04***	.075	−0.39	22.90***	.061	−0.36	13.11***	.049	−0.32	12.12***	.048	−0.32	10.60***	.044	−0.30

$^{*}p<0.05$

$^{***}p<0.01$

$^{****}p<0001$;

ISD = intraindividual standard deviation; CRT = choice RT Task; BRT = one-back choice RT task; Block 2 = ISD entered before plasticity; Block 3 = ISD entered following plasticity.

Table 3

Year 1 plasticity indices predicting year 6 cognitive performance.

		Cognitive Test														
Order of Entry	**Plasticity Index**	***Digit Symbol***			***Letter Series***			***Word Recall***			***Verbal Fluency***			***Vocabulary***		
		F	**$R^2\Delta$**	***β***	***F***	**$R^2\Delta$**	***β***	***F***	**$R^2\Delta$**	***β***	***F***	**$R^2\Delta$**	***β***	***F***	**$R^2\Delta$**	***β***
Univariate																
Model 1: **Block 2**	CRT plasticity	*ns*	*ns*	0.08	*ns*	*ns*	0.09	*ns*	*ns*	−0.04	*ns*	*ns*	*−0.05*	*ns*	*ns*	0.06
Model 2: **Block 3**	CRT plasticity	*ns*	*ns*	0.00	*ns*	*ns*	0.03	4.05 *	.015	−0.13	*ns*	*ns*	−0.11	*ns*	*ns*	−0.01
Model 3: **Block 2**	BRT plasticity	7.90**	.027	0.18	36.42 ***	.107	0.35	6.72**	.027	0.17	*ns*	*ns*	0.04	3.81 *	.016	0.14
Model 4: **Block 3**	BRT plasticity	*ns*	*ns*	0.00	8.99 ***	.024	0.19	*ns*	*ns*	0.03	*ns*	*ns*	−0.09	*ns*	*ns*	0.01

$^{*}p$<0.05

$^{***}p$<0.01

$^{****}p$<0001;

CRT = choice RT task; BRT = one-back choice RT task; Block 2 = plasticity entered before ISD; Block 3 = plasticity entered following ISD.

Table 4

Multilevel models of 6 year cognitive change as a function of time in study, age, education & RT inconsistency for CRT and BRT.

CRT Models	Digit Symbol		Letter Series		Word Recall		Verbal Fluency		Vocabulary	
Fixed Effects	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***
Intercept (γ_{00})	37.54***	0.91	7.04***	0.44	14.79***	0.42	10.72***	0.55	28.01***	0.47
CRT ISD (γ_{03})	−1.60***	0.20	−.68***	0.10	−0.56***	0.09	−0.71***	0.12	−0.47***	0.11
Slope (γ_{10})	0.36	0.22	0.00	0.07	0.08	0.10	−0.02	0.13	−0.02	0.06
CRT ISD (γ_{13})	−.02	0.06	0.01	0.02	−0.06*	0.27	−0.01	0.03	−0.04*	0.02
Random Effects										
Intercept (u_{0i})	42.01***	4.69	11.42***	1.11	9.14***	1.00	15.30***	1.73	14.04***	1.26
Slope (u_{1i})	0.64**	0.24	0.01	0.03	0.19***	0.05	0.16*	0.08	0.02**	0.01
Covariance	1.80*	0.79	0.08	0.13	0.33	0.17	0.23	0.29	−0.16	0.12
Residual (e_{ij})	24.25***	1.27	3.49***	0.18	4.87***	0.25	9.25	0.48	2.39***	0.12

BRT Models	Digit Symbol		Letter Series		Word Recall		Verbal Fluency		Vocabulary	
Fixed Effects	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***
Intercept (γ_{00})	38.40***	0.88	7.54***	0.40	15.01***	0.43	11.09***	0.55	28.27***	0.47
BRT ISD (γ_{03})	−1.59***	0.17	−0.88***	0.07	−−0.44***	0.08	−0.68***	0.10	−0.49***	0.09
Slope (γ_{10})	0.37	0.22	−0.01	0.07	0.11	0.10	−0.01	0.13	−0.00	0.06
BRT ISD (γ_{13})	−.02	0.04	0.01	0.01	−0.05*	0.02	−0.01	0.02	−0.01	0.01
Random Effects										
Intercept (u_{0i})	37.71***	4.33	8.58***	0.88	9.32***	1.01	14.63***	1.67	13.52***	1.22
Slope (u_{1i})	0.64**	0.24	0.01	0.03	0.18***	0.05	0.16*	0.08	0.02**	0.01
Covariance	1.78*	0.76	0.13	0.11	0.33	0.17	0.21	0.28	−0.13	0.11
Residual (e_{ij})	24.24***	1.26	3.49***	0.18	4.87***	0.25	9.25	0.48	2.40***	0.12

NOTE: For all multilevel analyses, Age was centered at 75 years and Education was categorized as > or ≤ 12 years of formal education.

γ_{00} = average cognitive performance for a 75 year-old individual with ≤12 years of education at Year-1; γ_{03} = average difference in cognitive performance for a 1-unit increase in variability (CRT ISD, BRT ISD) at year 1; γ_{10} = average amount of cognitive change per year increase of being in the study; γ_{13} = average difference in rate of change associated with a 1-unit increase in time in study with a 1-unit increase in variability (CRT ISD, BRT ISD); u_{0i} = between-person variance in the intercept of cognitive ability; u_{1i} = between-person variance in the slope of cognitive ability; e_{jj} = within-person variance.

[*] $p<0.05$;

[**] $p<0.01$;

[***] $p<0.001$

Table 5

Multilevel models of 6 year cognitive change as a function of time in study, age, education & cognitive plasticity for CRT and BRT.

CRT Models	**Digit Symbol**		**Letter Series**		**Word Recall**		**Verbal Fluency**		**Vocabulary**	
Fixed Effects	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***
Intercept (γ_{00})	37.42***	0.98	6.97***	0.47	14.70***	0.44	10.59***	0.58	27.92***	0.49
CRT plasticity (γ_{03})	0.16**	0.06	0.05	0.03	0.01	0.03	−0.00	0.04	−0.00***	0.03
Slope (γ_{10})	0.37	0.22	0.00	0.07	0.09	0.10	−0.01	0.13	−0.01	0.06
CRT plasticity (γ_{13})	−0.01	0.01	0.00	0.00	−0.00	0.01	−0.00	0.01	0.00	0.00
Random Effects										
Intercept (u_{0i})	51.91***	5.48	13.36***	1.26	10.56***	1.11	17.47***	1.90	15.06***	1.35
Slope (u_{1i})	0.64**	0.24	0.00	0.03	0.20***	0.05	0.16*	0.08	0.02**	0.01
Covariance	1.97*	0.85	0.04	0.14	0.42*	0.18	0.21	0.30	−0.10	0.12
Residual (e_{ij})	24.27***	1.27	3.50***	0.18	4.87***	0.25	9.27***	0.48	2.42***	0.13

BRT Models	**Digit Symbol**		**Letter Series**		**Word Recall**		**Verbal Fluency**		**Vocabulary**	
Fixed Effects	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***
Intercept (γ_{00})	37.50***	0.91	7.04***	0.45	14.76***	0.43	10.65***	0.57	27.96***	0.49
BRT plasticity (γ_{03})	0.06***	0.01	0.03***	0.00	0.02***	0.00	0.02*	0.01	0.01	0.01
Slope (γ_{10})	0.37	0.22	0.00	0.07	0.09	0.10	−0.01	0.13	−0.01	0.06
BRT plasticity (γ_{13})	−0.00	0.00	0.00	0.00	0.00	0.00	−0.00	0.00	0.00	0.00
Random Effects										
Intercept (u_{0i})	46.83***	5.07	11.77***	1.14	9.97***	1.06	17.02***	1.87	14.90***	1.33
Slope (u_{1i})	0.63**	0.24	0.00	0.03	0.19***	0.05	0.16*	0.08	0.02**	0.01
Covariance	2.06*	0.81	−0.02	0.13	0.39*	0.18	0.24	0.30	−0.13	0.12
Residual (e_{ij})	24.28***	1.27	3.50***	0.18	4.87***	0.25	9.27***	0.48	2.41***	0.12

NOTE: For all multilevel analyses, age was centered at 75 years and education was categorized as > or ≤ 12 years of formal education.

γ_{00} = average cognitive performance for a 75 year-old individual with ≤12 years of education at Year-1; $\leq_{03}$ = average difference in cognitive performance for a 1-unit increase in plasticity (CRT plasticity, BRT plasticity) at year 1; $\leq_{10}$ = average amount of cognitive change per year increase of being in the study; $\leq_{13}$ = average difference in rate of change associated with a 1-unit increase in time in study with a 1-unit increase in plasticity (CRT plasticity, BRT plasticity); u_{0i} = between-person variance in the intercept of cognitive ability; u_{1i} = between-person variance in the slope of cognitive ability; e_{jj} = within-person variance.

[*] $p<0.05$;

[**] $p<0.01$;

[***] $p<0.001$