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Intraindividual Coupling of Daily Stress and Cognition

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Most psychological theories predict associations among processes that transpire within individuals. However, these theories are often tested by examining relationships at the between-persons (BP) rather than the within-persons (WP) level. The authors examined the WP and BP relationships between daily stress and daily variability in cognitive performance. Daily stress and cognitive performance were assessed on 6 occasions in 108 older adults and 68 young adults. WP variability in stress predicted WP variability in response times (RTs) on a 2-back working memory task in both younger and older adults. That is, RTs were slower on high-stress days compared with low-stress days. There was evidence of an amplified WP stress effect in the older adults on a serial attention task. There was no evidence of stress effects on simple versions of these tasks that placed minimal demands on working memory. These results are consistent with theories that postulate that stress-related cognitive interference competes for attentional resources.

Keywords: aging, cognition, working memory, stress, intraindividual variability

There is impressive evidence of stable individual differences on cognitive measures, even across very long time spans (Deary, Whiteman, Starr, Whalley, & Fox, 2004). Accordingly, most theories of intellectual and cognitive function have focused on these stable individual differences for inferences regarding relationships among cognitive processes (e.g., Carroll, 1993). Despite impressive stability in intellectual functioning, individuals do vary in cognitive performance even over very short retest intervals (Hertzog, Dixon, & Hultsch, 1992; Li, Aggen, Nesselroade, & Baltes, 2001). Such "state-based" variability is often relegated to the domain of measurement error and viewed as both a theoretical and a methodological nuisance. However, a number of psychologists have argued that the focused study of intraindividual or within-persons (WP) cognitive variability is critical for understanding developmental cognitive changes (Hultsch & MacDonald, 2004; Nesselroade & Ram, 2004; Siegler, 1994). We concur with this view and hope to demonstrate that modeling WP cognitive variability can facilitate understanding of basic cognitive function.

A number of researchers have postulated that trial-to-trial performance variability is a fundamental characteristic of both brain function and individual differences in human intelligence. Specifically, higher levels of cognitive variability correlate with lower levels of intelligence (Jensen, 1992; Rabbitt, Osman, Moore, & Stollery, 2001). A recent life span study (Li et al., 2004) demonstrated that trial-to-trial variability becomes increasingly predictive of fluid intelligence in older age. Such increased trial-to-trial variability in aging may represent the effects of degraded neural processing efficiency associated with neurological disease (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000) or the aging brain (Li, Lindenberger, & Frensch, 2000).

Salthouse and Berish (2005) identified several reasons why understanding the causes and correlates of WP variability is important on both practical and theoretical grounds. These reasons emphasize how studying WP variability can facilitate understanding of individual differences, or between-persons (BP) variability. We offer an additional reason to motivate direct modeling of WP cognitive variability, namely, that it allows testing hypotheses regarding associations among cognitive processes that transpire within individuals (e.g., Sliwinski & Buschke, 2004; Sliwinski, Hofer, & Hall, 2003). Recently, Borsboom, Mellenbergh, and van Heerden (2003; see also Molenaar, Huizenga, & Nesselroade, 2003) argued that analysis of BP individual differences is not theoretically informative regarding patterns of associations among psychological processes that operate within individuals. Their argument suggests that psychologists are often guilty of a type of "ecological fallacy" (Robinson, 1950) by assuming patterns of associations observed at the BP level of analyses also exist at the WP level. Molenaar (2004) forcefully argued that only under very strict conditions can "a generalization be made from the structure of interindividual variation to the analogous structure of intraindividual variation" (p. 201). Therefore, an important, yet often neglected, step in psychological research is to translate hypotheses from the BP level of analysis to the WP level.

Although a number of studies have conducted BP analyses to examine why some individuals are more variable than others, there is little empirical work involving WP analyses of why an individual's cognitive performance is sometimes better than at other times. There is, however, both theoretical and empirical support to

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motivate examination of stress as a reliable predictor of WP cognitive variability. Since McEwen, Weiss, and Schwartz's (1968) discovery of glucocorticoid (GC) receptors in the rat hippocampus, much research has been directed at understanding how cortisol (a GC that is secreted more rapidly during a physiological stress response) can influence memory performance. Elevated levels of cortisol are observed following the experience of major negative life events (Rose, 1984) as well as following even minor daily hassles (Smyth et al., 1998). In general, the findings from corticosteroid infusion and oral administration studies (Kirschbaum, Wolf, May, Wippich, & Hellhammer, 1996; Newcomer et al., 1999; Wolf, Schommer, Hellhammer, McEwen, & Kirschbaum, 2001; see Lupien & McEwen, 1997, for a review), as well as from longitudinal studies (Lupien et al., 1994, 1998), have consistently shown cortisol-related memory deficits. Recent research has identified a high concentration of corticosteroid receptors in the frontal lobe (Murros, Fogelholm, Kettunen, & Vuorela, 1993), suggesting that the physiological stress response may also impact frontal or executive cognitive functions, such as working memory (Kane & Engle, 2002) and mental set shifting (e.g., DiGirolamo et al., 2001; Rushworth, Hadland, Paus, & Sipila, 2002).

The research linking cortisol and cognition does not, however, establish an association between the experience of stress and cognitive impairment. However, there is some evidence to suggest that the experience of stress competes for attentional resources and thereby impairs attention-dependent cognitive processing (Kahneman, 1973). Specifically, this view predicts that stress will impair effortful or controlled processing but leave intact processing that does not place heavy demands on attentional control. That is, stress should not impair performance that relies on chronically or immediately accessible information but should impair performance that relies on information that lies outside of the focus of attention (Garavan, 1998; McElree 2001; Verhaeghen & Basak, 2005). In a related line of reasoning, Klein and Boals (2001a, 2001b) have postulated that stress-related cognitions (i.e., intrusive thoughts, thought suppression) occupy attentional resources and thereby produce deficits in information processing that rely heavily on controlled attention (see also Eysenck & Calvo, 1992). For example, life events stress has been shown to correlate with decision making (Baradell & Klein, 1993), problem solving (Klein & Barnes, 1994), working memory (Klein & Boals, 2001a), and inductive reasoning (Yee, Edmonson, Santoro, Begg, & Hunter, 1996). An intervention study (Klein & Boals, 2001b) demonstrated that college students who underwent a stress-management intervention improved their working memory scores significantly more than a control group.

This line of research suggests not only that "usable [working memory capacity] is not a static variable" (Klein & Boals, 2001a, p. 531) but that it might fluctuate as a function of experienced stress. Hasher and Zacks (1988; Hasher, Zacks, & May, 1999) have similarly argued that when there is deficient inhibitory control over the contents of working memory, this results in "mental clutter" in which extraneous (off-task) thoughts can interfere with goal-relevant thoughts. Although Hasher and Zacks's theorizing emphasized aging as a primary cause of inhibitory deficiency, their reasoning implies that whenever such a deficiency is present (e.g., from stress), cognitive performance will suffer.

This brief review of the literature on stress and cognition can be summarized as supporting an *attention-depletion hypothesis*. Because this hypothesis pertains to the interaction of psychological processes that transpire within individuals, it demands verification at the WP level of analysis. This hypothesis predicts that individuals should have more available attentional resources when their stress is low compared with when their stress is high. This reasoning leads to the prediction of a negative relationship between the experience of stress and cognitive performance within individuals when those individuals are performing attention-demanding tasks, but no relationship when performing low-demand tasks.

A number of experimental studies have demonstrated a negative effect of laboratory stressors on cognitive performance within individuals. However, these laboratory studies have yielded inconsistent results, with some studies showing the predicted effect (Jelicic, Geraerts, Merckelbach, & Guerrieri, 2004; Lupien et al., 1997; Payne, Nadel, Allen, Thomas, & Jacobs, 2002; Sorg & Whitney, 1992) and other studies showing no stress effect on cognitive performance (Domes, Heinrichs, Reichwald, & Hautzinger, 2002; Hoffman & Al'Absi, 2004; Kuhlmann, Piel, & Wolf, 2004; Wolf et al., 2001). Deleterious effects of stress on cognitive performance are most consistently demonstrated using paradigms that use task-relevant manipulations (e.g., time pressure, task difficulty) to induce stress (Chajut & Algom, 2003; Van Gemmert & Van Galen, 1997). However, there is evidence that experimental stressors do not produce the same patterns of stress responsivity as do naturally occurring stressors (Van Eck, Nicolson, Berkhof, & Sulon, 1996). Moreover, task-relevant manipulations, such as time pressures, produce stress that is highly related to task performance and therefore very likely to produce interfering effects. However, a number of studies (Baradell & Klein, 1993; Klein & Barnes, 1994; Klein & Boals, 2001a, 2001b; Yee et al., 1996) have shown that life stress that is not directly relevant to performance negatively correlates with attention-demanding cognitive tasks. For example, Klein and Boals (2001a, 2001b) have shown that college students who reported high levels of stressful events during the 6 months preceding cognitive testing performed worse on a working memory task than did students who reported fewer stressors. The primary goal of the present study was to extend this work by providing the first examination of the relationship between naturally occurring daily stress and cognitive performance at the WP level of analysis.

In order to examine the WP association between stress and cognitive performance, it is important to select measures of both that would exhibit variability over relatively short time intervals. As the type of life events stress measured by Klein and colleagues focuses on major, infrequent occurrences that do not exhibit much WP variability over short intervals (e.g., Baradell & Klein, 1993; Klein & Barnes, 1994; Klein & Boals, 2001a; 2001b), we opted to use a measure that was specifically designed to examine variability in the daily experience of stress. We selected the semistructured Daily Inventory of Stressful Experiences (DISE; Almeida, Wethington, & Kessler, 2002) because it is relatively quick to administer and has been used extensively with both younger and older adults (Almeida & Horn, 2004). We acknowledge that day-to-day stressors (e.g., having an argument) differ in kind from major life events (e.g., marriage) that produce enduring intrusive thoughts that persist over months and years. However, cognitive performance in close temporal proximity to the occurrence of daily stressors does not require that stress-related cognitive interference persist for more than a few hours. If the attention-depletion hypothesis is correct, then any stressor, even relatively mild daily hassles, should draw on limited attentional resources and influence cognitive performance. Showing that fluctuations in the experience of relatively mild daily stressors predict WP cognitive variability could provide a strong test of the attention-depletion hypothesis.

We selected two tasks to measure short-term WP cognitive variability. These tasks were selected in order to provide a method of testing the specificity of the attention-depletion hypothesis by showing stress-related deficits only on high-attention-demanding tasks, and no stress impairment on less demanding tasks. The first task was a variant of the *n*-back task (Awh et al., 1996) that is often used to assess working memory and attention switching (McElree, 2001; Verhaeghen & Basak, 2005). This version of the *n*-back consisted of displaying a sequence of single digits on a computer display and required participants to determine whether the displayed digit matched the *n*th digit back in the sequence (where $n = 1$ or 2). The second was a serial attention task based on Garavan's (1998) running counting procedure that requires keeping a running count of two randomly presented objects (*n*-count). The *n*-count task also consisted of two conditions: a 1-count condition that required participants to keep a running count of one type of shape and a more demanding 2-count condition that required participants to maintain a running count of two different shapes (a triangle and rectangle).

There is an important difference between performance on these tasks where $N = 1$ and $N = 2$. Recent research (Garavan, 1998; McElree 2001; Verhaeghen & Basak, 2005; Verhaeghen, Cerella, & Basak, 2004) has introduced the notion that working memory operations involving only a single item have privileged access because that item can be maintained in the focus of attention. Access to information held inside the focus of attention is immediate, whereas access to information outside the focus is slower and effortful (e.g., Cowan, 1994, 2001). Although estimates of the number of items that can be held in the focus of attention range between one and four, there is strong evidence to indicate only a single item can be held in the focus of attention on the *n*-back (McElree, 2001; Verhaeghen & Basak, 2005) and *n*-count (Garavan, 1998) tasks. Therefore, performance in the *n*-back and *n*-count conditions where $N = 2$ requires controlled and effortful switching of attentional focus from one item to another. In conditions where $N = 1$, the relevant item (either the comparison stimulus on the *n*-back task or the running count on the *n*-count task) remains in a state of immediate accessibility. Therefore, the attention-depletion hypothesis predicts stress effects on the *n*-count and *n*-back task when $N = 2$, but not when $N = 1$. The rationale for this differential prediction is that individuals should have sufficient attentional resources to successfully perform low-demand tasks ($N = 1$), even in the presence of stress. However, under high attentional demand ($N = 2$) performance should be sensitive to the presence of stress-related effects.

The second goal of the present study was to test the hypothesis that older adults are more cognitively vulnerable to stress effects than younger adults. The effect of cognitive interference has been implicated in both age-related (Hasher & Zacks, 1988; Hasher et al., 1999) and stress-related (Klein & Boals, 2001a) cognitive deficits. Hasher and colleagues argued that older adults have a diminished capacity to inhibit off-task or goal-irrelevant information (Hasher et al., 1999). If older adults do have such a deficit in inhibitory control, then the cognitive interference hypothesis would predict that cognitive performance in older adults should be affected by stress to a greater extent than in younger adults. Another perspective on differential stress effects in aging is to view performance under stress as simulating a dual-task condition. That is, performance under stress could be similar to performance under a dual-task load in the sense that both stress and dual tasking occupy attentional resources, leaving fewer available for performing the primary task. In either case, one would expect age to increase the magnitude of the stress effect on cognitive performance.

A third goal was to examine whether daily fluctuations in stress influenced trial-to-trial RT variability. Although high trial-level variability correlates with a number of individual-differences variables (e.g., age, intelligence, fluid intelligence), little is known about the WP processes that drive this variability. Although trial-to-trial variability has been found to vary from one day to the next (Nesselroade & Salthouse, 2004), variables that can predict why an individual is more variable on one day compared with another have not been identified. Demonstrating greater trial-level variability on high-stress days compared with low-stress days would indicate that processing is less efficient under stress (e.g., Eysenck & Calvo, 1992), perhaps indicating stress-related lapses of attention (West, 1999; West, Murphy, Armilio, Craik, & Stuss, 2002).

In summary, we tested three specific hypotheses:

1. That stress would impair performance on task conditions that require switching the focus of attention (2-back, 2-count), and not on control (1-back, 1-count) or perceptual comparison speed tasks that do not require attention switching. This hypothesis was evaluated at the WP level of analysis.

2. That WP stress effects would be larger in older compared with younger adults. Testing this hypothesis involved a BP comparison of the average WP stress effect in younger and older adults.

3. That stress would increase trial-to-trial variability in RT on affected variables (i.e., 2-back and 2-count) by differentially affecting slow responses compared with fast responses. This involved a WP test to compare the magnitude of the stress effect on fast responses compared with slow responses.

Method

Overview

Participants were given a brief introduction to the study, and the experimenter obtained informed consent as approved by the Syracuse University Institutional Review Board. Participants were told that they were participating in a study examining changes in health and cognition in adulthood. Half of the sessions for each participant were scheduled in the a.m. hours (approximately before 11 a.m.) and half were scheduled in the p.m. hours (approximately after 1 p.m.). The six testing sessions occurred over a period of 8 to 14 days. The same research assistant tested each participant individually on each of the six sessions.

Participants

One hundred-eight older adults were recruited for participation in a longitudinal study of health and cognition. Sixty-five older adults were recruited from the Syracuse area by advertising in local newspapers and posting flyers in senior centers. Fifty-three were residents of a senior retirement community who volunteered their participation in the study. All older adults had intact mental status as indicated by making fewer than 8 errors on the Blessed mental status exam (Blessed, Tomlinson, & Roth, 1968). Sixty-eight younger adults were recruited from the Syracuse undergraduate student body by using ads posted in student centers and by recruiting from undergraduate psychology courses. Each participant was compensated $60 for his or her involvement in the study. The average age was 80.23 (SD = 6.30, range = 66–95) for the older adults and 20.21 (SD = 1.09, range = 18–24) for the younger adults. The average years of education were similar for young (M = 15.10, SD = 1.40) and older adults (M = 14.90, SD = 2.40). The younger and older adult samples had similar proportions of males (.22 vs. .28, respectively).

Stimuli and Procedure

The order of administration of the measures was fixed across sessions and individuals: the *n*-count task, perceptual speed, the *n*-back task, and the daily stress assessment. Daily stress was assessed using a version of the DISE. We omitted two questions from the DISE because we wanted to have items that would be relevant to both our young college-age sample and our sample of older adults. One of the omitted questions asked about whether the respondent experienced any age discrimination, and the second omitted question asked whether anything stressful had happened at work or school. None of our older adults were enrolled in school and all but one were retired and not working. The version of this instrument used in this study consisted of the following five questions: (a) Did you have an argument or disagreement with anyone? (b) Did anything else happen that you could have argued or disagreed about, but you decided to let it pass? (c) Did anything happen to a close friend or relative (other than what you have already mentioned) that turned out to be stressful for you? (d) Did anything stressful happen (other than what you have already mentioned) regarding your personal health? (e) Did anything else happen (other than what you have already mentioned) that most people would consider stressful? Given that there were so few days with multiple stressors (see the Results section), daily stress was indexed as dummy variable coded as 1 for stress days and 0 for nonstress days. The DISE was administered by a trained tester at the end of each session.

We examined performance on three cognitive tasks: the *n*-back, *n*-count, and number string comparison. This version of the *n*-back consisted of displaying a single digit on a computer display and required participants to determine whether the displayed digit matched the *n*th digit back (where $n = 1$ or 2) by pressing the "*/*" key for a match and the "*z*" key for a nonmatch. Participants were instructed to be both fast and accurate. As soon as a response was made, the next stimulus appeared. Half of the trials were match, and half were nonmatch trials. Participants performed three blocks of 20 trials for $n = 1$ and three blocks of 20 trials for $n = 2$ each session (for a total of 60 trials for $n = 1$ and $n = 2$). RTs from correct trials in each block served as the dependent measures for this task. The running count task also consisted of two conditions: a single-task condition with low attentional demands (1-count) that required participants to keep a running count of one type of shape and one with high-attentional demands (2-count) that required participants to maintain a running count of two different shapes (a triangle and a rectangle). Participants were instructed to press the space bar as soon as they had counted the displayed object. The next object appeared immediately following each response. The 1-count and 2-count conditions were blocked and consisted of 60 trials each. Object counts were reported after runs of 8, 10, 12, or 16 objects. RTs from runs with correct object counts were averaged and served as the dependent measures for this task. The number comparison task (NC) required participants to compare two strings of either 3 or 5 digits to determine whether the same digits were in each string, regardless of their order. Participants performed a block of 40 trials with string sizes of 3 and another block of 40 trials with a string size of 5. The next number string appeared 500 ms after each response. The average RT from correct trials served as the dependent measure for this task.

In the first session, sufficient practice trials for all tasks were provided until participants become comfortable with each procedure. Approximately 10 warm-up trials were given prior to commencing each task during Sessions 2 through 6. A high-resolution monitor controlled by a Pentium IV-based computer displayed stimuli. A computer-based vision check was administered to verify that all participants could identify test stimuli within video displays of 10.4° of visual angle.

Because daily stress is related to variations in negative affect (NA), we measured NA using a five-item adjective checklist (Lawton, Kleban, Dean, Rajagopal, & Parmelee, 1992). Participants had to rate on a 5-point scale (*not at all, a little, moderately, quite a bit, or extremely*) whether they felt irritated, depressed, worried, annoyed, or sad. The instructions emphasized that ratings should reflect how they *felt right now, at this moment*. We also measured physical symptoms to determine whether possible relations between daily stress and cognition were a by-product of variations in pain or other physical ailments. Symptoms were assessed using a brief version of the Larsen and Kasimatis (1991) physical symptom checklist. This checklist assessed five constellations of symptoms: aches–pain (headaches, backaches, joint paint, and muscle soreness), gastrointestinal symptoms (poor appetite, nausea–upset stomach, constipation–diarrhea), symptoms associated with cardiovascular functioning (chest pain, dizziness, heart pounding), upper respiratory symptoms (cold–flu symptoms, allergy–hay fever symptoms) and a category for "other" physical symptoms or discomforts. During each testing session, participants indicated whether they had experienced each symptom over the past 24 hr. The symptom score consisted of a simple sum of the number of experienced symptoms.

Results

Frequency of Daily Stressors

Table 1 indicates that the frequency of reported stressors was higher in younger adults, who reported at least one stressor on 74% of testing days, compared with older adults, who reported at least

Table 1
Stressor Frequency

Stressor	% days on which a given stressor occurred	
	Older	Young
Did you have an argument or disagreement with anyone?	5	26**
Did anything else happen that you could have argued or disagreed about, but you decided to let it pass?	11	24**
Did anything happen to a close friend or relative that turned out to be stressful for you?	17	13
Did anything stressful happen regarding your personal health?	8	10
Did anything else happen that most people would consider stressful?	20	37**
Any of the above stressors	44	74**

** $p < .01$

one stressor on 44% of days. Young adults reported multiple stressors on 37% of testing days compared with 16% for the older adults. Younger adults reported having more arguments and opportunities for arguments than older adults, but there was age equivalence in reports of health-related stressors or stressful events happening to friends and family. The most frequently endorsed stress fell into the "other" category, and younger adults reported nearly twice as many unspecified stressors as did older adults.

Modeling Practice Effects

Figure 1 shows the mean RTs as a function of session for young and older adults on each of the cognitive tasks. There is clear visual evidence of practice effects in both younger and older adults across the six sessions. Because such practice-related mean trends could produce a spurious WP association between stress and RT, we examined two different statistical models for statistically removing the effect of retest. The first was a three-parameter negative exponential function that included asymptote, rate, and gain parameters. The second model was a second-order polynomial that included an intercept, linear effect, and quadratic effect. Because these data included repeated measures on the same individuals, we used mixed models methodology (Laird & Ware, 1982), also referred to as *multilevel modeling* (Snidjers & Bosker, 1999). The multilevel polynomial model specifies two levels of analysis:

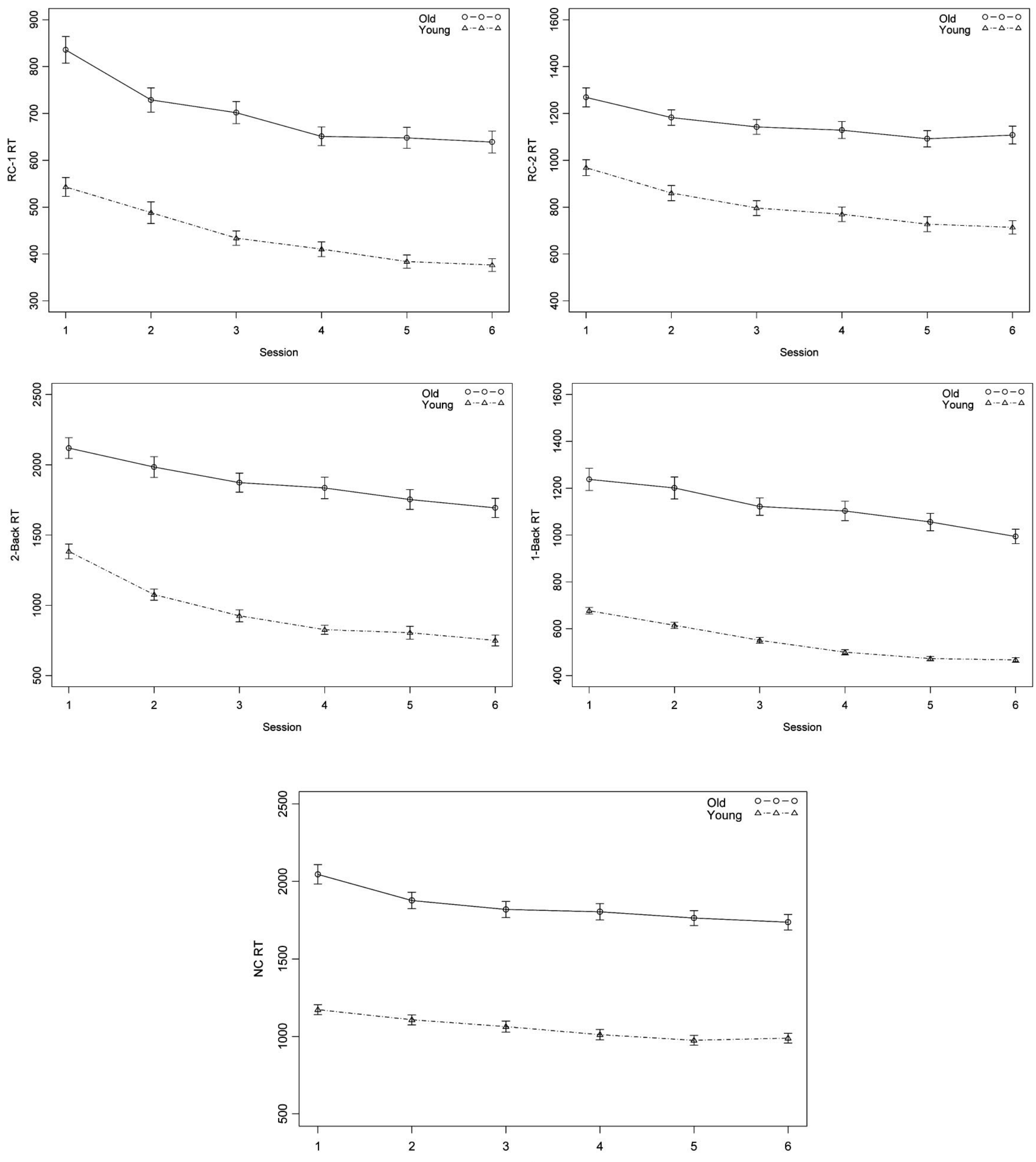

Figure 1. Plots of mean number comparison task (NC) response times (RTs) on each task for younger and older adults across sessions. Error bars indicate the standard error of the means.

Level 1, or the WP level, and Level 2, or the BP level. The following Level 1 equation models performance as a linear and quadratic function of session:

$$\mathrm{RT}_{ij} = b_{0j} + b_{1j}(session_{ij}) + b_{2j}\,(session_{ij}^2) + e_{ij} \qquad (1a)$$

where the RT for person j at session i is a function of an intercept (b_{0j}), linear session effect (b_{1j}), quadratic session effect (b_{2j}) and residual (e_{ij}). All predictor variables designed to model WP cognitive variability are included in the Level 1 model.

$$b_{0j} = \beta_{00} + u_{0j}$$

$$b_{1j} = \beta_{10} + u_{1j}$$

$$b_{1j} = \beta_{20} + u_{2j}, \qquad (1b)$$

where $\beta_{00,}$ $\beta_{10,}$ and β_{20} are the average WP intercept, WP linear, and WP quadratic effects (i.e., fixed effects) and the terms u_{0j}, u_{1j}, and u_{2j} reflect person-specific deviations from the average values of the intercept, linear, and quadratic effects (or random effects).

The polynomial model was compared with the following negative exponential multilevel model:

$$\mathrm{RT}_{ij} = a_j + g_j\{\exp[-r_j(session - 1)]\} + e, \qquad (2a)$$

which models the RT for each person, j, at each session, i, as a function of an asymptotic value (a_j), the difference or gain between initial value and asymptote (g_j), and a rate parameter (r_j) that governs how quickly performance moves from the initial to asymptotic level. The corresponding Level 2 equations were as follows:

$$a_j = A + u_{aj}$$

$$g_j = G + u_{gj}$$

$$r_j = R, \qquad (2b)$$

where A, G, and R are the average (or fixed) asymptote, gain, and rate parameters, and the u_{aj} and u_{gj} are the person-specific (or random) asymptote and gain effects. We allowed only parameters that enter the model linearly (i.e., a_j and g_j) to be random, and we constrained nonlinear parameters as fixed. Constraining nonlinear parameters to be fixed results in a "conditionally linear" mixed effects model (Daniels & Pourahmadi, 2002) and facilitates estimation and convergence of the mixed model (the model would not converge with a random rate parameter). Both polynomial and negative exponential models were fit separately to the young and older adult data to allow for age differences in the variances of the Level 1 residuals and Level 2 random effects.

Table 2 displays the comparative fit of the two models for practice effects using the Akaike information criterion correction for small samples (AICc; Akaike, 1973; Burnham & Anderson, 1998). The AICc compares the –2 log-likelihood values adjusted for sample size and the number of parameters, penalizing models with more parameters. Inspection of Table 2 indicates that the negative exponential model fits the data slightly but consistently better than the polynomial model for the younger participants. The fits of the negative exponential are slightly better than the polynomial fits in the older participants for the 2-back, 2-count, and 1-count. The polynomial provides a better fit for the speed data, and the two models show comparable fit for the 1-back data. Plots of residuals did not indicate systematic misfit across sessions by either model for any of the variables. Anticipating the results of the daily stress analysis, we found no difference in the WP or BP effects of stress whether practice was modeled by a polynomial or negative exponential. Therefore we opted to use the polynomial model for our primary analyses in order to simplify presentation of the results, and to facilitate comparison of stress effects across the different variables. Where appropriate, we report results from both the polynomial and negative exponential models that demonstrate WP stress effects in order to verify that these effects are not a by-product of improper specification of across-sessions practice effects.

Further preliminary model fitting provided strong evidence that older and younger adults differed in the magnitude of both their BP and WP variability. Therefore, all subsequent analyses allowed these variances to be estimated separately for the two age groups. Because variability in RT is known to increase with the mean, we examined whether allowing residual variance to increase as a function of the predicted mean (i.e., a power-of-means model) would change our results. Fitting power-of-means models did not substantially improve model fit for either the younger or older adults, and more important, we found no difference between the estimates of either the WP or BP stress obtained from this model compared with the simpler models that allowed variances to differ between age groups but constrained the variances to be equal within each age group.

Table 2
Akaike Information Criterion-Corrected (AICc) Comparative Fit Index for Polynomial and Negative Exponential Practice Model

AICc	2-back	1-back	2-count	1-count	Speed
Young adults					
Negative exponential	−80.5	−1,071.0	−559.4	−890.2	−306.7
Second-order polynomial	−73.1	−1,078.0	−549.0	−889.1	−299.0
Older adults					
Negative exponential	708.4	86.2	−153.4	−548.2	32.1
Second-order polynomial	735.6	86.4	−119.6	−526.4	19.5

Note. Smaller values indicate comparatively better fit.

Reliability of BP and WP Cognitive Variability

BP variability and WP variability reflect both systematic and nonsystematic sources. Therefore, it is informative to consider the relative reliability of BP and WP cognitive variability. *Reliability* in this context does not refer to measurement precision but rather to the ability of RTs to differentiate between the relevant units of analysis. In the context of this study, BP reliability reflects the extent to which the average RT in each session can discriminate between individuals. This discrimination is indexed by comparing the relative amounts of variability in the RTs that is BP to the variability that exists WP measured across sessions. Thus, the intraclass correlation (ICC), defined as $Var(BP)/[Var(BP) + Var(WP)]$, provides a measure of BP reliability. Table 3 shows that the ICCs range from .81 to .91, indicating that most of the variability in the RTs exists between individuals. These ICCs were obtained after detrending the data using the polynomial practice model.

Although most of the variability in RTs is BP, the critical quantity is the percentage of WP variability that is systematic across sessions. After detrending for across-sessions practice effects, the residual variance may be all or mostly "error" and not reflect any systematic WP differences across the sessions. To assess this possibility, we categorized RTs from each task as coming from an odd or an even trial in each of the six sessions. This enabled us to calculate two RTs for each person for each session for each task: the mean RT of odd trials and the mean RT of even trials. Before calculating these mean RTs, we detrended the data for within-session and across-sessions practice and time of day effects. The mean odd and even RTs were then correlated WP, across sessions using a multivariate multilevel model (Snidjers & Bosker, 1999; see Sliwinski et al., 2003, for a detailed example). If there were no systematic differences in RTs across sessions, then an individual's odd and even RTs from the same session should be no more similar to each other than they are to RTs obtained from other sessions. However, if there is systematic WP variability, then odd and even RTs should covary WP across sessions. Table 3 shows these WP correlations (adjusted using the Spearman–Brown prophecy formula) obtained from fitting multivariate multilevel models to data from each task. These Spearman–Brown adjusted WP correlations ranged between .57 and .78 and were statistically significant ($p < .01$) in all cases. These results demonstrate systematic day-to-day WP cognitive variability, but the amount of reliable WP variance is somewhat less than the amount of reliable BP variance. It is important to note that unreliability in WP cognitive variability would result in an underestimate of the true WP effects of stress. Thus, the degree to which we unreliably measure WP variability produces a more conservative test of our hypotheses.

Table 3
Reliability Analysis of Between-Persons (BP) and Within-Persons (WP) Variability

Variable	BP		WP	
	Young	Older	Young	Older
2-back	.88	.81	.69	.73
1-back	.86	.91	.65	.73
2-count	.92	.83	.73	.74
1-count	.91	.84	.78	.70
Speed	.92	.94	.78	.65

Note. The intraclass correlation was used to estimate BP reliability. Odd–even trial correlations, adjusted using the Spearman–Brown prophecy formula, were used to estimate WP reliability.

Age Differences and the Covariation Between Daily Stress and Cognition

Given the low number of days with multiple stressors reported, daily stress was indexed as a dummy variable, coded as 0 (if there were no stressors reported that day) or 1 (if there was at least one stressor reported that day). Thus, the variable $stress_{ij}$ was coded as 1 if individual j reported a stressor at session i and 0 otherwise. Because $stress_{ij}$ reflects both WP variability (i.e., variability across session) and BP variability (i.e., variability across individuals), two additional variables were constructed to separate WP and BP stress effects. BP stress effects were indexed by taking the average value of $stress_{ij}$ for each person across the six sessions ($\overline{stress}_{.j}$). This variable can differ across individuals but is constant within individuals across sessions and can therefore be used to model the BP stress effect on cognition. Because $stress_{ij}$ is a binary variable, its average reflects the probability of each person's reporting a stressor during any given session. WP stress effects were measured as deviations of each individual from his or her own average stress index ($stress_{ij} - \overline{stress}_{.j}$). This variable is constant across individuals (with a mean of 0) and therefore reflects only WP variability.

The primary analysis involved adding these stress variables to the polynomial practice model. The WP stress variable was added to the Level 1 practice effects model, and the BP stress variable was added the Level 2 intercept model. Data from both conditions of the *n*-back task and data from both conditions of the *n*-count task were modeled simultaneously to allow direct comparisons of stress effects for $n = 1$ and $n = 2$ conditions. The processing speed task was analyzed separately.

Table 4 presents the results from the multilevel models predicting performance as a function of daily stress. The top portion of the table presents estimates of the intercepts, linear effects, quadratic effects, and stress effects for young and older adults. The bottom portion of the table presents the estimated BP variances for intercepts and linear effects as well as the WP variances for both age groups. Results for the *n*-back task revealed significant WP stress effects for older and younger adults in the 2-back condition, indicating that older adults were 99.5 ms slower and younger adults were 65.2 ms slower on stress compared with no stress days. These estimates of WP stress effects were very close to those obtained by fitting separate negative exponential models to the young (60.1 ms, $SE = 0.20$, $p < .01$) and older adult (89.0 ms, $SE = 0.19$, $p = .01$) data for the 2-back. These results indicate the WP stress effect obtained from the polynomial model was not a by-product of improperly modeling practice effects. The age difference in the WP stress effect was not significantly different, $t(1807) = 0.81$, *ns*. Because older adults reported significantly fewer stressors than younger adults, we examined how this might have affected estimates of WP stress. The interaction between BP stress and WP stress was not statistically significant, $t(1806) = 1.50$, $p = .18$, which implies that the total amount of stress

Table 4
Within-Persons (WP) and Between-Persons (BP) Effects of Daily Stress on Cognitive Performance (N = 173)

Characteristics	2-back	1-back	2-count	1-count	Speed
Fixed effects					
Intercept					
Young	1,752.9**	788.7**	1,034.0**	595.5**	1765.3**
Older	2,147.2**	1,253.1**	1,394.3**	975.0**	3023.9**
Linear effect					
Young	−334.9**	−98.1**	−123.6**	−77.5**	−148.2**
Older	−162.3**	−35.5*	−91.5**	−111.8**	−127.4**
Quadratic effect					
Young	31.2**	7.7**	10.5**	6.3**	12.5**
Older	12.1**	−0.8	8.9**	10.9**	13.5**
Stress (WP)					
Young	65.2**	−6.1	1.3	4.7	−15.8
Older	99.5**	21.3	43.6**	5.0	−14.3
Stress (BP)					
Young	−146.7	−25.3	20.7	42.7	152.7
Older	225.3	−27.9	−119.2	−132.6	−351.9
AM					
Young	25.4	6.9	29.3**	8.8	43.7**
Older	19.2	15.6	24.4	14.6	6.8
Variance components					
WP variance					
Young	21,355.0	2,155.2	6,361.9	3,095.4	17,234.0
Older	98,195.0	21,335.0	25,125.0	12,351.0	33,628.0
BP variance					
Intercept					
Young	156,803.0	13,117.0	77,183.0	31,770.0	188,210.0
Older	430,853.0	228,766.0	119,172.0	67,030.0	559,755.0
Linear					
Young	3961.1	179.0	454.7	381.5	2368.7
Older	3375.6	2597.9	1,876.8	995.8	2650.2
Covariance (Int, Linear)					
Young	−1,220.2	−17,013.0	−3,173.1	−2,896.7	−8202.1
Older	−18,156.0	−6,207.1	−5,118.9	−5,164.9	−14,771.0

Note. Time of day was coded 0 for a.m., 1 for p.m. Covariance (int, linear) = covariance between the random intercepts and random linear practice effects.
* $p < .05$. ** $p < .01$.

individuals experienced did not substantially impact the magnitude of their WP stress effect.

Analysis of the 1-back condition did not indicate any evidence of either a WP or BP stress effect for older or younger adults. Contrasting the WP stress effect on the 2-back with the 1-back yielded statistical significance, $t(1807) = 3.40$, $p < .01$, indicating a significantly larger stress effect on the 2-back in both age groups. RTs on the 2-back were slowed by 0.32 and 0.45 standard deviation units for older and younger adults, respectively (obtained by dividing the WP stress effect by the WP standard deviation), on stress compared with nonstress days. Another way to calibrate the WP stress effect size is to compare it to the effect of age. Figure 2 shows the effect of a 1-year age difference on the 2-back task, determined both by comparing the older and younger adults' mean performance and by estimating the age effect in just the older adults. The effect of experiencing a daily stressor (in the older adults) is equivalent to approximately a 6-year age difference. There was no evidence of reliable BP stress effects on either the 2-back or 1-back task.

Analysis of the *n*-count task indicated a significant WP stress effect in the 2-count condition that was qualified by an interaction with age group. Similar WP stress effects were obtained by fitting separate negative exponential functions to younger (–0.1 ms, SE = 1.1, *ns*) and older adults' (40.5 ms, $SE = 16.8$, $p = .02$) 2-count data. The older adults had a significant WP stress effect, indicating slower performance on stress days, that was larger than the WP effect for the younger adults, $t(1860) = 2.31$, $p < .05$. There was no evidence of either a WP or a BP stress effect for the 1-count task in either older or younger adults. The older adults also exhibited a significantly larger WP stress effect in the 2-count compared with the 1-count task, $t(1860) = 2.06$, $p < .05$. Analysis of the NC did not indicate evidence of a WP or a BP stress effect for either age group.

Older and younger adults performed above 90% accuracy on all tasks, except for the 2-back task, on which the older adults had a mean accuracy of 84% (chance performance = 50%). Sensitivity analyses indicated that accuracy on the 2-back (or any other task) did not vary as a function of daily stress, and including accuracy as a covariate did not alter the results. Time-of-day effects were significant on only two of the five tasks, with faster performance occurring during the p.m. sessions. There was also no evidence of a Stress × Time of Day interaction ($ps > .30$ for all tasks).

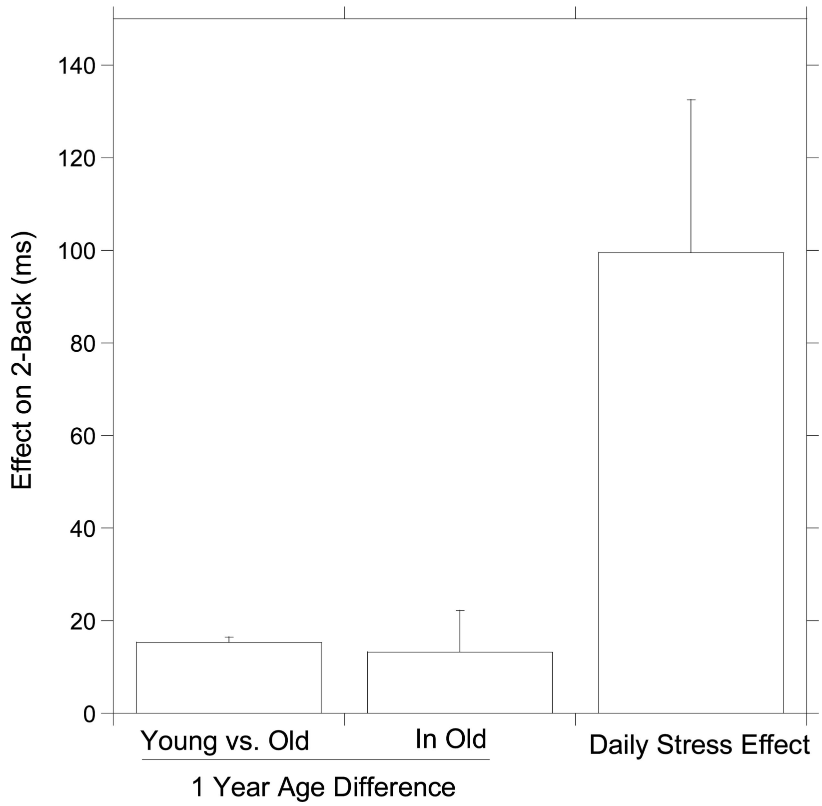

Figure 2. A display of the within-persons stress effect calibrated against age effects for the 2-back task. The left bar shows the effect of a 1-year age difference (based on a young–older comparison) on response time (RT), the middle bar shows a 1-year age difference based on just the older sample, and the right bar shows the effect of one daily stressor on RT. Error bars indicate the standard error of the effect.

Covariate Analysis

Daily stress correlates with NA and self-reports of physical symptoms (Pennebaker, 1982). We therefore examined whether the observed effect of daily stress on 2-back and 2-count performance could be attributed to stress-related WP variability in NA and physical symptoms. Variables reflecting WP and BP NA and symptom variability were constructed in the same way as the WP and BP stress variables. Adding NA to the analysis of the 2-back data did not attenuate estimates of the WP stress effect for either the young (68.9 ms), $t(1789) = 3.20$, $p < .01$, or the older participants (105.2 ms), $t(1789) = 2.90$, $p < .01$. There was no evidence of an interaction between NA and stress, either at the WP or BP level. The WP effect of NA was not statistically significant, $t(1789) = 1.60$, $p = .10$, and was in the direction of faster performance on high NA days. Reanalysis of the 2-count data with NA added also did not influence the WP stress effect for older (44.3 ms), $t(1847) = 2.90$, $p < .01$, or younger adults (1.9 ms), $t(1847) < 1$, *ns*. The interaction between NA and WP stress was not statistically significant (ts < 1, *ns*) for both the 2-back and 2-count data.

Daily fluctuations in physical symptoms also did not account for the WP stress effect. After we adjusted for physical symptoms, the WP stress effect on the 2-back was 61.9 ms for the young, $t(1803) = 2.20$, $p < .05$, and 98.2 ms, $t(1803) = 2.70$, $p < .01$, for the older participants. However, daily fluctuation in self-reported physical symptoms was significant in predicting 2-back performance, $t(1803) = 2.10$, $p < .05$. We reanalyzed the stress data after omitting the question that asked about personal health to determine whether the WP stress effect might be attributable to health-related problems that were not adequately captured by the symptom self-report. The WP stress effect for the young participants on the 2-back task remained relatively unchanged (63.6 ms), $t(1807) = 3.10$, $p < .01$, whereas the WP stress effect for the older participants increased (134.4 ms), $t(1807) = 3.40$, $p < .01$, after excluding health-related stressors from the analysis. There was no evidence of a WP effect of symptoms on 2-count performance, $t(1856) < 1$, *ns*, and reanalyzing these data after omitting health-related stressors did not noticeably alter estimates of the WP stress effects for the young (–5.8 ms), $t(1860) < 1$, *ns,* or the older participants (41.9 ms), $t(1860) = 2.40$, $p = .01$. Therefore, we can conclude that the observed WP stress effects on cognition cannot be attributed to fluctuations in NA or physical symptoms.

Daily Stress and Trial-Level Variability

We next examined how daily stress affected RTs at the trial level. One possibility is stress added a constant overhead to task performance, resulting in an overall slowing of response speed. Another possibility is that stress resulted in periodic lapses of attention (West et al., 2002) and affected performance by causing some responses to be extremely slow while leaving other responses unimpaired. This latter explanation predicts a greater proportion of slow responses on stress compared with nonstress days. Individuals' fastest responses, however, should be similar on stress compared with no-stress days. We conducted an analysis of individual RT distribution to determine whether stress increased performance variability by differentially affecting slow compared with fast RTs. We repeated the previously described analyses of WP stress effects, but this time instead of using the mean RT from each session, we used RT measures that reflected both slow and fast responses. This was done by dividing the RT distribution for each individual in each session into five equal parts. Then, we selected the midpoint of each of these five parts, and these midpoints corresponded to the .10, .30, .50, .70, and .90 RT quantiles. If stress increases processing variability, then the RT distribution should be more variable on stress compared with nonstress days. This would result in a Stress × Quantile interaction, with the largest stress effect in the slowest RTs. The case of no Stress × Quantile interaction would indicate that stress exerted an additive effect on performance by shifting trial-level RT distributions without affecting processing variability.

Quantile was treated as a quantitative variable in the model. Although there is technically no repeated measurement that underlies the ordering of the quantiles, there was evidence of a serial correlation across quantiles, which we modeled using a first-order autoregressive covariance structure. The critical Stress × Quantile interaction was significant, $t(4873) = 5.40$, $p < .01$, for the 2-back task, indicating that the WP effect of stress was larger for slower compared with faster RTs. There was no evidence that the interaction between stress and quantile differed by age, $t(4873) < 1$, *ns*. Figure 3 shows how the stress effect increased across quantiles for both the younger and older adults. The effect of stress thus appears primarily to make slow RTs even slower, while having little or no effect on the fastest RTs. Analysis of the 2-count task did not reveal a significant Quantile × Stress interaction for either younger or older adults ($p > .30$ for both).

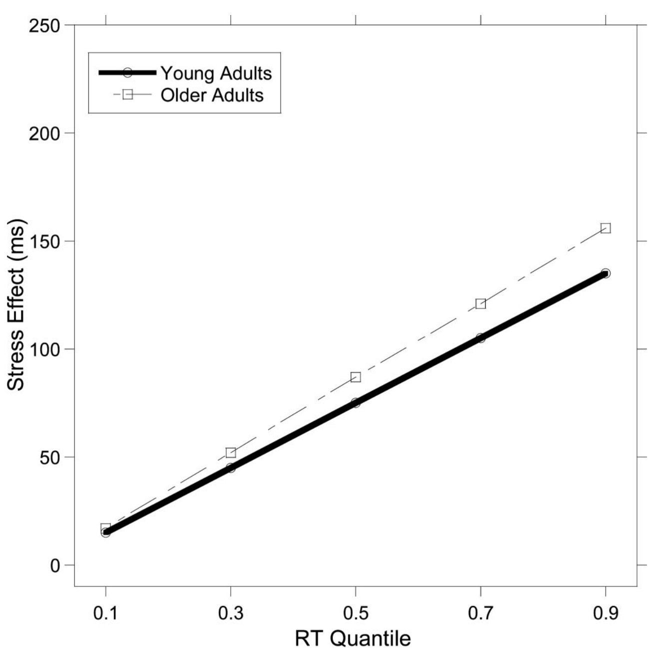

Figure 3. The effect of daily stress on the response time (RT) distribution for the 2-back task. The effects of stress on RT corresponding to each of five RT quantiles (.10, .30, .50, .70, .90) are plotted. The effect of stress increases from the fastest RTs to the slowest RTs.

Discussion

The primary goal of the present study was to examine the WP relationship between naturally occurring daily stress and cognitive performance. Our results demonstrated that WP variability in daily stress predicts WP variability on attention-demanding cognitive tasks. The second goal was to test the hypothesis that older adults would be more affected by stress than would younger adults. We showed that both younger and older adults performed worse on stress compared with nonstress days, and we provided mixed support of an amplified stress effect in older adults. The third goal of this research was to test whether daily fluctuations in stress influenced moment-to-moment performance variability. We provided evidence that individuals were not only slow but were more variable on stress compared with nonstress days.

Our study is the first to demonstrate a coupling between naturally occurring stressful experiences and cognitive performance within individuals. This result is important because the theories that postulate a negative stress–cognition relationship pertain to processes that transpire within the individual (e.g., the stress response and attention). In contrast to the WP results, BP differences in daily stress did not predict BP cognitive impairment for any of the variables. This likely results from our measurement of daily stress rather than major life events. Daily hassles of the type measured in the present study fluctuate over the span of days and are therefore useful for characterizing short-term intraindividual variability but likely less useful for measuring stable person characteristics. In contrast, the type of life-events stress measured by Klein and Boals (2001a, 2001b; e.g., death of a loved one) reflects relatively major and persistent events that might be better suited for characterizing more stable individual differences. Different measures of stress may be required depending on whether one's purpose is to test hypotheses regarding individual differences or hypotheses regarding intraindividual processes.

Self-reports of daily stress may also reflect other sources of variability that could confound its relationship with cognition. In particular, self-reports of daily stress are correlated with NA, both WP and BP (Mroczek & Almeida, 2004). NA did not predict either WP or BP variability in the 2-back or 2-count conditions, and including NA in our statistical models did not attenuate or interact with the WP stress effects. Therefore, it is unlikely that either short-term fluctuations or stable individual differences in mood moderated or mediated WP stress effects. Another possible confound involves the possibility that variability in physical symptoms produced both stress and impaired cognitive performance. Two analyses ruled out this possibility. First, including direct measures of self-reported physical symptoms in the statistical models did not influence the magnitude of the WP stress effects. And second, the WP stress effect was just as strong after omitting the "personal health" item from the DISE. Therefore, it is unlikely that the obtained WP stress effects were attributable to short-term fluctuations in physical health.

A likely explanation for the present findings is that the experience of stress occupied attentional resources that resulted in impaired performance on the 2-back and 2-count tasks, but not on the control tasks (i.e., 1-back, 1-count, and processing speed). This depletion may occur as a direct result of the experience of stress (e.g., Kahneman, 1973) or as a by-product of stress-related intrusive thoughts (e.g., Klein & Boals, 2001a, 2001b). This attention-depletion hypothesis predicts that as an individual's level of stress fluctuates from day to day, his or her effective cognitive resources should also fluctuate. The present results satisfy this prediction by demonstrating worse performance in individuals on high-stress days compared with low-stress days. Unsworth, Heitz, and Engle (in press) recently argued for a link between the ability to control one's thoughts and working memory capacity, both of which reflect an individual's capacity to keep mental representations active in the focus of attention in the face of distraction. The specificity of the WP stress effect to tasks that require attention switching is in accord with Unsworth et al.'s position. One important implication of the present findings is that attentional capacity is not a fixed quantity and that it fluctuates systematically and predictably across short time intervals.

With regard to aging, Hasher et al. (1999) argued that older adults have depleted attentional resources that impair their ability to inhibit task-irrelevant information. If Hasher et al. were correct in claiming that older adults experience deficient inhibitory control, then one might expect that cognitive performance in older adults should be affected by stress to greater extent than in younger adults. Although there is evidence of amplified stress effects in older adults on the 2-count task, it is notable that the WP stress effect in younger and older adults did not differ on the more demanding 2-back task. Demonstrating a significantly larger WP stress effect in older adults on the 2-count may simply reflect that the task was not sufficiently difficult to be sensitive to stress in younger adults. These results are consistent with those of Verhaeghen and Basak (2005), who showed age insensitivity in RTs to switching the focus of attention. They argued that older adults can retrieve items outside the focus of attention just as quickly as can younger adults. Given age equivalence in the speeded aspect of focus switching, the effect of stress may have been to add a constant overhead to performance. Thus, stress could operate much like a dual-task setting in which the cognitive task (e.g., 2-back) is primary, and coping with stress-related interference (e.g., intrusive thoughts) is secondary.

However, examination of trial-level data indicates that the effect of stress was not simply additive but rather that it differentially affected slower RTs. Li et al. (2004) introduced the term *processing robustness* to indicate the degree of trial-to-trial consistency in RT. They demonstrated that decreases in processing robustness (i.e., increases in trial-level RT variability) are an important indicator of cognitive changes across the life span. Work by Hultsch, MacDonald, and Dixon (2002) also showed age-related increases in trial-level RT variability that may reflect degradation in information processing in the aging brain (see also Li et al., 2000). The present results indicate that increased trial-level variability may also result from transient stress-related effects. Analysis of RT quantiles indicated that the stress effect on the 2-back task was larger for slower compared with faster RTs. This differential effect on slow RTs results in a stretched out (i.e., more variable) RT distribution on stress compared with no stress days. This effect was statistically equivalent in older and younger adults, indicating that the former were no more susceptible to the stress-related interference than the latter.

The present finding that stress affects performance by impairing slow RTs while leaving fast RTs relatively unimpaired suggests that stress may affect controlled attention. A number of studies have found that a person's slowest RTs correlate more strongly with IQ measures than do fast RTs (Coyle, 2001; Larson & Alderton, 1990). One explanation for these findings is that some proportion of slow RTs result from lapses in attention (Jensen, 1992; West et al., 2002) or working memory (Larson & Alderton, 1990), which are more likely to occur in low-IQ compared with high-IQ individuals. This account is in accordance with the argument that both working memory capacity and fluid intelligence reflect the ability of individuals to control attention in the face of distraction (Engle, 2002; Engle & Kane, 2004).

There are some limitations to the present study. First, it is important to acknowledge that age or cohort differences in stressor reporting thresholds could have influenced the results. Older adults may tend to identify only severe stressors, whereas younger adults would be more inclined to report even minor hassles. This might account for the age difference in stressor frequency and could have amplified the stress effect in older adults (if they only reported severe stressors) and attenuated the stress effect in younger adults (if they reported even relatively trivial hassles as stressors). Second, this study required individuals to recollect the occurrence of stressors during the previous 24 hr, and there might be age differences in the accuracy of this recollection. This could have resulted in older adults' underreporting stressor frequency. Third, there was a lack of direct measures that could distinguish between potential mechanisms by which stress influences cognition. Future studies could obtain, for example, measures of diurnal cortisol and daily measures of intrusive thinking to identify mediators of WP stress effects. The fourth limitation involves the temporal resolution of the stress–cognition relationship. Reports of daily stressors were recollections of stressors that occurred within the 24 hr prior to cognitive testing. The analyses assumed that stressors occurring at any time in the 24 hr prior to cognitive testing would have equal impact on performance, whereas stressors that were more proximal to the cognitive assessment could exert a more powerful affect than more distal stressors. Thus, future studies should obtain better and more sensitive measures of stressor severity and the time of occurrence (e.g., via experience-sampling techniques; Smyth & Stone, 2003) to evaluate the influence of severity and proximity on the stress–cognition relationship. And finally, this study was correlational, which constrains support for statements regarding the causal relationship among variables.

Despite these limitations, the present study is unique in its demonstration that variability in daily stressors predicts intraindividual fluctuations in cognitive performance. The magnitude of stress-related daily cognitive performance fluctuations is substantial, corresponding to the performance difference that would be expected by a 6-year age difference per stressor. Hultsch and MacDonald (2004) argued that studying intraindividual cognitive variability can provide a unique theoretical window onto cognitive aging. We concur and argue further that modeling the WP correlates of short-term cognitive fluctuations can elucidate fundamental aspects of cognitive performance.

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