An analysis of age differences in perceptual speed

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Tests of the generalized slowing hypothesis have demonstrated the strong predictive power of tests of perceptual comparison speed in accounting for age differences across a range of cognitive domains. The goals of this study were to determine whether short-term memory (STM) and perceptual demands contribute to age differences on two commonly used tests of perceptual comparison speed, the letter and pattern comparison tests, and to test whether these task components account for unique variance in predicting age differences in working memory and reasoning. Results showed that, after controlling for visual contrast sensitivity and a general slowing factor, age differences increased with increases in both STM load and perceptual degradation. Only STM load, however, accounted for a significant portion of the relationship of age with higher level cognition. We concluded that perceptual comparison tests are dependent on multiple age-sensitive abilities, not all of which are related to age differences in higher level cognition.

A large body of work has demonstrated the lack of independence in age-related declines across a wide range of cognitive domains (Salthouse, 1991, 1996). Furthermore, relatively simple cognitive skills, as measured by perceptual comparison speed tasks, such as the letter and pattern comparison tests (LC–PC tests; Salthouse & Babcock, 1991) and variants of the Digit–Symbol Substitution Test (Wechsler, 1997), are among the strongest predictors of age-related variance in higher level cognition, including long-term memory, working memory (WM), and reasoning (Babcock, 1994; Finkel, Reynolds, McArdle, & Pedersen, 2007; Fisk & Warr, 1996; Fristoe, Salthouse, & Woodard, 1997; McCabe & Hartman, 2003; Salthouse, 1991, 1996). Perceptual comparison tests consistently account for more age-related variance in higher level cognition than do tests that are either cognitively simpler or more complex (Salthouse, 1991, 1994, 1996).

The most prominent interpretation of the role of perceptual comparison tests attributes the shared effects of age to the slowing of a relatively small number of low-level cognitive processes (Salthouse, 1996; Salthouse & Ferrer-Caja, 2003). The challenge remains, however, to specify these processes, and existing theory provides little guidance. Furthermore, isolating the critical processes is difficult because of the imprecise mapping of cognitive processes to tasks and because of the intrinsic impossibility of creating process-pure tests. The Digit–Symbol Substitution Test, for example, has separable components related

to feature encoding, memory, and visual search (Gilmore, Royer, Gruhn, & Esson, 2004) and relies on visuomotor coordination and response speed as well (Lezak, 2004; Piccinin & Rabbitt, 1999). The LC–PC tests are likely to be similarly complex. On each item of these paper-and-pencil tests, participants compare two letter strings or two geometric patterns and decide as quickly as possible whether they are the same or different. Performance is likely to involve visual sensory ability, visual perception, short-term memory (STM), comparison processes, response selection, and motor speed. Age differences in many of these abilities have been well documented in the research literature. For instance, older adults have reduced sensory and perceptual function (Schneider & Pichora-Fuller, 2000) and STM function (Verhaeghen, Marcoen, & Goossens, 1993), as well as slowed decision and response selection processes (Kausler, 1991; Salthouse, 1996) and motor speed (Deary & Der, 2005). Reduced speed for older adults on the LC–PC tests may involve any one or more of these abilities.

To date, most researchers of perceptual comparison tests have used them in statistical models (e.g., hierarchical, structural equation) to predict age-related declines in cognition. Additional research strategies are needed, however, in order to decompose the sources of age differences on these tests at the level of cognitive operations and to assess their contributions to generalized cognitive decline. At present, we do not know which component or compo-

nents of the LC–PC tests account for age-related variance in higher level cognition, nor do we know whether these tests predict age effects in different higher level tasks for different reasons. For example, slowing of the STM component may be most important in predicting age differences in a WM test, whereas slowing of response selection may account for age differences on a higher level test with complex response selection demands.

In sum, there are important, unresolved questions about the measurement and conceptualization of cognitive processing speed. We know that perceptual comparison test scores show higher correlations with age than do those of most other measures of cognition, and that they are among the best predictors of age-related cognitive decline. It is also reasonable to hypothesize that age differences in relatively low-level cognitive processes are important in understanding age differences in all types of cognition. It follows, then, that by identifying the locus or loci of age differences on perceptual comparison tests and the nature of their predictive power, we may learn more about the nature of cognitive aging.

Overview of Study

The present study focused on the measurement of cognitive processing speed, using computerized versions of the LC–PC tests. The goals were to identify age-sensitive cognitive abilities that contribute to performance on these tests and to examine their contributions to age differences on tests of higher level cognition. We identified two lower level cognitive abilities that we hypothesized were important for efficient performance: STM and perception. As measures of higher level cognition, we selected two tests of WM (verbal and location three-back versions of the *n*-back test) and two tests of reasoning ability (the Shipley Test of Abstraction [Shipley, 1940] and Raven's Advanced Progressive Matrices [Raven, Raven, & Court, 1998]).

We hypothesized that STM processes play a critical role in performance on the LC–PC tests for several reasons. First, many of the stimuli have more elements than can be attended simultaneously, and because the stimuli are meaningless, the elements are not easily organized into a single perceptual unit. In addition, the stimuli are presented several centimeters apart and cannot be viewed simultaneously. Temporarily storing all or part of a stimulus should facilitate performance, and being able to do so quickly and efficiently may contribute to overall speed.

To evaluate the role of STM, defined here as temporary storage—but not manipulation—of information, we implemented an experimental manipulation intended to affect the likelihood of test takers using STM. The manipulation involved varying the physical distance between the stimuli in each pair. Three conditions were utilized: the standard condition, for which spacing was the same as in the paper-and-pencil tests; a far condition; and a near condition. We assumed that the smaller the distance, the more easily stimuli could be compared using purely sensory-perceptual mechanisms. When stimuli are far apart, either all of the information must be loaded into STM or, if that is not possible, participants must load a portion at a time and compare the two stimuli in a piecemeal fashion. In ei-

ther case, using STM takes time and would be expected to produce an increase in response times (RTs), as well as an increase in age differences. We also tested the hypothesis that performance in the standard and far conditions would explain additional age-related variance on the WM and reasoning tasks, above and beyond the predictive ability of the near condition.

In addition, we examined the role of STM using the variations in information load found in the paper-and-pencil LC–PC tests (i.e., three, six, or nine letters in each string; three, six, or nine lines in each pattern). We assumed that longer letter strings and more complex patterns represented larger information loads and, thus, should require more STM resources in order to complete the comparison process. A pattern of increased age differences with increases in load could be interpreted as a decline in STM (i.e., if older adults have lower memory for elements in the first array as the second array is examined, this would necessitate more movements of attention and more eye movements between the arrays in order to compare the two arrays, resulting in slower RTs). We predicted that age differences would increase as information load increased and that conditions with higher information load would lead to unique WM and reasoning task variance beyond that of the lower load conditions.

The second hypothesized component of the perceptual speed tests was perception. Efficient perceptual mechanisms are important for bottom-up identification of the stimuli on these tests, especially since the stimuli have no preexisting mental representations. In order to test the role of perception, we compared performance on the standard version of the perceptual speed tests with performance on conditions in which either 15% or 30% of the pixels were removed from the stimuli. We predicted that increased perceptual degradation would lead to slower RTs and an increase in age differences. We also tested whether performance with perceptually degraded stimuli would account for a significant amount of age-related variance in higher level cognitive tests of WM and reasoning, above and beyond the contribution of performance in the standard LC–PC test condition.

In sum, the present study focused on two components of performance on the LC–PC tests: STM and perception. We hypothesized that the levels of demand for each component would affect age differences, even after we transformed the RT data in order to account for a general slowing factor. Additional regression analyses were used in order to determine whether either type of demand shared age-related variance with performance on tests of higher level cognition. All analyses were conducted after controlling for low-level vision, as measured by visual contrast sensitivity (VCS) scores.

METHOD

Participants

Participants (see Table 1) included 44 younger (ages, 18–27 years) and 44 older (ages, 60–81 years) adults. Younger adults were undergraduate students; older adults were community-dwelling individuals. All of the participants were paid for their participation. Inclusion criteria included self-reports of good health and normal

Table 1
Participant Characteristics

Descriptive Measure	Younger Adults		Older Adults	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Age	21.6	2.9	69.3	5.7
Years of education	14.8	1.7	16.7	2.4
Mini-Mental Status Exam (MMSE) ^a	—	—	29.2	0.9
Beck Depression Inventory ^b	5.5	4.4	3.3	3.3
Beck Anxiety Inventory ^b	5.1	3.9	2.8	3.4
Shipley Vocabulary ^c	32.6	3.3	36.5	3.1
Snellen visual acuity, left ^d	20.2	1.1	21.5	2.8
Snellen visual acuity, right ^d	20.3	1.7	22.6	4.3
FACT VCS ^e (cycles/degree)				
1.5 (Row A)	97.6	6.5	83.8	19.6
3 (Row B)	150.2	17.2	116.2	32.9
6 (Row C)	164.1	23.9	101.4	40.6
12 (Row D)	90.9	18.0	38.4	24.6
18 (Row E)	47.6	17.1	16.5	12.9

Note—FACT, Functional Acuity Contrast Test; VCS, visual contrast sensitivity. ^aMaximum score = 30. The MMSE was not administered to younger adults. ^bMaximum score = 63. ^cMaximum score = 40. ^dSnellen visual acuity is reported as 20/____, with 20/20 corresponding to perfect vision. ^eEach row on the FACT card displayed a different spatial frequency (i.e., cycles/degree). Scores represent the lowest level of contrast correctly identified on each row and were computed by taking the log of 1/contrast.

or corrected-to-normal vision. Exclusion criteria included a history of neurological disorders, serious psychiatric illness, or other major illnesses that could affect cognitive functioning (e.g., heart attack, diabetes, lung disease, kidney disease, uncontrolled high blood pressure), current use of psychotropic medications, reported learning disabilities (younger adults), current consumption of more than four alcoholic drinks per day (older adults), or scores of less than 27 on the Mini-Mental State Exam (MMSE; Folstein, Folstein, & McHugh, 1975; older adults). In addition, screening with the Beck Depression Inventory–II (Beck, Steer, & Brown, 1996) and the Beck Anxiety Inventory (Beck & Steer, 1990) was used in order to eliminate individuals with scores above the normal-to-mild range for depression and anxiety. Three older adults were replaced because they scored below criterion on the MMSE; 2 younger adults were replaced on the basis of their scores on the depression and anxiety measures.

The older adult group had completed more years of education than the younger adult group had [$t(86) = 4.28, p < .001$] and had higher scores on the Shipley–Hartford Vocabulary Test (Shipley, 1940) [$t(86) = 5.87, p < .001$].

Younger adults had better visual acuity than did older adults [right eye, $t(85) = 3.20, p = .002$; left eye, $t(86) = 2.80, p = .006$], as determined using the Snellen chart on the MIS Pocket Vision Guide, with participants utilizing the visual aids that they normally used for reading.

Measures

LC–PC Tests

These tests were computerized versions of the paper-and-pencil tests of the same name (Salthouse & Babcock, 1991; see Figure 1). All aspects of stimulus construction and layout were identical to those in the original version, except that the computerized tasks presented one pair of stimuli at a time. Participants pressed a response box button marked “Same” if the two stimuli in a pair were identical and a button marked “Different” if they were not identical. They were asked to respond as quickly as possible without making errors.

For the LC conditions, there were three levels of information load—low, medium, and high—as there were in the original LC–PC tests. These levels were represented by stimuli consisting of three, six, or nine letters, respectively. The stimuli were created by ran-

domly generating sequences of consonants. Care was taken to avoid common acronyms within the sequences. Stimuli were presented in 10-point Arial Alternative Regular font. To create pairs that were not identical, one letter was changed in the beginning, middle, or end of one of the letter strings.

For the PC conditions, low, medium, and high levels of information load were represented by stimuli consisting of three, six, or nine line segments, respectively. The stimuli were created by randomly combining line segments in an invisible 4×4 grid. Nameable patterns were excluded. Each pattern was enclosed in a black box measuring 1.4×1.4 cm. In order to create pairs that were not identical, one line segment was changed in one of the patterns.

One block of 60 trials was constructed for each condition in each part of the experiment. Each block contained equal numbers of items with low, medium, and high information load, with their order randomized. A random half of the pairs in each block in each condition contained stimuli identical to each other; the other half contained stimuli that were different. Practice trials for each condition were completed prior to the test trials.

Spacing: Standard, near, and far conditions. In the standard condition, pairs of stimuli were presented side by side, with spacing comparable to the spacing of items in the original paper-and-pencil tests. The first letters of the letter strings in each pair were separated by 6.5 cm, and the boxes containing the patterns were separated by 2.9 cm. In the near condition, the stimuli were presented close to one another, with one stimulus in the pair presented directly below the other in the center of the computer screen, separated by 0.1 cm. The rationale for choosing to align the near stimuli in this manner was to minimize as much as possible the distance that the eyes had to travel in order to compare them. This was particularly critical for the letter stimuli, since even the closest horizontal arrangement would have necessitated substantial left-to-right eye movements. In the far condition, the stimuli were presented side by side but farther apart, in such a way that the start of the letter strings in each pair of letter stimuli was separated by 25 cm, and the boxes containing the patterns were separated by 28 cm.

Perceptual degradation: Standard, medium-degradation, and high-degradation conditions. The standard condition was identical to the standard condition described above. For the medium-degradation condition, 15% of the pixels in each letter string or pattern were randomly removed. In the high-degradation condition, 30% of the pixels were randomly removed.

Original LC–PC Tests

In these paper-and-pencil versions (Salthouse & Babcock, 1991), participants compared stimuli in each pair of letter strings or patterns. They were instructed to respond by writing an “S” on the line separating the pair if the stimuli were identical and a “D” if they were different. For each test, the goal was to complete as many items as possible in 30 sec on each of two pages. The score for each test was the number of correct responses minus the number of incorrect responses.

Tests of WM

The WM tests consisted of a verbal and a location three-back test. Both tests require temporary storage of stimuli and information about their recency. This information must also be continuously updated, with relevant information changing as each stimulus is presented. Older adults have been shown to perform more poorly than younger adults on this task (Dobbs & Rule, 1989; Hartley, Speer, Jonides, Reuter-Lorenz, & Smith, 2001; McCabe & Hartman, in press; Vaughan, Basak, Hartman, & Verhaeghen, 2008; Verhaeghen & Basak, 2004).

On these computerized tests, one stimulus was presented at a time, with the instruction to decide whether it matched the stimulus that appeared three positions earlier. Participants responded by pressing the “Yes” key if the current stimulus was identical to the three-back stimulus and the “No” key if it was not. In the letter three-back test, stimuli consisted of single consonants presented in 18-point Arial Alternative Regular font in the center of the screen.

A **B**

Figure 1. Stimuli from the letter comparison and pattern comparison tests. (A) From top to bottom row: Near spacing with high information load, standard spacing with low information load, far spacing with medium information load. (B) From top to bottom row: Standard condition with medium information load, medium degradation with high information load, high degradation with low information load.

Stimuli were drawn from a pool of nine consonants (B, H, K, L, N, Q, R, S, and X). The location three-back condition utilized a 3×3 grid (4.25×4.25 in.) that was always present in the center of the screen. Each stimulus consisted of a black "X" placed in one of the nine boxes in the grid.

Each test consisted of four 30-item sequences of stimuli, with 10-sec breaks between sequences. Thirty percent of the items in each sequence were three-back matches. There were no constraints placed on the occurrence of lure items (e.g., four-back matches). Stimuli were presented at the rate of 750 msec per item with 1,750-msec interstimulus intervals. Before beginning the test, participants were shown sample items, followed by two short practice sequences.

Tests of Reasoning

The Abstraction Test is a subtest of the Shipley Institute of Living Scale (Shipley, 1940) and a standardized measure of verbal reasoning ability. Each of the 20 items, worth two points apiece, comprised a sequence of letters, numbers, or words constructed according to a different rule. Participants were instructed to discover the rules and write down the next item in each sequence. This test had a 10-min time limit.

Raven's Advanced Progressive Matrices (Raven et al., 1998), a nonverbal reasoning test, comprised a set of series-completion prob-

lems. Participants were required to select the pattern that completed each series of patterns. Set 1 was a practice set; Set 2 contained 36 problems. The score consisted of the number of correct Set 2 items completed within 20 min.

Visual Contrast Sensitivity

All analyses were conducted after statistically controlling for VCS. Older adults are known to have reduced VCS (Schneider & Pichora-Fuller, 2000), and a number of studies have shown significant relationships between age differences in sensory function and intelligence (e.g., Anstey, Luszcz, & Sanchez, 2001; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Salthouse, Hancock, Mein, & Hambrick, 1996).

VCS was measured using the Functional Acuity Contrast Test (FACT; Ginsburg, 1998), with participants wearing the visual aids (i.e., glasses, contact lenses) that they normally used for reading. The test consisted of a chart of patches of parallel lines that varied in spatial frequency and contrast. It was placed approximately 18 in. from each participant's face. Participants were asked to decide for each patch whether the lines were vertical, tilted to the right, or tilted to the left. Responses were recorded separately for each eye. Scores represented the mean performance for both eyes, except for several individuals with poorer than 20/50 visual acuity in one eye, for whom only performance for the better eye was included.

Procedure

The tests were administered individually across two sessions on different days. Each session lasted approximately 90 min, and the two sessions were separated by no more than 10 days. All participants were screened for health problems via telephone prior to testing. At the start of Session 1, older adults completed the MMSE (Folstein et al., 1975). There were no other differences in procedure for younger and older adults.

During the first session, the computerized LC-PC tasks that involved the manipulation of spacing were administered. The standard condition was always administered first, followed by the far and the near conditions, presented in counterbalanced order across participants. The order of the LC and PC tests was also counterbalanced, with a consistent ordering for each participant for the three conditions. After finishing these tests, participants completed the Vocabulary and Abstraction Tests, followed by one of the three-back tests. Half of the participants received the letter task, and the other half received the location task. The depression and anxiety screening inventories were administered next. The VCS and visual acuity tests were administered either at the end of Session 1 or at the start of Session 2.

Session 2 included the administration of LC-PC conditions in order to examine the effects of perceptual degradation. The standard conditions of the LC and PC tests were completed first by all participants, followed by the medium-degradation and the high-degradation conditions in counterbalanced order. All other counterbalancing procedures were identical to those used during Session 1. Following the computerized LC-PC tasks, participants completed the Raven's Advanced Progressive Matrices. Next, either the letter or location three-back test was given, depending on which had been administered in the first session. Participants then completed the paper-and-pencil LC-PC tests.

RESULTS

The level of significance was set at $p = .05$.

The results are presented in five sections. In the first section, we present preliminary analyses involving VCS, and the second through fourth sections constitute the primary analyses and focus on the computerized LC-PC tests. The second section includes analyses of the standard condition of the computerized LC-PC tests. The third section focuses on the spacing manipulations, and in the fourth section, we examine the perceptual degradation manipulations. In analyzing the computerized LC-PC tests, we included results of ANCOVA procedures that included VCS as a covariate, as well as hierarchical regression models with which we examined the contributions of VCS, information load, spacing, and perceptual degradation to age differences on tests of WM and reasoning. The fifth and final section comprises a check on the validity of the computerized version of the LC-PC tests, including analyses that test the equivalence of the computerized and paper-and-pencil versions of the LC-PC tests. In these last analyses, we also compared the two versions of the tests in their ability to account for age differences on tests of higher level cognition.

In each section, we focused analyses on RTs rather than on accuracy. Preliminary examination of accuracy indicated high levels of performance for younger and older adults, with the proportion correct varying between .91 and .99, and no significant age differences.

Analyses of RTs included only correct responses. Excluding RTs more than 3 *SDs* from the mean RT for a given participant and condition resulted in the elimina-

tion of very few RTs (younger adults, 1.0%; older adults, 0.9%). Four younger and 4 older adults were also replaced because their accuracy was less than 80% in at least one LC-PC test condition.

All ANCOVAs were conducted after a z score transformation of latencies—that is, $z = (\text{condition } M - \text{overall } M) / \text{condition } SD$, for each individual for each condition. The transformation was used in order to rescale RTs to a standardized scale (Faust, Balota, Spieler, & Ferraro, 1999; see also Bush, Hess, & Wolford, 1993), which should equate global processing parameters, such as speed, between the two age groups. Any significant age-related interactions found after this z transformation should therefore reflect the contribution of factors above and beyond a basic slowing factor.

In the regression analyses involving WM and reasoning, we used the combined mean of the raw RTs for the LC and PC tests when entering these tests as a predictor. All partial correlations between the LC and PC tests for each condition, controlling for age group, were significant (all $ps < .001$; range of $r(85) = .42$, for medium-degradation with low information load, to $r(85) = .74$, for near spacing with low information load). To measure WM ability, we used the three-back tests (Table 2). With age group partialled out, the two three-back measures were significantly correlated [$r(85) = .46, p < .001$]. Preliminary analysis of these tests, using an age group $\times$ stimulus type (letter, location) ANOVA, indicated reduced accuracy for older adults [$F(1,86) = 96.33, MS_e = 0.01, p < .001, \eta_p^2 = .53$] and higher accuracy on the location than on the letter test [$F(1,86) = 5.06, MS_e = 0.01, p = .03, \eta_p^2 = .06$]. The interaction was not significant. In regression analyses, we used the mean of the scores on the letter and location three-back tests.

For predicting reasoning ability, we used a composite score consisting of the mean of the z scores for the Abstraction and Matrices tests. The results on the two reasoning tests were significantly correlated with each other, after partialing out age group [$r(85) = .60, p < .001$], and both sets of scores showed reliable age differences [Abstraction Test, $t(86) = 6.30, p < .001$; Matrices, $t(86) = 10.28, p < .001$] (see Table 2).

Table 2
Performance of Younger and Older Adults on Tests of Working Memory, Reasoning, and the Paper-and-Pencil Letter and Pattern Comparison (LC-PC) Tests

Measure	Younger Adults		Older Adults	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Three-Back ^a				
Letters	0.80	0.10	0.64	0.09
Locations	0.83	0.09	0.66	0.10
Raven's APM ^b	21.8	4.3	11.4	5.1
Shipley Abstraction ^c	35.1	4.4	27.8	6.3
Paper-and-Pencil LC-PC Tests ^d				
Letter comparison	25.6	5.2	18.3	4.7
Pattern comparison	42.7	6.6	31.9	5.7

Note—APM, Advanced Progressive Matrices. ^aScores, mean proportion correct. ^bScores, no. items completed correctly in 20 min. ^cScores, no. items completed in 10 min out of a maximum score of 40. ^dScores, no. correct minus no. errors, for items completed in 1 min.

Visual Contrast Sensitivity

For the analysis of VCS FACT scores, averaged across left and right eyes (see Table 1), we used a logarithmic transformation [$\log(1/\text{contrast})$], as was recommended by Gilmore (2002). A 2 (age group) $\times$ 5 (spatial frequency: 1.5, 3, 6, 12, 18 cycles/degree) ANOVA showed significant main effects of spatial frequency [$F(4,340) = 480.22$, $MS_e = 0.02$, $p < .001$, $\eta_p^2 = .85$] and of age group [$F(1,86) = 102.09$, $MS_e = 0.08$, $p < .001$, $\eta_p^2 = .55$]. These main effects were qualified by an interaction [$F(4,344) = 46.80$, $MS_e = 0.02$, $p < .001$, $\eta_p^2 = .36$]. Performance differed among all five levels of spatial frequency ($ps < .05$), with the exception of 3 versus 6 cycles/degree. Age differences were significant ($ps < .05$) at all frequencies and increased in magnitude as spatial frequency increased.

In order to assess the relationship between age and cognitive factors after controlling for the contribution of basic

visual ability, a composite mean of the z scores for each spatial frequency of the FACT was used as a covariate in all ANCOVAs and as a first predictor in all hierarchical regression analyses. This composite score was justified by high intercorrelations among VCS scores (range: .59 to .86, $ps < .001$).

Computerized LC–PC Tests: The Standard Condition

These analyses utilized combined RT data from the standard condition in both testing sessions. With age partialled out, the RTs from the two sessions were significantly correlated [low information load, $r(85) = .879$, $p < .001$; medium information load, $r(85) = .799$, $p < .001$; high information load, $r(85) = .731$, $p < .001$]. See Table 3 for raw RTs. The z -transformed RTs were analyzed by means of a 2 (age group: young, old) $\times$ 2

Table 3
Letter and Pattern Comparison (LC–PC) Tests: Means and Standard Deviations
of Response Times (RTs, in Milliseconds) of Younger and Older Adults As a
Function of Information Load, Spacing, and Degradation

LC–PC Test Condition	Younger Adults				Older Adults			
	LC		PC		LC		PC	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Standard Condition ^a								
Low load	1,075	160	949	129	1,650	408	1,439	372
Medium load	1,948	343	1,232	254	3,102	696	1,965	418
High load	2,997	551	1,407	375	4,637	1,004	2,394	585
Mean	2,007	331	1,196	244	3,130	671	1,933	438
Spacing Conditions								
Near Spacing								
Low load	916	165	968	177	1,217	286	1,367	311
Medium load	1,427	255	1,337	309	2,092	441	2,106	545
High load	2,014	395	1,657	409	2,899	514	2,776	753
Mean	1,449	258	1,317	281	2,070	394	2,082	521
Standard Spacing								
Low load	1,108	175	1,007	164	1,692	472	1,563	500
Medium load	2,025	391	1,341	334	3,206	852	2,129	485
High load	3,137	607	1,586	501	4,810	1,283	2,664	736
Mean	2,087	362	1,308	316	3,240	849	2,124	539
Far Spacing								
Low load	1,157	217	1,182	249	1,662	382	1,759	372
Medium load	2,257	455	1,466	380	3,366	712	2,531	696
High load	3,394	734	1,816	532	5,113	1,024	3,439	845
Mean	2,267	439	1,488	380	3,383	673	2,598	618
Degradation Conditions								
Standard								
Low load	1,043	162	891	125	1,608	391	1,316	277
Medium load	1,871	337	1,123	229	2,999	635	1,801	392
High load	2,857	563	1,229	320	4,463	937	2,124	518
Mean	1,922	331	1,078	216	3,024	604	1,743	381
Medium Degradation								
Low load	1,128	202	986	219	1,760	421	1,823	879
Medium load	2,116	448	1,347	468	3,223	729	2,659	1,116
High load	2,886	607	1,578	526	4,645	1,105	3,429	1,425
Mean	2,048	388	1,319	406	3,211	713	2,699	1,209
High Degradation								
Low load	1,346	343	1,243	271	2,236	554	2,292	901
Medium load	2,447	497	1,685	496	3,793	842	3,441	1,461
High load	3,403	772	1,964	642	5,595	1,386	4,378	1,711
Mean	2,417	514	1,649	455	3,907	877	3,430	1,373

^aThese data represent mean RTs from the standard LC–PC conditions in Sessions 1 and 2.

(stimulus type: letters, patterns) $\times$ 3 (information load: low, medium, high) ANCOVA.

Results showed main effects of stimulus type [$F(1,85) = 1,323.12$, $MS_e = 0.08$, $p < .001$, $\eta_p^2 = .94$] and of information load [$F(2,170) = 5,881.13$, $MS_e = 0.01$, $p < .001$, $\eta_p^2 = .99$], which were qualified by a two-way interaction between stimulus type and information load [$F(2,170) = 1,481.52$, $MS_e = 0.02$, $p < .001$, $\eta_p^2 = .95$] and a three-way interaction among stimulus type, information load, and age [$F(2,170) = 5.85$, $MS_e = 0.02$, $p = .004$, $\eta_p^2 = .06$]. The two-way interaction was driven by a significant RT advantage for patterns relative to letters at all load levels (all $ps < .05$), which increased in magnitude as load increased. The three-way interaction indicated that both age groups showed significant increases in RTs as information load increased and also showed slower RTs for letters; however, in contrast to the similar performance for older and younger adults at the low- and medium-load levels, younger adults were significantly faster for both letters ($p = .001$) and patterns ($p = .002$) in the high-load condition, and this age difference was numerically larger for patterns.

There was no effect of the VCS covariate nor any interactions involving the covariate.

Predicting higher level cognition. We used a set of hierarchical regression models using raw RTs to test the contribution of the standard LC–PC tests—in particular, the role of information load—to age differences on tests of WM and reasoning (see Table 4 for correlations and Table 5 for regression analyses).

In all subsequent analyses, VCS was entered as the first predictor, followed in hierarchical order by versions of the LC–PC tests from least to most complex.

In all models, age group was a significant predictor above and beyond VCS. VCS alone predicted 35.7% of three-back test variance ($p < .001$), and entering age in the next step contributed an additional 18.5% ($p < .001$);

including VCS in the model as a first predictor reduced the contribution of age by 65.0% relative to the model with age as the sole predictor. When the low information load condition was entered as a predictor after VCS, it explained a significant 17% additional variance ($p < .001$). Including medium information load in the next step contributed 3.1% unique variance ($p = .02$), but adding the high-load condition did not significantly increase the amount of variance accounted for ($p = .98$). In the final model, with all predictors included, age group still contributed a significant 3.8% of variance ($p = .007$) and showed a reduction of 79.5% of the age effect relative to the unique variance from age group after entering the VCS predictor.

Similar to the analytic method presented above, in all subsequent descriptions of age effect reductions, the percentage reported reflects the degree of reduction in variance from the age group predictor when comparing the unique variance from age group after removing the VCS predictor (i.e., the age-alone model) with the unique variance from age group that remains in a fuller model after including VCS and several LC–PC predictors.

When predicting reasoning ability, age group was a significant factor after VCS was entered as a first predictor (31.3%, $p < .001$), although the unique variance attributable to age was lowered by 62.5%, to 18.2% ($p < .001$). Beyond VCS, the low information load condition was significantly predictive of reasoning ability (18.5%, $p < .001$). As with the prediction of WM, medium information load accounted for additional unique variance (4.3%, $p = .006$), but adding high information load did not ($p = .27$). In the full model, age group still explained an additional 2.7% of the variance ($p = .03$), but the age effect at this point was reduced by 85.2%.

Computerized LC–PC Tests: Effects of Spacing

With the next set of analyses, we examined the effects of spacing between stimuli on the LC–PC tests. The re-

Table 4
Intercorrelations of Variables Included in Regression Analyses With and Without Age Group Partialled Out

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Low load	—	.94**	.93**	.91**	.94**	.91**	.93**	.78**	.81**	-.75**	.55**	-.67**	-.67**
2. Medium load	.87**	—	.98**	.91**	.98**	.94**	.96**	.83**	.85**	-.79**	.57**	-.71**	-.71**
3. High load	.85**	.96**	—	.91**	.97**	.96**	.97**	.83**	.87**	-.79**	.56**	-.70**	-.71**
4. Near spacing	.82**	.81**	.82**	—	.89**	.93**	.92**	.85**	.85**	-.72**	.55**	-.63**	-.68**
5. Standard spacing	.88**	.96**	.93**	.77**	—	.92**	.91**	.76**	.80**	-.77**	.54**	-.70**	-.69**
6. Far spacing	.81**	.86**	.90**	.84**	.83**	—	.94**	.86**	.88**	-.78**	.56**	-.68**	-.68**
7. Standard	.86**	.91*	.94**	.83**	.80**	.86**	—	.86**	.88**	-.77**	.54**	-.70**	-.69**
8. Medium degradation	.57**	.63**	.64**	.69**	.53**	.71**	.70**	—	.94**	-.71**	.53**	-.61**	-.69**
9. High degradation	.61**	.66**	.70**	.69**	.59**	.73**	.73**	.89**	—	-.72**	.53**	-.59**	-.69**
10. Paper-and-pencil LC–PC	-.50**	-.56**	-.57**	-.44**	-.55**	-.53**	-.53**	-.43**	-.43**	—	-.51**	.71**	.77**
11. VCS	.10	.06	.07	.09	.08	.06	.07	.04	-.05	—	—	-.60**	-.56**
12. Three-back	-.33**	-.35**	-.33**	-.22*	-.38**	-.28**	-.27*	-.21	-.13	.41**	—	—	.77**
13. Reasoning	-.34**	-.39**	-.40**	-.36**	-.37**	-.32**	-.38**	-.39**	-.37**	.56**	-.14	.53**	—

Note—The bivariate correlations are presented above the diagonal. The partial correlations, after controlling for age group, are beneath the diagonal. Low load, mean of letter comparison (LC) and pattern comparison (PC) raw response times (RTs) for the standard and low information load conditions in Sessions 1 and 2. Load conditions corresponded to the number of elements in a stimulus (three, six, or nine letters or line segments). Medium load, mean of LC and PC raw RTs for the standard and medium information load conditions in Sessions 1 and 2. High load, mean of LC and PC raw RTs for the standard and high information load conditions in Sessions 1 and 2. VCS, visual contrast sensitivity. Three-back accuracy was defined as the mean proportion correct for the combined letter and location tasks. The reasoning score was defined by the mean z score for the Shipley Abstraction and the Raven's Advanced Progressive Matrices tests.

Table 5
Results of Hierarchical Regression Analyses
of Standard Letter and Pattern Comparison (LC-PC) Tests
Using Information Load and Age to Predict Working Memory
and Reasoning Ability

Predictor	R^2	ΔR^2	F Change	df	p
Criterion: Three-Back Accuracy					
Age group	.528	.528**	96.33	1,86	<.001
VCS	.357	.357**	47.85	1,86	<.001
Age group	.185	.185**	34.50	1,85	<.001
VCS	.357	.357**	47.85	1,86	<.001
Low load LC-PC	.528	.170**	30.65	1,85	<.001
Medium load LC-PC	.559	.031*	5.88	1,84	.017
High load LC-PC	.559	.000	0.00	1,83	.982
Age group	.596	.038**	7.68	1,82	.007
Criterion: Reasoning Score					
Age group	.486	.486**	81.23	1,86	<.001
VCS	.313	.313**	39.24	1,86	<.001
Age group	.495	.182**	30.61	1,85	<.001
VCS	.313	.313**	39.24	1,86	<.001
Low load LC-PC	.498	.185**	31.32	1,85	<.001
Medium load LC-PC	.541	.043**	7.93	1,84	.006
High load LC-PC	.548	.007	1.23	1,83	.270
Age group	.575	.027*	5.11	1,82	.026

Note—The regression analyses utilized the combined LC and PC raw response times for each condition of the standard conditions in Sessions 1 and 2. Load conditions corresponded to the number of elements in a stimulus (three, six, or nine letters or line segments). Three-back accuracy was defined as mean proportion correct for the combined letter and location tasks. The reasoning score was defined by the mean z score for the Shipley Abstraction and the Raven's Advanced Progressive Matrices tests. VCS, visual contrast sensitivity. * $p < .05$. ** $p < .01$.

sults of primary importance comprised the effects involving the spacing manipulation. Although there were also significant main effects of stimulus type and information load, as well as interactions between them and of each with age group, these showed the same pattern as the analysis of the standard condition (see above) and will not be reported here. See Table 3 for raw RTs in the spacing conditions.

The z -transformed RT data were analyzed by means of a 2 (age group: young, old) $\times$ 2 (stimulus type: letters, patterns) $\times$ 3 (information load: low, medium, high) $\times$ 3 (spacing level: near, standard, far) ANCOVA. The main effect of spacing was significant [$F(2,170) = 450.78$, $MS_e = 0.11$, $p < .001$, $\eta_p^2 = .84$] but was qualified by several interactions. Spacing interacted with stimulus type [$F(2,170) = 311.11$, $MS_e = 0.07$, $p < .001$, $\eta_p^2 = .79$] and with information load [$F(4,344) = 164.87$, $MS_e = 0.03$, $p < .001$, $\eta_p^2 = .66$]. However, because two of the three-factor interactions were also significant, we focus here on describing these effects.

First, the results showed an interaction of spacing, information load, and stimulus type [$F(4,340) = 214.19$, $MS_e = 0.03$, $p < .001$, $\eta_p^2 = .72$]. An exploration of this interaction showed that in all spacing conditions, RTs increased as load increased. For letters, the standard and far spacing conditions were similar, whereas RTs in the near condition were significantly faster ($ps < .05$) and showed a less steep slope as load increased. For patterns, the near and standard spacing conditions were similar, whereas

RTs in the far condition were significantly slower ($ps < .05$), although RTs in all three spacing conditions showed similar slopes across information loads.

Second, there was an interaction of spacing, information load, and age [$F(4,344) = 3.26$, $MS_e = 0.03$, $p = .01$, $\eta_p^2 = .04$]. For both age groups, RTs were slower as information load increased and also as spacing increased; the interaction is driven by significantly slower RTs for older adults relative to younger adults for the far spacing, high-load condition ($p < .001$).

There was no main effect nor any interaction involving the VCS covariate.

Predicting higher level cognition. Regression analyses were next used in order to examine the contributions of spacing effects in the LC-PC tests to age differences in WM and reasoning (see Table 4 for correlations and Table 6 for regression analyses). In all models, age group was a significant predictor. As indicated above, age group alone accounted for a unique 18.5% ($p < .001$) of the variance in WM. Entering the near condition after VCS accounted for 12.8% ($p < .001$) of WM variance. When the standard condition was added, it accounted for an additional 7.3% variance ($p < .001$). Adding in the far condition did not account for any additional unique variance ($p = .34$). In the final model, with all three LC-PC conditions included in hierarchical order, age group remained a significant predictor, accounting for 4.8% of the variance ($p = .002$), but its contribution was reduced by 74.1% relative to the model with age group alone.

Analogous models were tested in the prediction of reasoning ability. As was presented earlier, age group by itself accounted for a unique 18.2% ($p < .001$) of the variance in reasoning ability. Beyond VCS, the near condition contributed 19.6% of reasoning variance ($p < .001$). When the standard condition was added to the model, it accounted for an additional 2.3% ($p = .04$). Adding the far condition did not account for additional variance ($p =$

Table 6
Results of Hierarchical Regression Analyses Using Letter and
Pattern Comparison (LC-PC) Spacing Conditions and Age
Group to Predict Working Memory and Reasoning Ability

Predictor	R^2	ΔR^2	F Change	df	p
Criterion: Three-Back Accuracy					
VCS	.357	.357**	47.85	1,86	<.001
Near LC-PC	.485	.128**	21.09	1,85	<.001
Standard LC-PC	.558	.073**	14.00	1,84	<.001
Far LC-PC	.563	.005	0.92	1,83	.339
Age group	.611	.048**	10.11	1,82	.002
Criterion: Reasoning Score					
VCS	.313	.313**	39.24	1,86	<.001
Near LC-PC	.510	.196**	34.00	1,85	<.001
Standard LC-PC	.533	.023*	4.14	1,84	.045
Far LC-PC	.533	.000	0.02	1,83	.888
Age group	.570	.038**	7.18	1,82	.009

Note—The regression analyses utilized the combined LC and PC raw response times for each condition. Three-back accuracy was defined as the mean proportion correct for the combined letter and location tasks. The reasoning score was defined by the mean z score for the Shipley Abstraction and the Raven's Advanced Progressive Matrices tests. VCS, visual contrast sensitivity. * $p < .05$. ** $p < .01$.

.89). In the final model, with all predictors entered in hierarchical order, age group still accounted for a significant 3.8% of the variance ($p = .009$), but the effect was reduced by 79.1% relative to the age-only model.

Computerized LC–PC Tests: Effects of Perceptual Degradation

Analysis of the effects of perceptual degradation was conducted in the same way as that for the spacing manipulation. The results of primary importance comprise those involving the degradation manipulation and its interactions with other variables. Thus, effects involving stimulus type and information load are not reported here, except when they interact with perceptual degradation. Overall, the pattern of results for effects not reported here was identical to those from the analysis of the standard condition (see Table 3 for raw RTs).

The ANCOVA showed a main effect of degradation [$F(2,170) = 392.91$, $MS_e = 0.12$, $p < .001$, $\eta_p^2 = .82$]. Degradation interacted with information load [$F(4,340) = 64.75$, $MS_e = 0.03$, $p < .001$, $\eta_p^2 = .43$], with stimulus type [$F(2,170) = 29.39$, $MS_e = 0.08$, $p < .001$, $\eta_p^2 = .26$], and with age group [$F(2,170) = 5.13$, $MS_e = 0.12$, $p = .007$, $\eta_p^2 = .06$]. The presence of several three-way interactions led us to focus on these for interpretation.

First, there was a three-way interaction among degradation, stimulus type, and information load [$F(4,340) = 19.68$, $MS_e = 0.03$, $p < .001$, $\eta_p^2 = .19$]. For all degradation and stimulus type conditions, there was an increase in RT as load increased. For letters, the standard and medium-degradation conditions were similar, with the high-degradation condition showing consistently higher RTs ($ps < .05$). For patterns, the three degradation conditions were all different ($ps < .05$), and the magnitude of these differences increased as load increased.

Second, the interaction between degradation, information load, and age was also significant [$F(4,340) = 3.89$, $MS_e = 0.03$, $p = .004$, $\eta_p^2 = .04$]. For the standard condi-

tion, there were similar age differences at each information load level, and both age groups showed increased RTs as information load increased ($ps < .05$); for the medium- and high-degradation conditions, however, the younger and older groups were different only for the high-load condition ($ps < .05$).

Neither the four-way interaction nor any effects involving the VCS covariate were significant.

Predicting higher level cognition. Hierarchical regression models were used in order to determine whether the perceptual demands of the LC–PC tests contribute to age effects in WM and reasoning (see Table 4 for correlations and Table 7 for regression analyses).

For WM, age group alone accounted for a unique 18.5% of the variance in WM, as presented earlier. In the present set of models, the standard condition was a significant predictor when entered after VCS, accounting for 16.8% of unique three-back variance ($p < .001$). Adding the medium- ($p = .65$) and high-degradation ($p = .27$) conditions to the hierarchical model did not significantly increase the amount of variance accounted for. With all degradation conditions included, age group remained a significant predictor, explaining an additional 5.4% variance ($p = .002$). Controlling for LC–PC test performance reduced the age group effect in WM by 70.8% relative to the age-only model.

Similar analyses were conducted using reasoning ability as the dependent variable. As was noted above, age group by itself accounted for a unique 18.2% of the variance in reasoning. Entering the standard condition as a predictor after VCS resulted in a significant 22.4% ($p < .001$) of variance accounted for. Adding neither the medium-degradation condition ($p = .05$) nor the high-degradation condition ($p = .70$) to the hierarchical model accounted for any additional unique variance in reasoning. In the model with all three levels of degradation, age group remained a significant predictor, accounting for 2.2% ($p = .04$) of reasoning variance. Thus, the contribution of age

Table 7
Results of Hierarchical Regression Analyses Using Letter and Pattern Comparison (LC–PC) Degradation Conditions and Age Group to Predict Working Memory and Reasoning Ability

Predictor	R^2	ΔR^2	F Change	df	p
Criterion: Three-Back Accuracy					
VCS	.357	.357**	47.85	1,86	<.001
Standard LC–PC	.525	.168**	30.06	1,85	<.001
Medium degradation LC–PC	.527	.001	0.21	1,84	.648
High degradation LC–PC	.533	.007	1.23	1,83	.272
Age group	.588	.054**	10.78	1,82	.002
Criterion: Reasoning Score					
VCS	.313	.313**	39.24	1,86	<.001
Standard LC–PC	.538	.224**	41.26	1,85	<.001
Medium degradation LC–PC	.558	.020	3.82	1,84	.054
High degradation LC–PC	.559	.001	0.15	1,83	.704
Age group	.581	.022*	4.36	1,82	.040

Note—The regression analyses utilized the combined LC and PC raw response times for each condition. Three-back accuracy was defined as the mean proportion correct for the combined letter and location tasks. The reasoning score was defined by the mean z score for the Shipley Abstraction and the Raven's Advanced Progressive Matrices tests. VCS, visual contrast sensitivity. * $p < .05$. ** $p < .01$.

group was reduced by 87.9% after controlling for performance at all three levels of degradation.

Equivalence of the Computerized and Original LC-PC Tests

Scores on the original paper-and-pencil LC-PC tests (see Table 2) were analyzed by means of an ANOVA, with age group as a between-subjects factor and stimulus type (letters, patterns) as a within-subjects factor. Results showed a significant main effect of age group [$F(1,86) = 79.42$, $MS_e = 45.45$, $p < .001$, $\eta_p^2 = .48$], with older adults completing fewer items correctly. There was also a significant effect of stimulus type [$F(1,86) = 613.17$, $MS_e = 16.86$, $p < .001$, $\eta_p^2 = .88$] and a significant interaction of stimulus type and age group [$F(1,86) = 8.10$, $MS_e = 16.86$, $p = .006$, $\eta_p^2 = .09$]. Similar to the results found with the computerized tasks, these results indicated higher performance on the pattern than on the letter stimuli and a larger age effect for patterns than for letters.

Correlational analyses, with age group partialled out, showed a moderate association between performance on the original LC-PC tests [$r(85) = .47$, $p < .001$]. Correlations between these scores and RTs on the standard condition of the computerized LC-PC tests, with age partialled out, revealed moderate correlations as well [letter task, $r(85) = -.59$, $p < .001$; pattern task, $r(85) = -.49$, $p < .001$].

To test whether the paper-and-pencil and computerized versions of the LC-PC tests predicted age differences in higher level cognition in the same way, we conducted parallel regression analyses, first with the paper-and-pencil tests and then with the standard conditions of the computerized tests (see Table 4 for correlations and Table 8 for regressions). After entering VCS, the paper-and-pencil test accounted for 21.8% ($p < .001$) and 31.8% ($p < .001$) of the variance in WM and reasoning scores, respectively. The predictive value of age group remained significant for both measures of higher level cognition after controlling for the paper-and-pencil test and accounted for an additional 4.4% ($p = .002$) and 2.0% ($p = .03$) of the variance in WM and reasoning scores, respectively. These effects represented decreases of the effects of age group by 76.2% for WM and 89.0% for reasoning. Identical regression models using the standard condition of the computerized LC-PC tests as a predictor, entered after VCS (see Table 5), showed similar, significant unique contributions of age of 3.8% ($p = .007$) and 2.7% ($p = .03$) in predicting WM and reasoning, respectively, representing reductions in the effects of age group on higher level cognition by 78.4% and 85.2%. Thus, the two versions of the LC-PC tests have similar predictive power in accounting for age differences in cognition.

Despite these similarities, including the paper-and-pencil LC-PC task as an additional, final predictor in the models used to examine effects of load, spacing, and degradation indicates some unique variance contributed by the original tasks. In the standard condition regression analysis involving load conditions, the paper-and-pencil tasks explained a significant additional 4.6% ($p = .003$) of variance in WM and 9.7% ($p < .001$) of variance in rea-

soning, when entered after VCS and all load conditions. This reduced the contribution of age to nonsignificance in the case of reasoning ($p = .11$) but not in the case of WM ($p = .02$). A similar pattern emerged in the analyses for spacing conditions. Following VCS and the near, standard, and far conditions of the computerized tasks, the paper-and-pencil tasks accounted for a significant 4.5% ($p = .003$) and 11.9% ($p < .001$) of variance in WM and reasoning, respectively, and the contribution of age was reduced to a significant 3.2% ($p = .009$) for WM and a nonsignificant 1.5% ($p = .06$) for reasoning. For the degradation regressions, the paper-and-pencil tasks also explained significant variance in the higher level cognitive tasks beyond VCS, standard, medium-degradation, and high-degradation conditions (6.5%, $p < .001$, and 9.8%, $p < .001$, for WM and reasoning, respectively). Including the paper-and-pencil tasks rendered the age effect nonsignificant in predicting reasoning (0.9%, $p = .15$) but not WM (3.6%, $p = .006$).

DISCUSSION

The first goal of this study was to examine the source of age differences on the LC-PC tests of processing speed (Salthouse & Babcock, 1991). The results demonstrated the sensitivity of age differences to both the STM and perceptual demands of these tests in that age differences increased when demands on each of these increased. These findings held even after controlling for lower level visual ability (i.e., VCS) and after accounting for a general slowing factor. Our results are consistent with independent evidence of age differences in perception (Schneider & Pichora-Fuller, 2000) and STM (Verhaeghen et al., 1993) and, for the first time, demonstrate the relevance of these age differences to performance on the LC-PC tests. The importance of memory in processing speed is also consistent with research on another measure of processing speed: the digital symbol substitution task (Piccinin & Rabbitt, 1999).

The second goal of the study was to test the relationship of the LC-PC tests, and particularly of their age-sensitive STM and perceptual components, to age differences in higher level cognition. In the present study, hierarchical regression analyses confirmed the predictive power of the LC-PC tests in accounting for age-related variance in higher level cognition, above and beyond reduced visual ability (i.e., VCS). As in previous studies, the effect of age on tests of WM and reasoning remained significant but was greatly reduced after controlling for performance on the standard version of the LC-PC tests. Findings relevant to the role of STM showed that LC-PC conditions with higher STM demand accounted for additional variance over conditions with lower STM demand. Specifically, the medium information load condition contributed uniquely to both WM and reasoning ability above and beyond VCS and the low-load condition. Similarly, the standard-spacing condition accounted for unique variance to WM and reasoning beyond VCS and the closest spacing condition. In contrast, conditions with high perceptual demand (i.e., degradation) did not explain any further age-related variance in WM or reasoning relative to the standard con-

Table 8
Results of Hierarchical Regression Analyses Using Letter and Pattern Comparison (LC-PC) Paper-and-Pencil Tests, Computerized LC-PC Tests, and Age Group to Predict Working Memory and Reasoning Ability

Predictor	R^2	ΔR^2	F Change	df	p
Criterion: Three-Back Accuracy					
VCS	.357	.357**	47.85	1,86	<.001
LC-PC paper-and-pencil tests	.575	.218**	43.57	1,85	<.001
Age group	.619	.044**	9.77	1,84	.002
Information Load					
VCS	.357	.357**	47.85	1,86	<.001
Standard low load LC-PC	.528	.170**	30.65	1,85	<.001
Standard medium load LC-PC	.559	.031	5.88	1,84	.017
Standard high load LC-PC	.559	.000	0.00	1,83	.982
LC-PC paper-and-pencil tests	.605	.046**	9.56	1,82	.003
Age group	.629	.024*	5.31	1,81	.024
Spacing					
VCS	.357	.357**	47.85	1,86	<.001
Near spacing LC-PC	.485	.128**	21.09	1,85	<.001
Standard spacing LC-PC	.558	.073**	13.90	1,84	<.001
Far spacing LC-PC	.563	.005	0.92	1,83	.339
LC-PC paper-and-pencil tests	.608	.045**	9.47	1,82	.003
Age group	.640	.032**	7.11	1,81	.009
Perceptual Degradation					
VCS	.357	.357**	47.85	1,86	<.001
Standard degradation LC-PC	.525	.168**	30.06	1,85	<.001
Medium degradation LC-PC	.527	.001	30.06	1,84	.648
High degradation LC-PC	.533	.007	1.23	1,83	.272
LC-PC paper-and-pencil tests	.598	.065**	13.27	1,82	<.001
Age group	.634	.036**	7.92	1,81	.006
Criterion: Reasoning Score					
VCS	.313	.313**	39.24	1,86	<.001
LC-PC paper-and-pencil tests	.631	.318**	73.20	1,85	<.001
Age group	.651	.020*	4.87	1,84	.030
Information Load					
VCS	.313	.313**	39.24	1,86	<.001
Standard low load LC-PC	.498	.185**	31.32	1,85	<.001
Standard medium load LC-PC	.541	.043**	7.93	1,84	.006
Standard high load LC-PC	.548	.007	1.23	1,83	.270
LC-PC paper-and-pencil tests	.645	.097**	22.44	1,82	<.001
Age group	.656	.011	2.58	1,81	.112
Spacing					
VCS	.313	.313**	39.24	1,86	<.001
Near spacing LC-PC	.510	.196**	34.00	1,85	<.001
Standard spacing LC-PC	.533	.023*	4.14	1,84	.045
Far spacing LC-PC	.533	.000	0.02	1,83	.888
LC-PC paper-and-pencil tests	.652	.119**	28.03	1,82	<.001
Age group	.667	.015	3.69	1,81	.058
Perceptual Degradation					
VCS	.313	.313**	39.24	1,86	<.001
Standard degradation LC-PC	.538	.224**	41.26	1,85	<.001
Medium degradation LC-PC	.558	.020	3.82	1,84	.054
High degradation LC-PC	.559	.001	0.15	1,83	.704
LC-PC paper-and-pencil tests	.656	.098**	23.26	1,82	<.001
Age group	.665	.009	2.11	1,81	.150

Note—The regression analyses utilized the combined LC and PC scores. Three-back accuracy was defined as the mean proportion correct for the combined letter and location tasks. The reasoning score was defined by the mean z score for the Shipley Abstraction and the Raven's Advanced Progressive Matrices tests. VCS, visual contrast sensitivity. * $p < .05$. ** $p < .01$.

dition. Thus, even though older adults were less efficient in perception, and degradation of perceptual integrity on the LC-PC tests led to larger age effects, reduced perceptual ability did not appear to contribute to reduced WM or reasoning.

The central conclusion from the regression analyses is that the STM, rather than perceptual demands of the LC-PC tests, is most predictive of age differences in higher level cognition. Indeed, our results highlight the broader role of STM in explaining cognitive decline in older adults. In

interpreting these results, it is important to point out that up to this point, we have used the term STM to refer primarily to storage processes; nevertheless, attentional and executive processes that support the use of STM may also be involved. For example, attention is needed in order to select relevant elements of the stimuli in making perceptual comparisons and to monitor the comparison of multiple elements. Within the framework of WM models (Baddeley & Hitch, 1994; Cowan, 1999), one could hypothesize that LC-PC tests require the STM storage components of WM to temporarily hold activated representations, as well as the central executive to control the focus of attention (Cowan, 1999). By such an account, the spacing manipulation could be considered to impact both the need for storage and the difficulty of selectively attending portions of the stimuli during the comparison process. Thus, our findings regarding STM suggest involvement of a combination of storage and executive functions of the WM system, although our results do not permit us to separate them.

The presence of STM deficits in older adults is consistent with prior findings in the cognitive aging literature. Although age differences in digit span are often small or nonsignificant, effects of age in other simple span tasks (e.g., word or letter span) are as large as in complex working memory span tests such as reading, listening, or computation span tests (Verhaeghen et al., 1993). Furthermore, older adults have a reduced ability to keep even single verbal stimuli accessible over short time intervals (e.g., less than 2.5 sec; Johnson, Reeder, Raye, & Mitchell, 2002), and on tests of prospective memory, older adults perform more poorly than do younger adults over an unfilled delay of 5 sec (McDaniel, Einstein, Stout, & Morgan, 2003). Nevertheless, despite evidence for reduced STM, age differences in simple span tasks do not share as much variance with higher level cognition as tests of perceptual speed do (Bryan & Luszcz, 1996). It is possible, however, that capacity measures of STM (e.g., simple span measures) are less sensitive to critical operations affected by age than are RT measures of efficiency, which we used in the present study.

Findings of slowed storage and/or attention in WM are potentially consistent with the generalized slowing hypothesis (Salthouse, 1996; for a review, see Hartley, 2006). Slowing of storage or attention mechanisms would be expected to lead directly to increased RTs if each cognitive operation involved took longer to complete. Slowed processing also might result in the decay of stored information whenever comparisons must be conducted piecemeal. If information were lost, storage and attention processes might need to be repeated, resulting in further slowing. These interpretations are consistent with mechanisms proposed by Salthouse (1996) to explain slowing. A simple increase in the time needed to complete each cognitive process fits the definition of the limited time mechanism, in which basic cognitive operations are slowed; the possibility of information loss from early cognitive operations corresponds to the simultaneity mechanism (Salthouse, 1996). Both of these mechanisms are compatible with the present findings.

Despite support for the slowing of attention and storage mechanisms, there is also evidence in the present study

that a single slowing factor cannot explain all age differences. One piece of evidence comes from a consideration of the analyses for the LC-PC test. For these analyses, we used *z*-score-transformed RTs (Faust et al., 1999), which were expected to reduce the overall size of age effects, because transforming the data controls for individual differences—and thus age group differences—in speed. Indeed, it had this effect, and the main effect of age in analyses with transformed RTs was not significant. Nevertheless, several age-related interaction effects remained. These indicated significant age differences for the LC-PC conditions with the highest perceptual and/or STM demands but not for those with lower demands. Thus, the pattern of differential age effects across conditions cannot be attributed to a single slowing factor.

Although results from the LC-PC tests suggest a multifactorial explanation of cognitive changes in older adults, they do not tell us how many factors are involved. Age effects were found to be sensitive to both perceptual and memory demand, but we do not know from these results alone whether these effects represent one or more independent aging factors. One issue specific to the information load manipulation in the present study is the possibility that, although treated as a manipulation of STM, it could also reflect other processes, such as comparison speed. Indeed, a micro approach is not well suited to examining the relationships among age-related cognitive deficits (e.g., the perceptual and STM deficits), because it is designed primarily to illuminate cognitive components of tests and to identify the age sensitivity of specific task demands. In fact, a major criticism of the micro approach to studying cognitive aging is that it implicitly assumes modularity in the effects of age and ignores the possibility that age $\times$ manipulation interactions may represent a broad underlying deficit rather than domain-specific and independent age-related deficits (Salthouse, 2000).

The results from the regression analyses are more informative on this issue, however, and they suggest a dissociation of STM and perceptual components of the LC-PC tests and, thus, of age-related changes in these two components of cognition. Although our findings remain to be replicated, particularly with other cognitive domains, the present results suggest the existence of a broad age factor involving temporary storage and attentional processes and a separate and more specific factor reflecting perceptual ability. In addition, given that even the low-STM demand condition of the LC-PC tests accounted for a significant portion of variance in higher level cognition, there may be additional factors associated with age that remain to be identified.

Convergent Validity

In the interpretation of results from the present study, two issues potentially affect our ability to generalize fully to the larger literature. One issue is the use of extreme group methodology; the other concerns the use of computerized versions of the LC-PC tests, rather than the original paper-and-pencil version. With respect to the first, it is well known that the use of extreme group methodology may inflate age-related effects relative to studies using the full age range of adults (Conway et al., 2005). Indeed, age

group alone as a predictor accounted for more variance in WM and reasoning in the present study than in prior studies using the entire age range (e.g., 49%–53% vs. 20%–30% in Salthouse, 1991, 1992). Nevertheless, other aspects of the results were similar to those of previous studies. For instance, the degree of attenuation of the effect of age on cognition when controlling for LC–PC tests is usually close to 80% in studies with a wide age range (Salthouse, 1991, 1994, 1996; Salthouse, Toth, Hancock, & Woodard, 1997). This result is very similar to the findings in our study, in which attenuation ranged from 71% to 88%. Thus, although percentages of variance accounted for may exaggerate age effects, the pattern of relationships among variables appears constant.

As to the use of computerized tests, several aspects of the data indicated differences between the computerized and paper-and-pencil tests. First, the two versions of the test had only moderate correlations between them ($r_s = -.49$ and $-.59$, for PC and LC tests, respectively). Also, the original paper-based tasks added unique variance beyond the inclusion of the computerized LC–PC condition as predictors, for both WM and reasoning. These differences may be due in part to the fact that performance on the original tests is influenced by time spent moving attention from one item to the next, whereas in the computerized version, the time interval between trials is experimenter controlled and not a part of the measure of performance. Furthermore, speed of motor responding and visuomotor coordination may be more important in the paper-and-pencil tests than on computerized tests requiring only a simple keypress. More important, perhaps, the paper-and-pencil versions present a full page of items simultaneously, whereas the computerized tests present one item at a time. Simultaneous presentation has been shown previously to increase the size of age differences on these tests, presumably because of visual interference affecting older more than younger adults (Lustig, Hasher, & Tonev, 2006).

Despite differences between the two tests, interpretation of STM and perceptual effects on the computerized versions probably can be generalized to the original test. First of all, the manipulation of information load is built into the original tests. In addition, spacing between stimuli is relevant to performance, given that each test item in the original version is presented with space between the two stimuli. It is less obvious how the perceptual degradation manipulation is related to the original version, since stimuli are always presented in nondegraded form. Nevertheless, because the LC–PC tests are not commercially available, the perceptual quality of the stimuli may be less than optimal in some experimental settings. This should be a concern to researchers using this instrument. This may be less of an issue, however, if the LC–PC tests are used in order to predict higher level cognition, because the perceptual component does not appear to be relevant in this context.

Given that the computerized and original versions of the LC–PC tests may tap somewhat different combinations of cognitive operations, it is interesting that similar results were obtained for analogous analyses. The relationship to WM and reasoning was similar as well, with R^2 change, following the inclusion of VCS as a predictor, equal to

.20 (for predicting WM) and .23 (for predicting reasoning) for the computerized tests, and .22 (for WM) and .32 (for reasoning) for the pencil-and-paper tests. The degree of reduction in the age effect after controlling for perceptual comparison speed was also similar: 78.4% (for WM) and 85.2% (for reasoning) for the computerized tests and 76.2% (for WM) and 89.0% (for reasoning) for the paper-and-pencil tests. Just as important, the amount of shared age-related variance for the LC–PC tests and WM and reasoning in the present study was similar to that in previous studies using the paper-and-pencil version of the task (see also Salthouse, 1994, for an additional study using computerized LC–PC tests). Thus, despite our use of extreme age groups and some differences in the cognitive demands of the computerized tests, our results are comparable to those from other studies. The computerized versions are as sensitive as paper-and-pencil tests to age differences and show similar relationships to other tests of cognition.

Conclusions

The importance of this study lies in its contribution to our understanding of age differences on perceptual comparison tests and of the reasons that these tests are such strong predictors of age differences in higher level cognitive function. Basic cognitive processing speed may be a useful heuristic, but it remains an elusive construct to conceptualize and measure. Results of the present study indicate that inefficient STM processes necessary for temporary storage of information and/or attentional control are important components of one of the most common measures of processing speed and can explain a significant portion of slowing in older adults across a range of cognitive domains. It is likely that additional processes, as yet unidentified, are involved as well. For instance, cognitive operations needed for rapid decision making, response selection, and response production may also play a role. It is also possible that perceptual ability is relevant for domains of higher level cognition not examined in this study. It remains for additional studies to completely identify these abilities and to evaluate their relative importance. Only then will we attain a full theoretical understanding of the types of age-related declines in cognition that cut across cognitive domains and be able to distinguish these from domain-specific deficits.

AUTHOR NOTE

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