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General Cognitive Slowing in the Nonlexical Domain: An Experimental Validation

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Older and younger adults were tested on 4 nonlexical tasks: choice reaction time, letter classification, mental rotation, and abstract matching. A positively accelerated relation was observed between older and younger adults' latencies. Consistent with general slowing, the relation observed with the same subjects in each condition was more than 3 times as precise as in a comparable meta-analysis. Further analyses compared the ability of various models to describe the present data and also to predict the data on the basis of parameters estimated from a previous meta-analysis. Compared with linear models, the information-loss and overhead models provided more accurate accounts of general cognitive slowing in the nonlexical domain.

Cerella, Poon, and Williams (1980), in their meta-analysis of the literature on age-related cognitive slowing, observed a simple and orderly relation between older and younger adults' performances: The longer it took younger adults to perform a task, the larger the age-related difference in response latencies. Based on this relation, more than 90% of the variance in the older adults' latencies could be accounted for without considering the nature of the task (Cerella et al., 1980). Thus, Cerella et al.'s (1980) results strongly suggest a general, age-related slowing of all information processing.

An orderly relation between older and younger adults' performances similar to that reported by Cerella et al. (1980) has also been observed in subsequent meta-analyses of response latency data from healthy older and younger adults (Cerella, 1990; Hale, Myerson, & Wagstaff, 1987; Nebes & Madden, 1988) as well as in individual studies in which the same subjects performed a single task complicated in different ways (Madden, 1989; Salthouse & Somberg, 1982) or a number of different tasks of varying complexity (Smith, Poon, Hale, & Myerson, 1988). Moreover, the relation between the shorter (e.g., 25th percentile) latencies of older and younger adults as well as that between their longer (e.g., 75th percentile) latencies is the same as the relation between their average (i.e., mean or median) latencies (Smith et al., 1988). In addition, general slowing is already apparent in early middle age, as evidenced by the orderly relation between corresponding percentile latencies when an older adult group whose average age is 40 years is compared with younger adults of traditional college age (Myerson, Hale, Hirschman, Hansen, & Christiansen, 1989).

Although the robustness of Cerella et al.'s (1980) original finding is now clearly established, further clarification and evaluation of the general slowing hypothesis is needed. The strongest form of the hypothesis implies that all one needs to know about a specific task to predict either the latency of an older adult group or the size of the age difference in latencies is the latency of a younger adult group, which serves as an index of the amount of information processing required by the task. For example, if all information-processing components in older adults are slowed by a fixed proportion, then older adults' latencies on all tasks may be predicted by multiplying the younger adults' latencies by a constant.

Such proportional slowing is general in this sense, but Cerella's (1990) overhead model and the information-loss model (Myerson, Hale, Wagstaff, Poon, & Smith, 1990) also predict general slowing. In these models, the degree of age-related slowing is not constant as in the proportional slowing model; instead, these models assume a progressive increase in the degree of slowing with successive processing steps, but this increase is independent of the information-processing components involved. Both the overhead and information-loss models yield equations for predicting older adults' latencies on the basis of younger adults' latencies on the same task, regardless of the nature of the task, and hence both models are general according to present usage.

Whereas the proportional slowing model, the overhead model, and the information-loss model instantiate the strongest form of a general slowing hypothesis, another possibility is

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that general slowing is domain specific. In domain-specific slowing, more than one relation is hypothesized between older and younger adults' latencies, with distinct domains characterized by different relations. For example, Cerella's (1985) multilayered slowing model is based on the assumption that peripheral, sensorimotor processes in the elderly are slowed to a lesser degree than central, cognitive processes. In addition, Lima, Hale, and Myerson (1991) have reported that performance on lexical tasks (i.e., tasks in which the stimuli are words) is slowed to a lesser degree than performance on nonlexical tasks (i.e., tasks in which the stimuli are not words). Nevertheless, Cerella and Lima et al. suggested that within a specific domain, age-related slowing is general in the sense that older adults' latencies are predictable from those of younger adults regardless of the nature of the task.

Another possibility consistent with the available data is that age-related cognitive slowing may be general in the sense that all cognitive processes slow with age, yet local factors may also be important; that is, some information-processing components may be slowed much more than others. On the one hand, as predicted by general slowing, a high percentage of the variance in previous meta-analyses can be accounted for without considering the nature of the task. On the other hand, the unexplained variance may be due to data from tasks that involve components that are especially sensitive or insensitive to aging. If local factors are important, then latencies from studies that tap more age-sensitive components should be longer than expected based on an equation fit to the complete data set, whereas latencies from studies that tap less age-sensitive components should be shorter than expected. Alternatively, the scatter seen in meta-analytic data (see Figure 2 of Cerella, 1985, for an example) may be due entirely to statistical error. Typically, sample sizes are chosen so as to permit discrimination of group differences but are not necessarily large enough for accurate point estimation of population means (Salthouse, 1985).

When different subjects are tested on different tasks, different interpretations of scatter in the data are possible. However, if the same subjects are tested on multiple tasks, much of the ambiguity disappears. Under these circumstances, with the variability between subject samples eliminated, the general slowing hypothesis predicts that the relation between older and younger adults' latencies should be more precise. In contrast, the local factors hypothesis predicts that using the same subjects should not greatly improve the precision of the relation between older and younger adults' latencies because the major source of variability is the componential makeup of different tasks.

One purpose of this investigation is to evaluate these predictions concerning the precision of the relation between older and younger adults' latencies. A second purpose is to compare alternative mathematical models of cognitive slowing. Previously, several authors (Cerella, 1990; Myerson et al., 1989; Myerson et al., 1990; Nebes & Madden, 1988; Smith et al., 1988) have compared different mathematical descriptions of the relation between older and younger adults' latencies, but the results of these comparisons have not been conclusive. To date, no consensus has emerged regarding even whether the relation is linear or nonlinear. Part of the difficulty is that both linear and nonlinear models are very successful, generally accounting for more than 90% of the variance in the latencies of older adults. Therefore, to provide a more rigorous test of alternative models, this study not only compares how well various models describe the current data when parameters are free to vary but also how well the models can predict the current results using parameters estimated from a previous meta-analysis.

Finally, it should be noted that, from the perspective of the study of cognitive aging, the high percentage of variance accounted for in previous analyses of the relation between the latencies of older and younger adults may be misleading. This is because, as Cerella et al. (1980) pointed out, the percentage of variance accounted for in these analyses is based on both task effects and age effects, with task effects contributing more of the variance to be explained. Consideration of this problem prompted Cerella et al. (1980) to replace each older latency with an old-minus-young difference value. Under these circumstances, the percentage of variance in the age differences that is accounted for provides a better measure of a model's ability to account for age effects. Following Cerella et al. (1980), in this investigation we evaluate the ability of various models to describe and predict not only the response latencies of older adults but also the magnitude of age differences in latencies in order to provide more discriminating tests of alternative models of cognitive slowing.

Method

Subjects

Young adults were recruited from an introductory course in psychology, and community-dwelling older adults were recruited using an advertisement in a local newspaper. All volunteers were administered two subtests, vocabulary and block design, from the Wechsler Adult Intelligence Scale—Revised (WAIS–R) before the experimental tasks. Participants were excluded if the scaled score on either of the WAIS-R subtests was lower than 8 or if the error rate in any condition was 33% or more. Application of these criteria resulted in excluding 2 younger adults and 4 older adults from the study. The participants who were included in the present study were 16 younger adults (mean age = 19.6, SD = 0.9) and 16 older adults (mean age = 69.3, SD = 4.5). The younger adults were the same as those described in Hale (1990) in which they provided a baseline against which to compare the performances of three groups of children. Vocabulary scores of the older (M = 14.1, SD = 3.7) and the younger (M = 12.3, SD = 2.9) adults were not significantly different, $t(30) = 1.49$. However, the block design scores of the older adults (M = 10.2, SD = 2.3) were reliably lower than those of the younger adults (M = 12.6, SD = 2.7), $t(30) = 2.75$, $p < .05$.

Apparatus

The stimuli for all four information-processing tasks were presented on a Zenith 1380-C video monitor controlled by a Zenith 159 computer equipped with CTS hardware (Digitry, Inc.) and a response panel interface. Pascal programs conjoined with CTS software controlled the computer display and recorded response latencies with 0.1-ms accuracy. The response panel held three buttons: a left response button, a right response button, and a third button, centered below the two response buttons, which was used by participants to initiate each trial.

Information-Processing Tasks

The set of nonlexical information-processing tasks consisted of (a) a two-alternative-choice reaction time task, (b) a letter classification task, adapted from Posner and Mitchell (1967), (c) a rotated flag task, adapted from Shepard and Cooper (1982), and (d) an abstract matching task, adapted from Hoyer, Rebok, and Sved (1979). These tasks were selected because they vary in terms of both complexity and component processes: The first task requires recognition of a single pattern, the second task requires recognition and comparison of two patterns, the third task requires mental transformation of a pattern, and the fourth task requires judging the similarity of three nonidentical patterns. Because the sensorimotor aspects of the tasks are equivalent, that is, all require the same motor response (a button push) to a high-contrast, visual stimulus, the relation between older and younger adults' latencies should reflect only age differences in cognitive processing, and because all of the tasks use nonlexical stimuli, the relation should not be an average of possibly different, domain-specific forms.

The four tasks were presented in the following order: letter matching, mental rotation, choice reaction time, and abstract matching. This order, in which easier tasks alternated with harder tasks, was selected to prevent practice and fatigue effects from systematically biasing the outcome. The number of trials for all conditions was 20, except where counterbalancing required otherwise. Stimuli were presented in pseudorandom sequences within each task.

Procedure

All information-processing tasks began with presentation of a fixation point. When participants pressed the button on the panel labeled *ready*, the stimuli for the next trial were presented following a 300-ms interval. The stimulus remained on the screen until participants reached a decision and pressed either the left or right response button. Errors triggered a 2-s error message on the video monitor. Following general instructions, specific instructions and practice trials were given for each task, followed by the experimental trials.

Choice reaction time task. The stimuli for this task were left arrows (←) and right arrows (→), and participants were instructed to press the corresponding response button on each trial. Following four practice trials, there were 40 experimental trials consisting of 20 left arrows and 20 right arrows.

Letter classification task. The stimuli for this task were five different letters of the alphabet in either upper or lowercase (A, a, D, d, E, e, R, r, H, h). Two letters were presented simultaneously, and participants were instructed to press the right button if both were the same letter of the alphabet (i.e., they had the same name even if one was uppercase and the other was lowercase) and to press the left button if they were different. Following six practice trials, there were 80 experimental trials consisting of 20 pairs of physically identical letters (name same, physically same; NSPS), 20 pairs of letters with the same name that differed in case (name same, physically different; NSPD), and 40 pairs of letters that differed in name (name different, physically different; NDPD).

Mental rotation task. The stimuli for this task were schematic flags with stars in either the upper left or the upper right corner presented in four different orientations (0°, 90°, 180°, and 270°). Participants were instructed to press the left button if the flag's stars were in the upper left corner and the right button if the flag's stars were in the upper right corner when the flag was upright. They were also told that if the flag was not upright on the video monitor, then they should turn the flag in their mind without moving their head in order to "see" the flag in an upright position. Following eight practice trials, there were 80 experimental trials (20 trials at each of the four orientations).

Abstract matching task. The stimuli for this task were composed of three different patterns: one on the left, one on the right, and one located below the other two. Each pattern was made up of two, three, or four letters (o, v, and x) presented in one of three orientations (vertical, horizontal, or diagonal). Participants were instructed to press the left or right button, depending on which of the two upper patterns was most like the lower pattern. On each trial, one relevant dimension (number, orientation, or type of letter) determined the best match to the lower pattern, and the other two dimensions were irrelevant. Stimuli were analogous to Level 2 and Level 3 problems described in Hoyer et al. (1979). That is, for Level 2 problems, one of the two irrelevant dimensions was held constant and one of the irrelevant dimensions was varied, and for Level 3 problems, both of the irrelevant dimensions were varied (see Figure 1). Following extensive instructions, which included sample problems and feedback, there were 4 practice trials and then 36 experimental trials (18 trials at each of the two levels).

Results

Single-Task Analyses

Each task was first analyzed separately using standard analysis of variance (ANOVA) techniques to compare the current results with those of previous experiments in the literature. Where appropriate, the Greenhouse-Geisser correction for heterogeneity of variance was used to determine the significance level (Elashoff, 1986). The mean latencies and standard deviations for all four tasks are given in Table 1.

Choice reaction time task. A 2 (age) × 2 (condition: dominant

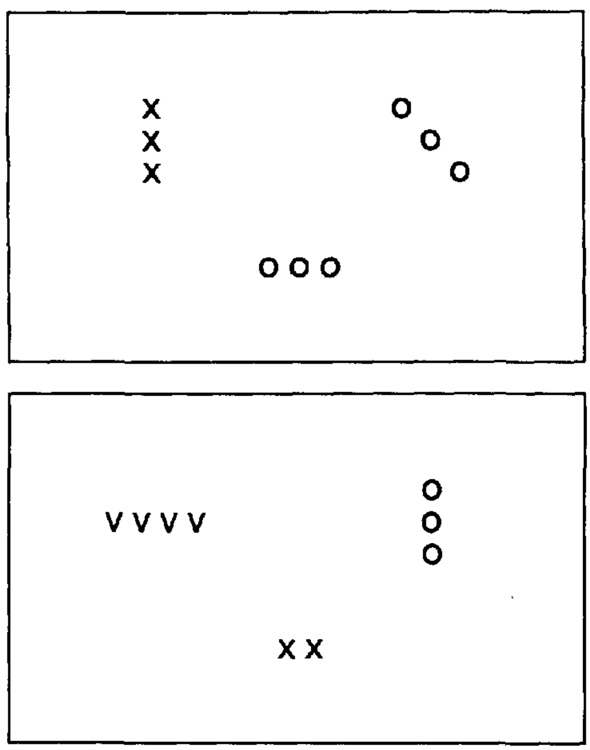

Figure 1. Two levels of the abstract matching task. (The upper panel illustrates a Level 2 problem in which one irrelevant dimension is varied—in this case, orientation—and the other irrelevant dimension is held constant—in this case, number. The correct match for this problem is the upper right pattern, based on the letter type dimension. The lower panel illustrates a Level 3 problem in which both irrelevant dimensions are varied—in this case, number and letter type. The correct match for this problem is the upper left pattern, based on the orientation dimension.)

Table 1
Mean Reaction Times (in Milliseconds), Standard Deviations, and Error Rates for Younger and Older Adults From All Four Tasks

	Choice reaction time (hand)		Letter classification (task condition)			Mental rotation (angle of orientation)				Abstract matching (task condition)	
Group	Dominant	Nondominant	NSPS	NSPD	NDPD	0°	90°	180°	270°	Level 2	Level 3
Younger adults											
RT	399	416	570	683	715	678	901	1,209	969	1,560	1,887
SD	80	71	111	156	135	151	241	394	289	322	357
% errors	0.6	0.6	1.6	8.1	6.0	0.3	5.6	5.6	6.3	5.7	3.3
Older adults											
RT	550	585	876	1,058	1,075	1,019	1,479	1,938	1,530	3,036	3,778
SD	127	178	229	240	273	346	523	913	534	916	1,191
% errors	0.6	0.9	1.3	8.4	1.5	0.6	4.7	2.8	3.8	7.7	6.3

Note. NSPS = name same, physically same; NSPD = name same, physically different; NDPD = name different, physically different; RT = reaction time.

vs. nondominant hand) repeated measures ANOVA was conducted on the mean individual latencies. A main effect of age was apparent, $F(1, 30) = 15.11$, $p < .001$. A main effect of condition was also observed, $F(1, 30) = 4.21$, $p < .05$, indicating that responses made with the dominant hand were reliably faster than responses made with the nondominant hand. The Age × Condition interaction was not statistically significant.

Letter classification task. A 2 (age) × 3 (condition: NSPS, NSPD, and NDPD) repeated measures ANOVA was conducted on the mean individual latencies. A main effect of age was apparent, $F(1, 30) = 25.80$, $p < .001$. A main effect of condition was also observed, $F(2, 60) = 71.19$, $p < .001$. The Age × Condition interaction was only marginally reliable, $F(2, 60) = 2.65$, $p < .09$. That is, there was a trend toward greater differences between the conditions for the older adults as compared with the younger adults.

Mental rotation task. A 2 (age) × 4 (target orientation—0°, 90°, 180°, and 270°) repeated measures ANOVA was conducted on the mean individual latencies. A main effect of age was present, $F(1, 30) = 13.16$, $p < .001$. A main effect for target orientation was also observed, $F(3, 90) = 48.35$, $p < .001$. In addition, the Age × Orientation interaction was reliable, $F(3, 90) = 3.49$, $p < .05$, revealing that the difference between the older and younger adult group reliably increased as a function of angle of orientation of the stimulus up to 180°. For both age groups, mean latencies were similar for the 270° and 90° condition.

Abstract matching task. A 2 (age) × 2 (levels—Level 2 and Level 3 from Hoyer et al., 1979) repeated measures ANOVA was conducted on the mean individual latencies. The main effect of age was reliable, $F(1, 30) = 39.97$, $p < .001$, and a main effect of level was also present, $F(1, 30) = 41.94$, $p < .01$. Consistent with the findings of Hoyer et al., Level 2 problems were associated with faster latencies than were Level 3 problems. Finally, the Age × Problem Level interaction was reliable, $F(1, 30) = 6.29$, $p < .05$.

Error analyses. Four separate ANOVAs were conducted on the error data analogous to the ANOVAs conducted on the latency data. These analyses did not reveal any main effects or interactions associated with age. Thus, the error analyses did not reveal any evidence of age-related differences in speed–accuracy tradeoffs. However, several main effects of condition were observed. In the letter classification task, more errors (false negatives) were made when the letters were the same in both name and case than in other conditions. In the mental rotation task, fewer errors were made in the 0° condition than in conditions where the stimuli were not upright. In the abstract matching task, Level 2, in which one irrelevant dimension was held constant, produced a higher error rate than did Level 3, in which both irrelevant dimensions were varied.

Multitask Analyses

As may be seen in Figure 2, there is an extremely orderly relation between the older adults' mean latencies in all 11 experimental conditions of the four different tasks and the corresponding mean latencies from the younger adult groups. The multitask analyses are concerned with two issues. First, how does the orderliness of the relation observed with the present data obtained from the same subjects on multiple tasks compare with the orderliness observed in previous meta-analyses in which data from different tasks were obtained from different subjects? Second, how do alternative theoretical models of general slowing compare with respect to their ability to describe and predict the relation between the latencies of older and younger adults? These questions are interrelated because orderliness must be assessed as some measure of scatter about a function that describes the data, and so some determination of the form of the relation must precede assessment of orderliness.

As a first step, polynomial regression was used to distinguish between linear and nonlinear forms of the relation. A second-order polynomial was fit to the data, and consistent with a nonlinear relation, the quadratic term was statistically significant, $t(8) = 4.45$, $p < .01$.

The most appropriate meta-analysis for the purpose of comparison with the present data is the Hale et al. (1987) effort as modified by Myerson et al. (1990). This meta-analysis examined the performances of older and younger adults on various nonlexical tasks, whereas other recent meta-analyses have either examined performances on lexical tasks (Madden, 1989; Nebes & Madden, 1988), on tasks drawn from both lexical and nonlexical domains (Cerella, 1985; Cerella et al., 1980), or on

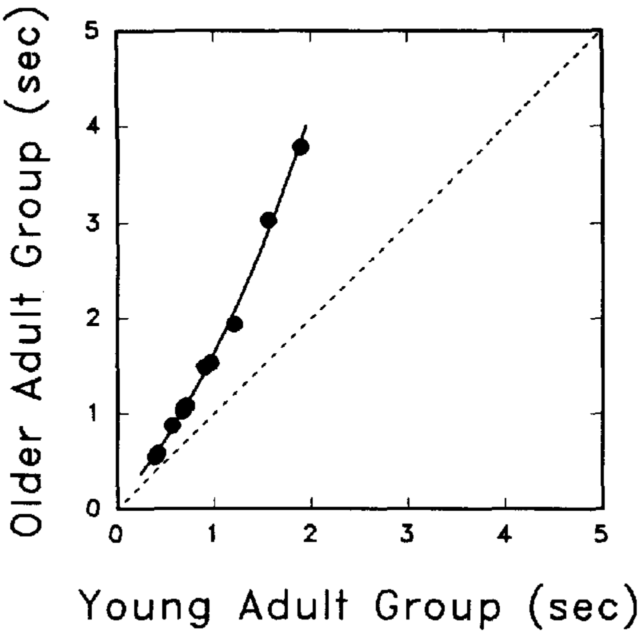

Figure 2. Mean latencies of the older adult group plotted as a function of the mean latencies of the young adult group in the same experimental condition. (The solid line is the best fitting second-order polynomial [$O = 0.072 + 1.064\,Y + 0.487\,Y^2$; $r^2 = 0.996$].)

different variations of a single task (Cerella, 1987; Madden, 1989).

Although a second-order polynomial accounts for 99.6% of the variance in the present data, this is only slightly more than in the Myerson et al. (1990) meta-analysis, where 98.9% of the variance was accounted for by a second-order polynomial. However, this may be because the percentage of variance accounted for in the meta-analysis is quite close to the maximum possible, leaving little room for improvement. Other measures reveal considerably less scatter in the present data as compared with the scatter in the data from the meta-analysis. The standard error (standard deviation of the residuals) and the mean percentage error of prediction for the meta-analysis are 250 ms and 9.1%, respectively, compared with 63 ms and 2.9%, respectively, for our data. Although the size of the residuals increased with the latency of the younger group, the greater precision in our data is not because the meta-analysis covered a greater range of latencies. When a second-order polynomial was fit to a subset of the meta-analytic data whose latency range matched that of our data, the standard error for this truncated meta-analytic data set was 213 ms and the mean percentage error was 8.9%, both more than three times the corresponding values for our data.

The preceding multitask analyses were based on polynomial regression because it provides an atheoretical description of the relation between older and younger adults' latencies. Further analyses were conducted to compare the various theoretical models of general slowing. Five alternative forms have been proposed for the relation between the latencies of older and younger adults: a proportional form,

$$O = aY; \quad (1)$$

a linear form,

$$O = aY + b; \quad (2)$$

a one-parameter quadratic form,

$$O = aY^2 + (a + 1)Y; \quad (3)$$

a power function form,

$$O = aY^b; \quad (4)$$

and a slightly more complicated power function form,

$$O = [(aY + 1)^{b/a} - 1]/b. \quad (5)$$

Equation 1 is derived from the assumption that all cognitive processes are proportionally slowed with advancing age (Cerella et al., 1980). Equation 2 is based on the multilayered slowing model (Cerella, 1985), which assumes that peripheral, sensorimotor processes slow less with advancing age than do central, cognitive processes; this equation describes the special case where the contribution of peripheral processes is held constant while the amount of cognitive processing varies. Equation 3 is based on the overhead model (Cerella, 1990) and is derived from the assumption that, in older adults, a constant amount of overhead is accumulated with each information-processing step. Equation 4 is derived from the assumption that latency increases exponentially (but at an age-related rate) with task complexity (Botwinick, 1984; Hale et al., 1987); this equation approximates the relation predicted by the information-loss model, which assumes that a constant (but age-related) proportion of information is lost with each processing step (Myerson et al., 1990). The information-loss model is represented more precisely by Equation 5.

It may be noted that the overhead model has one less parameter than the two other nonlinear forms. For purposes of comparison, a two-parameter form of the overhead model,

$$O = aY^2 + (a + b)Y, \quad (3')$$

may be derived by assuming that older adults differ not only in that they accumulate overhead with each step, but also in that their basic processing step duration is longer by some factor (b).

For the first analysis in this series, the proposed models were fit to the present data set, and the percentage of the variance accounted for (%VA) by each model is given in the first column of Table 2 (%VA for models free fit to data, i.e., fit with free parameters). Consistent with the results of the polynomial regression, the two linear function forms (Equations 1 and 2) were less successful in describing the data than were the four nonlinear forms (Equations 3, 3', 4, and 5), which each accounted for at least 99.5% of the variance in older adults' latencies.

Describing the age difference in the latencies of older and younger adults is a more exacting test than describing the relation between the groups' latencies. Therefore, the age differences were calculated for every condition and then fit using each of the proposed models by subtracting Y from both sides of each equation. The results are given in the second column of %VA in Table 2 (%VA for functions free-fit to difference data). By comparing the %VA in Columns 1 and 2 of Table 2, it can be

Table 2
Results of Multitask Analyses

Model	Free fit to data: Parameter values	Free fit to data: %VA	Free fit to data: %VA (difference)	Force fit to data[a]: Parameter values	Force fit to data[a]: %VA	Force fit to data[a]: %VA (difference)
Equation 1						
$O = aY$	1.785	.956	.706	2.167	.812	.364
	—			—		
Equation 2						
$O = aY + b$	2.150	.988	.959	2.677	.934	.776
	−0.413			−0.909		
Equation 3						
$O = aY^2 + (a + 1)Y$	0.338	.995	.981	0.296	.985	.948
	—			—		
Equation 3′						
$O = aY^2 + (a + b)Y$	0.426	.996	.988	0.268	.990	.967
	0.783			1.129		
Equation 4						
$O = aY^b$	1.664	.995	.983	1.597	.992	.973
	1.284			1.335		
Equation 5						
$O = [(aY + 1)^{b/a} - 1]/b$	4.807	.996	.986	4.473	.993	.977
	6.855			6.361		

Note. %VA = percentage of the variance accounted for.
[a] Parameter values reported for the meta-analysis presented in Myerson, Hale, Wagstaff, Poon, and Smith (1990) were used for calculating these fits. Dashes indicate no *b* parameter value.

seen that the linear functions lose a fair amount of descriptive power, and this is especially true of Equation 1.

The preceding two comparisons of the descriptive power of the alternative models were supplemented by two analyses that compared their predictive power. For these analyses, each of the equations was fit to the data from the Myerson et al. (1990) meta-analysis to estimate the values of the parameters. Then the ability of each equation to predict the results of the present experiment was assessed, but with its parameters fixed.

As may be seen in the third and fourth columns of %VA in Table 2 (%VA for equations force-fit to data, i.e., with parameter values forced rather than free), the pattern of results from comparisons of predictive power were similar to those of the comparisons of descriptive power. Note that greater separation between the models was observed in the comparisons of predictive power. Proportional and linear forms were clearly less successful than were nonlinear forms at predicting the present data, especially the age differences in latencies, and one-parameter models were less successful than were related two-parameter models.

The superiority of the nonlinear forms in the preceding analyses is consistent with the results of statistical tests. As reported previously, when a second-order polynomial was fit to the data, the quadratic term was statistically significant. Not only is this consistent with a nonlinear relation between older and younger adults' latencies, but in addition, the quadratic term was positive, indicating a positively accelerated increase in the latencies of older adults as predicted by both the overhead and information-loss models. Moreover, the intercept term was not significantly different from zero, $t(8) = 0.61$, consistent with the fact that all of the proposed nonlinear forms go through the origin.

The two-parameter nonlinear equations (Equations 3′, 4, and 5) were virtually indistinguishable in their ability to account for the relation between older and younger adults' latencies, whether describing or predicting the latency data or the age difference, and no attempt was made to compare them using inferential statistics. However, we did compare the one- and two-parameter versions of the overhead model (Equations 3 and 3′, respectively). The value of the additional parameter (b) in the two-parameter model was significantly greater than 1.0, $t(9) = 2.17$, $p < .05$, consistent with the hypothesis that older adults' basic processing step duration is longer than that of younger adults. Thus, the results of both statistical tests and the regression analyses presented in Table 2 favor the use of two-parameter models for describing the positively accelerated relation between older and younger adults' latencies.

The final multitask analysis examined the relation between the corresponding quartile latencies of older and younger adults. For each condition, each individual's 25th-, 50th-, and 75th-percentile response latencies were calculated, and then the mean for each quartile was calculated for each age group. Figure 3 shows the mean quartile values for the older adult group in each condition plotted as a function of the corresponding quartiles for the younger adult group. The tendency of the different quartiles to fall along a single mathematical function may be more clearly seen in the left panel, in which each quartile is represented by a separate symbol. The overlap between tasks—that is, the tendency of the 1st-quartile data from a more complex task to be approximately equivalent to the 3rd-quartile data from a less complex task—may be more easily seen in the right panel, in which each task is represented by a separate symbol.

The results of polynomial regression analyses confirm what is apparent from visual inspection of the data. A single func-

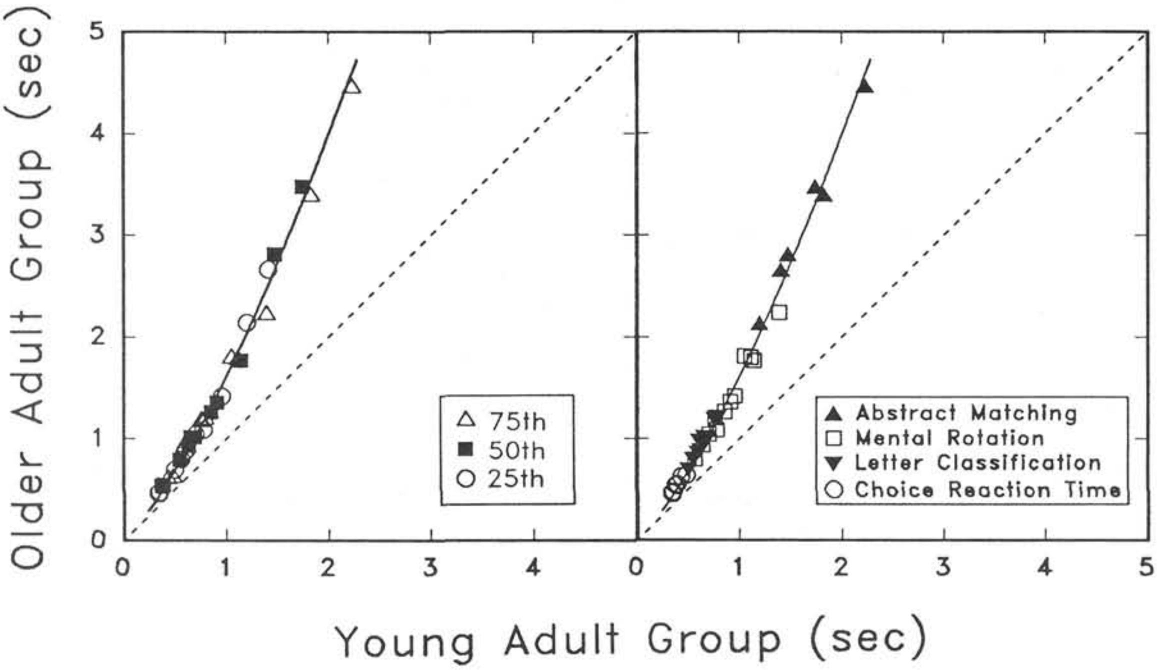

Figure 3. Quartile latencies of the older adult group plotted as a function of the corresponding quartile latencies of the younger adult group in the same experimental condition. (The left panel represents each quartile—25th, 50th, and 75th percentiles—with different symbols but does not differentiate tasks. The right panel shows the same data and represents each task [choice reaction time, letter classification, mental rotation, and abstract matching] with different symbols but does not differentiate the quartiles. The solid line in both panels represents the prediction of the information-loss model [Equation 5] using parameter values estimated from a previous meta-analysis [Myerson, Hale, Wagstaff, Poon, & Smith, 1990].)

tion, the best-fitting second-order polynomial from the Myerson et al. (1990) meta-analysis, was force fit to the 1st-, 2nd-, and 3rd-quartile data and accounted for 98.6%, 98.8%, and 99.3% of the variance, respectively. Similar results were obtained using the overhead model and the information-loss model.

Discussion

Performance on Individual Tasks

Although the major focus of this study is on phenomena emerging at the multitask level of analysis, the likely representativeness of the current findings at the multitask level depends on the typicality of the results at the individual-task level. In general, the results of the separate task analyses from this study were consistent with previous findings. That is, main effects of age were observed for all tasks, and Age × Task Condition interactions were observed for those tasks in which interactions had been reported.

More specifically, the choice reaction times of older adults in the present investigation were reliably slower than those of younger adults, consistent with the results of numerous earlier studies (e.g., Nebes, 1978, Experiment 2, manual responses; Rabbitt & Vyas, 1980; Simon & Pouraghabagher, 1978). The letter classification task produced typical condition effects (different responses were reliably slower than same responses, and NSPS responses were reliably faster than NSPD responses) and a significant age difference consistent with Cerella, DiCarra, Williams, and Bowles (1986). The mental rotation task produced results similar to those reported by Gaylord and Marsh (1975) as well as those reported by Cerella, Poon, and Fozard (1981): Older adults were slower than younger adults, and the Age × Orientation interaction indicated that the difference between the two groups increased as a function of the angle of orientation. The results for the abstract matching task were consistent with the findings of Hoyer et al. (1979): Older adults were slower than younger adults, and an Age × Level interaction revealed that the magnitude of the difference was much greater for Level 3 performance as compared with Level 2 performance.

Although the qualitative pattern of results was typical of previous findings for all tasks, actual latency values did not always replicate those obtained in previous research. For example, results from our letter classification task were qualitatively consistent with those reported by Cerella et al. (1986). However, they found differences between the NSPS and NSPD conditions of only 22 ms for younger adults and 25 ms for older adults, whereas this study revealed differences of 113 ms and 182 ms for younger and older adults, respectively. This appears to be because their task involved sequential presentation of two letters, whereas our procedure used simultaneous presentation of the letter pairs. Support for this interpretation comes from young adult data obtained using simultaneous presentation (Kail, 1986). Kail found a 136-ms difference between the NSPS and NSPD conditions for adults whose average age was 20 (very similar to the 113-ms difference that we obtained). Thus, consistent with the specifics of the procedure, our findings from the NSPS and NSPD conditions for the younger adults are more in agreement with results reported by Kail than with those reported by Cerella et al. (1986).

The latencies from our mental rotation task were somewhat shorter than those obtained by either Gaylord and Marsh (1975) or Cerella et al. (1981), and presumably this difference was due to the differences in the complexity of the stimuli used in the three experiments. In addition, the latencies were substantially greater in the Hoyer et al. (1979) study as compared with our results. This difference could result from the difference in stimuli or the reduced number of stimulus dimensions in the present study: Hoyer et al. used geometric shapes, whereas we used letters, and their study included color in addition to the three other dimensions of orientation, number, and shape. Presumably one or both of these differences is responsible for the difference in the magnitude of the latencies for both age groups. In summary, the present results are qualitatively similar to those of previous studies using similar tasks, and any quantitative differences in performances on individual tasks are readily interpretable in terms of differences in procedures.

General Slowing at the Multitask Level

The present results replicate the findings of previous meta-analyses within the context of an experimental investigation in which the same older and younger adults were tested on multiple information-processing tasks. Several aspects of the present results are consistent with general slowing of nonlexical information processing in older adults. First, the latencies of the older adults were predictable from those of the younger adults without regard to the nature of the task. Second, prediction of latencies obtained from the same subjects performing multiple tasks was more accurate than in meta-analyses where each task is performed by a different group of subjects. Third, the age difference in response latencies was accurately predicted using equations derived from specific general slowing models.

The relation between the latencies of older and younger adults when the performances on all four tasks are considered simultaneously is extremely precise, even more precise than that observed in previous meta-analyses (e.g., Cerella et al., 1980; Hale et al., 1987; Nebes & Madden, 1988). If the scatter observed in meta-analyses is due primarily to differences in the degree of age-related slowing associated with different cognitive processes, then a similar amount of scatter should be observed in an experimental investigation such as the present effort that uses diverse tasks. Alternatively, if the scatter in meta-analyses is due primarily to differences between the subjects in different experiments, then an investigation such as the present effort that uses only two groups of subjects should produce data with substantially less scatter. That the relation observed in the present investigation was more than three times as precise (as measured in terms of the predictive error of a second-order polynomial) as that observed in a comparable meta-analysis (Myerson et al., 1990) strongly supports the interpretation that differences between groups, rather than differences between processes, are responsible for the scatter observed in meta-analyses.

Although the present results testify to the role played by sampling error in meta-analysis, they also demonstrate the reliability of meta-analytic results when the number of studies included is sufficiently large. With parameter values estimated from a previous meta-analysis (Myerson et al., 1990), the equations derived from the overhead model and the information-loss model accurately predicted the relation between older and younger adults' latencies observed in the present investigation, accounting for more than 99% of the variance in the latencies of the older adults. Thus, not only the general form of the relation but also the specific values of the parameters that describe it are remarkably consistent from a meta-analysis to an individual investigation spanning a broad range of latencies.

Following Cerella et al. (1980), the effects of age on processing speed were also examined using analyses that focused directly on age differences in response latency. The two-parameter equations derived from the overhead and information-loss models generated precise predictions of the age differences in response latencies, accounting for more than 98% of the variance in the observed age differences when parameters were free and more than 96% of the variance when the parameters were estimated from a previous meta-analysis (Myerson et al., 1990). The accuracy of these predictions strongly supports not only the specific models involved but also the general slowing hypothesis, of which these models are specific instantiations.

The demonstrated descriptive and predictive power of the overhead and information-loss models clearly supports a nonlinear form of general slowing in the nonlexical domain. This conclusion is strengthened by the finding that when the data were fit with a second-order polynomial function, the quadratic term was statistically significant. Compared with the nonlinear equations derived from the overhead model and the information-loss model, the linear equations derived from the proportional and multilayered slowing models provided poorer accounts of the relation between older and younger adults' latencies, especially when parameters were fixed based on estimates from the Myerson et al. (1990) meta-analysis.

The nonlinear models are distinguished by their assumption that latency is a positively accelerated function of task complexity, at least in older adults. The overhead and information-loss models both attribute this positive acceleration to a progressive increase in the duration of successive processing steps: According to the former model, this is due to an attenuation process that operates only in aged neural networks (Cerella, 1990), whereas according to the latter model, it is due to a process of information loss that is characteristic of all neural systems but which may be exacerbated by any of a variety of age-related neurobiological changes (Myerson et al., 1990).

Despite the differences between the nonlinear models, and whatever the neural mechanism or mechanisms responsible for the age difference in the duration of individual processing steps, the overhead and information-loss models both assume that the effects are cumulative so that for a sequence of steps, the age difference between step durations increases with position in the sequence. This assumption, which is unique to these models, is supported by the present finding of significant nonlinearity in the relation between the latencies of older and younger adults.

The present conclusions are consistent with those of Cerella

(1990) concerning the proportional slowing model. Cerella found that this model provided a less accurate description of data from four meta-analyses than did the other three models, and the same is true regarding the present data. However, Cerella found that the information-loss, overhead, and multilayered slowing models provided equally accurate descriptions of the data from the meta-analyses, whereas the multilayered slowing model was less accurate than the others with respect to the present data.

Several factors may have contributed to the difference between the results of the present analyses and those of Cerella (1990). First, the scatter in data from meta-analyses due to differences between samples places a ceiling on the explainable variance and makes discrimination between models more difficult. Second, the latencies of older adults in two of the meta-analyses (Cerella, 1987; Nebes & Madden, 1988) spanned a range of approximately 1 s, compared with the more than 3-s range in the present study. And, notably, over a short range, a curve may be indistinguishable from a line. Third, a substantial difference between the multilayered slowing model and the nonlinear models did not emerge in the present analyses until the more stringent tests were applied. That is, when the three models are compared based on their fit to the present data with their parameters free to vary, the difference in the percentage of the variance accounted for is less than 1%.

Finally, two of the meta-analyses (Cerella, 1985; Nebes & Madden, 1988) considered by Cerella (1990) included data from both the lexical and nonlexical domains. We have recently presented evidence that slowing in the lexical domain is linear in form (Lima et al., 1991), in contrast to the nonlinear slowing observed in our previous meta-analyses of data from the nonlexical domain (Hale et al., 1987; Myerson et al., 1990). Therefore, the accuracy of the multilayered slowing model (which is linear in form) may improve when data from studies of lexical information processing are included in an analysis. *Linearity* implies that whatever factors (e.g., accumulation of overhead and differences in information loss) are responsible for the positive acceleration in the relation between the nonlexical latencies of older and younger adults, these factors are for some reason not operative in the lexical domain. However, as Lima et al. point out, precise characterization of the two domains is difficult at the present time because of the extent to which the lexical and nonlexical tasks used in previous research also differed in the degree to which they tapped crystallized versus fluid and verbal versus spatial abilities. Thus, although domain-specific slowing represents a major constraint on general slowing models, its proper theoretical interpretation is as yet unclear.

In addition to differences between domains with regard to the degree of general slowing, more local exceptions to general slowing have also been reported. Especially intriguing are the results of studies showing that even on tasks that reveal age-related slowing, the time course of processing a cue to shift attention (Hartley, Keiley, & Slabach, 1990; Madden, 1986) and the time course of spreading activation (Balota & Duchek, 1988) may be equivalent in younger and older adults. These findings suggest that although current general slowing models accurately account for large-scale age-related differences in performance on speeded cognitive tasks, a new generation of models may be required to account for the time course of processing information from sequential stimulus presentations by older and younger adults.

The common characteristic of general slowing models is that they assert that, at least within a specific domain, older adults' latencies and age differences in latencies may be predicted based solely on the latencies of younger adults without regard to the nature or componential makeup of the tasks. This assertion is based on the assumption that the average latency of the younger adults provides an index of the complexity of a task (represented in the information-loss and overhead models by the number of processing steps) and that the age difference is solely a function of task complexity. Recently, Smith et al. (1988) generalized this assumption to trial-to-trial fluctuations in response latency, which they proposed were analogous to fluctuations in task complexity. That is, Smith et al. suggested that a subject's faster performances on a given task occur on occasions when the task is less complex for the subject, and similarly, slower performances occur on occasions when the task is more complex for the subject. If trial-to-trial fluctuations in complexity are comparable in older and younger adults, then plotting older adults' faster, average, and slower latencies as a function of the corresponding latencies of younger adults should be equivalent to plotting performances on tasks of lesser, moderate, and greater complexity.

Smith et al. (1988) tested this hypothesis by examining the relation between the faster (e.g., 25th percentile), average (50th percentile), and slower (e.g., 75th percentile) latencies of older adults performing tasks of varying complexity and the corresponding percentile latencies of younger adults. They found that the data all fell along a single mathematical function, such that the latencies of the older adults could be predicted from the corresponding latencies of younger adults without regard to either the nature of the task or the level of performance. The present results replicate and extend this finding. Not only do the corresponding quartile latencies observed in the present study all fall along a single mathematical function, but also that function was predicted based on the results of a previous meta-analysis (Myerson et al., 1990) that examined only the mean latencies of older and younger adults.

In conclusion, the present findings strongly support the general slowing hypothesis, demonstrating the reliability of predictions based on mathematical models of general slowing as well as increasing the precision and extending the generality of the essential phenomenon: the ability to predict older adults' latencies and age differences based solely on the latencies of younger adults. General slowing models were used to generate parameter-free predictions that, at least in the case of the nonlinear models, were extremely precise no matter how stringent the test. Moreover, not only older adults' average performances, but also their faster and slower performances, were predicted with nearly equal accuracy.

The ability to make accurate, quantitative predictions is rare in psychology outside of psychophysics, but the evaluation of mathematical theories such as those recently proposed to account for age differences in information-processing speed (e.g., Cerella, 1985, 1990; Myerson et al., 1990) will require making and testing such predictions. In this effort, the reliability of meta-analytic results, as demonstrated in the present analyses, and the precision observed in data obtained from the same subjects tested on multiple tasks within a single domain may prove essential.

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