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Causes and Consequences of Age-Related Slowing in Speeded Substitution Performance

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Data from a computer-administered symbol digit substitution task were analyzed to determine the causes and consequences of age-related differences on this task. Causal variables are assumed to be those that are associated with a reduction in the age-related variance in symbol digit performance when they are controlled by statistical means. Consequences are inferred by the amount of reduction in the age-related variance in other variables when symbol digit performance is statistically controlled. Consistent with the results of other studies, perceptual comparison speed was found to share considerable age-related variance with speeded substitution performance, which in turn was found to share considerable age-related variance with measures of memory functioning.

Adult age differences in substitution tasks such as the Wechsler Adult Intelligence Scale Digit Symbol Substitution Task are well documented (e.g.,

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Salthouse, 1992) and have been found to be related to the age differences reported in a number of different cognitive measures. That is, the age-related variance in tasks ranging from memory to inductive reasoning to spatial visualization has been found to be greatly attenuated when statistical control procedures are used to eliminate the variation in digit symbol substitution speed (e.g., Salthouse, 1985, 1993). These results suggest that something that is measured by the Digit Symbol Substitution test plays a causal role in the age-related influences in various cognitive tests. Because the operations required in the Digit Symbol Substitution test are quite simple, Salthouse (1985, 1992) hypothesized that performance on it reflects the rate at which the individual can execute elementary cognitive operations. This interpretation was supported by recent findings that over 90% of the age-related variance in digit symbol performance was shared with measures of perceptual comparison speed derived from tests involving pairs of letters or line patterns (Salthouse, 1992, 1993).

We describe analyses similar to those conducted in the studies cited previously on data from three samples administered tests from the Neurobehavioral Evaluation System (NES; Letz, 1991) test battery. The NES was designed to assist in the detection of neurological and behavioral effects of exposure to toxic substances. It contains a variety of perceptual–motor and memory tests that can be administered in different combinations. One of the central tests in the battery and the test of primary interest in this article is the Symbol Digit test. The task for the subject in this test is to refer to a code table to determine the digit associated with a given symbol and then to type the appropriate digit below each symbol.

In addition to the Symbol Digit test, the NES also contains several tests of memory, sustained attention, hand–eye coordination, tapping speed, and perceptual comparison speed. These variables were used in two different types of analyses. In the first set of analyses, measures from the memory tests were used as criterion variables to determine the extent to which the age-related variance in those measures is reduced when the variance in the Symbol Digit test is controlled. If the results of earlier studies with other types of substitution tests were replicated, then statistical control of the digit symbol measure should result in a substantial attenuation of the age-related influences in the measures of memory functioning.

The second set of analyses used symbol digit performance as the criterion variable and examined the extent to which statistical control of other variables reduces the age-related variance in symbol digit performance. The reasoning is that variables associated with a substantial attenuation of the age-related variance are likely to be informative about the reasons for the influence of age on symbol digit performance. For example, if elimination of the variance in finger-tapping speed greatly reduced the magnitude of the age-related variance in symbol digit performance, then it would be reasonable to infer that motor speed, or whatever else is represented by the tapping measure, contributed to the age differences in symbol digit performance.

Two of the data sets to be analyzed were obtained from epidemiological studies of construction painters and printing pressmen working for a large newspaper (see Letz, in press, for further description of the samples and citations to other reports of these studies). Solvent exposure was observed to have a weak relationship with symbol digit performance in the painter sample. Solvent exposure was very low for the pressmen, and no relationship was found between it and test performance in this group. A third data set was obtained from two studies in the Netherlands. One was a study of volunteers contacted from telephone directory listings of a large Dutch city. Subjects were selected on the basis of age (two groups, 26 to 47 and 60 to 73 years) and education (only lower- and middle-education volunteers were included). The second Dutch sample came from a study of young (30 to 40 years) and retired (62 to 72 years) painters and a similar number of referents who were or had been employed in other construction trades. No relationship between solvent exposure and test performance was observed in the Dutch painter groups. The influence of solvent exposure is ignored in our report.

METHOD

Subjects

Characteristics of the samples are summarized in Table 1. Because less than 20% of the individuals in the original samples were women, only the data for men are reported. Also excluded from the analysis are subjects with a history of head trauma, alcoholism, cardiovascular problems, or major medical conditions such as diabetes and cancer.

Vocabulary was assessed with a 25-item test in which the subject was to select from a set of four alternatives the word that was closest in meaning to the target word. The Effort rating was a self-assessment of the effort expended on performing the tests. A 4-point scale ranging from *not at all* (1) to *as hard as I could* (4) was used in the pressmen sample, and a 5-point scale ranging from *not at all* (1) to *as hard as I could* (5) was used in the painter sample.

Procedure

An illustration of the display for a trial in the Symbol Digit test is presented in Figure 1. Notice that a code table containing pairs of symbols and digits is presented at the top of the screen, and symbols with blank boxes are presented at the bottom of the screen. The task for the subject is to type in the correct digit for each symbol as rapidly as possible. An initial practice trial is presented in which only correct responses are acceptable, followed by four or five trials containing all nine symbols in a scrambled order. A trimmed mean latency, calculated as follows, was employed as the summary measure of performance in this test. First, for each of the trials, the latency from the first response to the ninth response was divided by the number of correct responses. Then the mean latencies for correct trials are "trimmed" by averaging the two fastest ones to provide a stable estimate of the subjects' best performance. This summary measure has been demonstrated to be more reliable than alternative ones considered for this test (Eisen, Letz, Wegman, Baker, & Pothier, 1988).

The Symbol Digit task can be presented in one of two versions, either with the same pairing of symbols and digits on all five trials, which can be termed Consistent Mapping, or with a different arrangement on each trial, which can be termed Varied Mapping. Five trials of the Consistent Mapping version of the task were administered to the pressmen sample, and four trials

TABLE 1
Background Characteristics of Research Samples

Painters[a]					
Decade	*n*	*Age*	*Education*	*Vocabulary*	*Effort*[b]
20s	43	26.0	11.9	14.6	4.4
30s	61	33.6	12.2	17.1	4.4
40s	26	44.3	11.1	16.2	4.3
50s	25	55.2	10.0	15.4	4.6
60s	10	62.2	9.8	18.6	4.8
All	165	38.3	11.5	16.1	4.4
Pressmen[c]					
Decade	*n*	*Age*	*Education*	*Vocabulary*	*Effort*[d]
20s	46	25.7	13.7	17.4	3.3
30s	34	34.7	13.2	17.2	3.5
40s	53	45.3	12.6	17.0	3.6
50s	63	54.7	12.3	19.1	3.5
60s	27	62.7	12.1	18.7	3.6
All	223	44.4	12.8	17.9	3.5
Dutch Sample[e]					
Decade	*n*	*Age*	*Education*	*Vocabulary*	
20s	0	—	—	—	
30s	90	34.9	10.1	15.0	
40s	26	41.0	9.2	15.8	
50s	34	58.1	8.1	15.2	
60s	77	64.3	8.8	16.6	
70s	12	71.7	8.7	14.6	
All	239	50.2	9.2	15.6	

[a]n = 165. [b]*Low* (1) to *maximum* (5) scale. [c]n = 223. [d]*Low* (1) to *maximum* (4) scale. [e]n = 239.

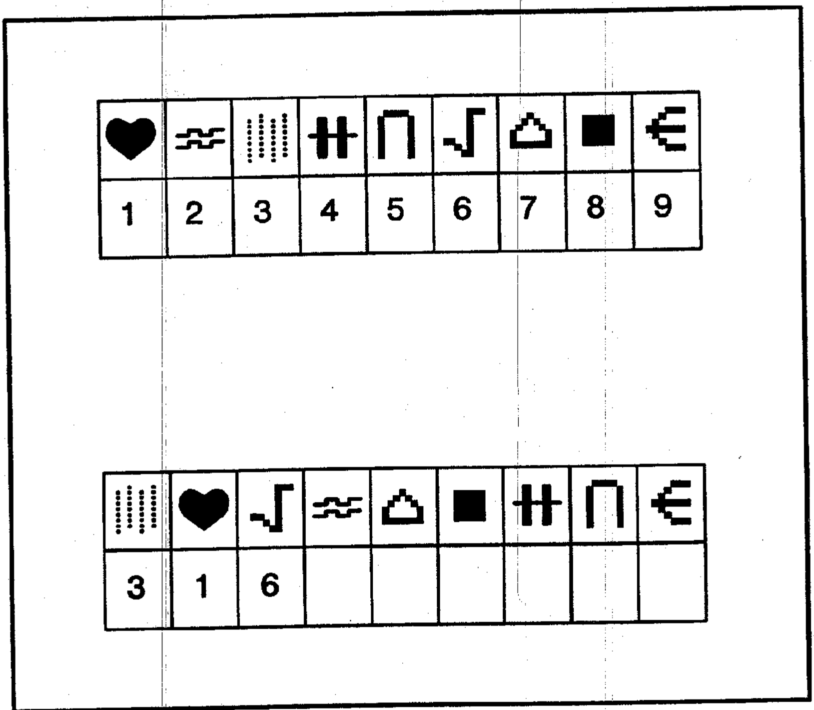

FIGURE 1 Illustration of computer screen display after three responses in a trial in the Symbol Digit task.

of the Varied Mapping version were administered to the painter and Dutch samples.

The other variables used in the analyses are described in Table 2. Different combinations of tests were used in the three samples, and the available variables in each sample are listed in Tables 3 and 4. In addition, the Pattern Memory test was administered for 25 trials in the pressmen sample but for 15 trials in the painter and Dutch samples. No information about the reliability of the measures in these samples is available, but previous reports (Letz, 1990) indicated that most of the test–retest correlations for the measures from the NES tests were between .65 and .80.

RESULTS AND DISCUSSION

In a few cases in each sample, observations were missing for one of the variables for a subject, and when this occurred, the missing values were replaced with the mean of the sample on that variable. (Subjects with miss-

TABLE 2
Variables Included in the Analyses

Variable	*Description*
Digit Span—Forward	Serial visual presentation of a series of digits with immediate typed recall in the original order of presentation. Sequence increases until the subject is incorrect on two trials with a given sequence length. The performance measure is the maximum number of digits recalled in the correct sequence.
Digit Span—Backward	Similar to Digit Span—Forward except that the subject is to recall the digits in the reverse order of presentation. The performance measure is the maximum number of digits recalled in the correct sequence.
Pattern Memory	A stimulus consisting of a pattern of filled cells in a 10 × 10 matrix is exposed for 4 sec, and after a 3-sec blank screen retention interval, three patterns are presented. The subject's task is to select the pattern that had been presented earlier. The performance measure is the number of trials correct out of 25.
Serial Digit Learning	Serial visual presentation of a sequence of 8 digits until the subject recalls the entire sequence correctly on two successive trials or until a maximum of 8 trials has been attempted. The performance measure is the number of errors over all trials attempted.
Symbol Digit Recall	After performing the Consistent Mapping version of the Symbol Digit task, the symbols are presented alone without the code table, and the subject attempts to recall the digits paired with each symbol. The performance measure is the number of correctly recalled digits.
Pattern Comparison	Displays of three patterns of filled and unfilled cells in 10 × 10 matrices are presented with the subject instructed to select the odd (nonmatching) pattern. The performance measure is the mean response latency across 25 trials.
Continuous Performance	Letters are presented at a rate of one every second for 5 min, and the subject is instructed to press a key whenever the target letter (S) appears. The performance measure is the sum of the number of misses (nonresponses) and false alarms (responses to nontargets) across the 5-min test.
Hand-Eye Coordination	Presentation of a moving sine wave pattern that the subject is to track by moving a cursor with a joystick. The cursor maintains a constant horizontal motion and so the subject need only respond to the vertical movements of the stimulus pattern. The measure of performance is the average root mean squared error across five trials.
Tapping	The subject taps a specified key on the keyboard as rapidly as possible for 30 sec. The performance measure is the average number of taps per trial for tapping with the preferred hand, the nonpreferred hand, and with alternate hands.
Associative Learning	Presentation of nine pairs of first names and occupations for 2 sec each, followed by the presentation of the name and all of the alternative occupations. The performance measure is the sum of the correct responses across three trials with the same pairs.

TABLE 3
Results of Hierarchical Regression Analyses on Cognitive Measures with Age and Symbol Digit Time as Predictors

Criterion	R^2 for Age: Age Alone	R^2 for Age: Age After Symbol Digit	% Reduction
Painters[a]			
Digit Span—Forward	.037*	.003	91.9
Digit Span—Backward	.034*	.001	97.1
Pattern Memory	.029*	.007	75.9
After Control of Education			
Digit Span—Forward	.008	.000	100.0
Digit Span—Backward	.007	.000	100.0
Pattern Memory	.011	.003	72.7
Pressmen[b]			
Serial Digit Learning	.085*	.017*	80.0
Pattern Memory	.047*	.000	100.0
Symbol Digit Recognition	.124*	.018*	85.5
After Control of Education			
Serial Digit Learning	.072*	.017*	76.4
Pattern Memory	.037*	.000	100.0
Symbol Digit Recall	.099*	.018*	81.8
Dutch Sample[c]			
Digit Span—Forward	.006	.000	100.0
Digit Span—Backward	.022*	.000	100.0
Pattern Memory	.057*	.021*	63.2
Serial Digit Learning	.092*	.051*	44.6
Associative Learning	.048*	.011	77.1
After Control of Education			
Digit Span—Forward	.000	.004	–
Digit Span—Backward	.006	.004	33.3
Pattern Memory	.037*	.015	59.5
Serial Digit Learning	.046*	.030*	34.8
Associative Learning	.017*	.003	82.4

[a] $n = 165$. [b] $n = 223$. [c] $n = 239$.
* $p < .05$.

ing data on the Symbol Digit test, however, were dropped from the analyses.) In the painter sample, three observations each were replaced for the Pattern Memory, Continuous Performance, and Pattern Comparison variables. With the pressmen sample, the number of missing values was 5 for Pattern Comparison, 4 for Tapping, 3 for Pattern Memory, and 2 for Continuous Performance. In the Dutch sample, there were 10 missing values for Serial Learning, 6 for Pattern Memory, 5 for Continuous Performance, 5 for Tapping, and 1 for Hand–Eye Coordination.

For initial analysis, the Symbol Digit times were converted into units of standard deviations for the group of adults in their 20s. (Because there were no adults in their 20s in the Dutch sample, these analyses were conducted only in the painter and pressmen samples). These data are plotted in Figure

TABLE 4
Hierarchical Regression Results With Symbol Digit Time as the Criterion Variable

	*R^2 for Age in Prediction of Symbol Digit = .237**		
Painters[a]	*R^2 for Predictor*	*Increment R^2 for Age*	*% Reduction*
Predictor			
1. Education	.152*	.129*	45.6
2. Vocabulary	.082*	.278*	−17.3
3. Effort	.002	.243*	−2.5
4. Pattern Comparison	.279*	.117*	50.6
5. Digit Span—Forward	.083*	.193*	18.6
6. Digit Span—Backward	.101*	.190*	19.8
7. Pattern Memory	.042*	.210*	11.4
8. Continuous Performance	.004	.234*	1.3
1 and 4	.328*	.081*	75.3
4 through 8	.348*	.089*	62.4
1 and 4 though 8	.372*	.070*	81.2
	*R^2 for Age in Prediction of Symbol Digit = .300**		
Pressmen[b]	*R^2 for Predictor*	*Increment R^2 for Age*	*% Reduction*
Predictor			
1. Education	.110*	.225*	25.0
2. Vocabulary	.004	.317*	−5.7
3. Effort	.000	.302*	−0.7
4. Pattern Comparison	.282*	.134*	55.3
5. Serial Digit Learning	.110*	.222*	26.0
6. Pattern Memory	.143*	.228*	24.0
7. Continuous Performance	.042*	.269*	10.3
8. Hand–Eye Coordination	.091*	.228*	24.0
9. Tapping	.082*	.225*	25.0
10. Symbol Digit Recall	.189*	.178*	40.7
1 and 4	.341*	.101*	70.4
4 through 10	.470*	.042*	86.0
1 and 4 through 10	.498*	.031*	93.8

(Continued)

TABLE 4 (*Continued*)

Dutch Sample[c]	R^2 for Age in Prediction of Symbol Digit = .237*		
	R^2 for Predictor	Increment R^2 for Age	% Reduction
Predictor			
1. Education	.066*	.188*	20.7
2. Vocabulary	.010	.257*	−8.4
3. Pattern Comparison	.170*	.135*	43.0
4. Digit Span—Forward	.035*	.225*	5.1
5. Digit Span—Backward	.122*	.194*	18.1
6. Continuous Performance	.084*	.192*	19.0
7. Serial Digit Learning	.048*	.195*	17.7
8. Pattern Memory	.054*	.198*	16.5
9. Hand–Eye Coordination	.100*	.155*	34.6
10. Tapping	.098*	.167*	29.5
11. Associative Learning	.066*	.195*	17.7
1 and 3	.202*	.113*	52.3
3 through 11	.315*	.074*	68.8
1 and 3 through 11	.319*	.071*	70.0

[a]$n = 165$. [b]$n = 223$. [c]$n = 239$.
*$p < .05$.

2 as a function of age decade. Note that the average performance in the decade of the 50s was approximately 1.5 standard deviations slower than that in the decade of the 20s. The correlations between age and symbol digit performance were .49 for the painter sample, .55 for the pressmen sample, and .49 for the Dutch sample. In both respects, these results are similar to those of studies with other substitution measures. For example, the correlation between number of items completed in 90 sec and age in the Salthouse (1992) study with 910 adults was 0.54, and correlations from other studies cited in that report ranged from −.46 to −.77. Moreover, the age correlation with a computer-administered version of the Digit Symbol Substitution task in a study with 362 adults reported by Salthouse, Kausler, and Saults (1988) was .54.

The next set of analyses considered the role of Symbol Digit performance in the relations between age and memory. Only a limited number of memory variables were available in these data sets, but the results of the hierarchical regression analyses, summarized in Table 3, are consistent with those of other studies. That is, in each case the significant age-related variance in the measure of memory was greatly reduced after controlling the variance in symbol digit performance. In fact, only with the Serial Digit Learning measure in the Dutch sample (but not in the pressmen sample) was the reduction in age-related variance after control of the Symbol Digit measure less than 50%. As in earlier studies, therefore, these results indicate that speeded substitution tasks share considerable age-related variance with tasks assessing memory or other types of cognitive functioning.

It is also apparent in Table 3 that in the painter and Dutch samples, the relations between age and the memory measures are greatly reduced when

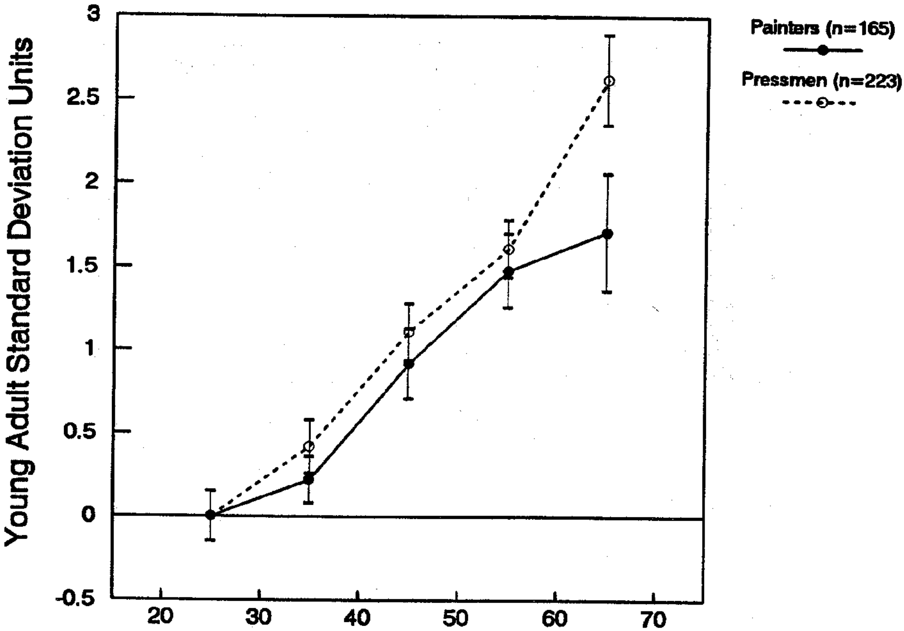

FIGURE 2 Mean performance as a function of decade in the Symbol Digit task expressed in standard deviations of the subjects in their 20s. *Note.* Bars above and below each point correspond to one standard error.

amount of education is controlled. The education influence was much smaller in the pressmen sample, however, and control of the Symbol Digit measure resulted in the same pattern of attenuated age differences in the memory measures, even when the variance in amount of education was eliminated by statistical means.

The final analyses, summarized in Table 4, indicate the relations of other variables to symbol digit performance and to the age-related influences on symbol digit performance. Of particular interest in this table are the variables with the greatest percentage reductions of the age-related variance in symbol digit performance. One such variable is amount of education, because the amount of age-related variance is reduced 45.6% in the painter sample, from an R^2 of .237 to one of .129. The influence of education is weaker in the pressmen and Dutch samples, however, and relatively small influences of education have been reported in other studies (e.g., Salthouse, 1992).

Of the remaining variables, pattern-comparison time appears to share the largest amount of age-related variance with the Symbol Digit measure. As mentioned earlier, similar results have been reported for paper-and-pencil measures of substitution speed and pattern-comparison speed (Salthouse, 1992, 1993).

The results with the Symbol Digit Recall measure in the pressmen sample are interesting because they suggest that learning of the symbol–digit associations accounts for only a portion of the age-related influence of symbol digit performance. That is, the significant age-associated variance (increment in R^2 = .178) after performance in the Symbol Digit Recall test is controlled indicates that other factors contribute to the age differences in the Symbol Digit task. Comparable results have recently been reported by Salthouse and Kersten (1993). The very similar pattern of age relations in Figure 2 for the Consistent Mapping (pressmen) and Varied Mapping (painters) versions of the task also suggests that learning of the associations plays a minor role in the age differences in the Symbol Digit task because this type of learning cannot facilitate response speed in the Varied Mapping version of the task.

Perhaps the most surprising results in Table 4 are the generally low relations exhibited by the memory (Digit Span, Serial Digit Learning, Pattern Memory), sustained attention (Continuous Performance), and manual coordination and speed (Hand–Eye Coordination, Tapping) variables. Although it is true that between 70% and 90% of the age-related variance in symbol digit performance can be accounted for by a combination of all of these variables plus amount of education, any given variable is associated with a relatively small proportion of age-related symbol digit variance. Furthermore, the attenuation of the age-related variance is nearly as great when only amount of education and pattern-comparison performance are controlled. The apparent implication is that the constructs assessed by these variables may be relatively unimportant factors for the age differences in symbol digit performance.

In conclusion, the analyses reported here both replicate and extend the findings of earlier studies. Previous results are replicated by the finding that statistical control of speeded-substitution performance greatly reduces the age-related variance in measures of memory functioning and by the finding that a considerable portion of the age-related variance in speeded-substitution measures is shared with measures of perceptual comparison speed. The results of earlier studies are extended by the discovery that similar relations are evident with a different type of substitution task and by the results suggesting that memory, sustained attention, and manual coordination and speed have little influence on the relations between age and speeded-substitution performance.

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