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Age Effects in Coding Tasks: Componential Analysis and Test of the Sensory Deficit Hypothesis

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Multiple forms of a symbol–digit substitution task were used to provide a componential analysis of age differences in coding task performance. The results demonstrated age differences in feature encoding, memory, and visual search. A 2nd experiment was conducted with young adults to investigate a sensory deficit as a locus of age differences. The spatial contrast sensitivity deficit of older adults was simulated on forms by applying a digital filter. Persons in the age-simulated contrast condition performed worse than those in the normal contrast condition. The stimulus degradation effect was linked to visual search speed. The study illustrates the utility of componential analysis and offers direct support for the hypothesis that sensory deficits affect performance on tasks used to assess intelligence.

Keywords: coding task, intelligence, contrast sensitivity, sensory deficit hypothesis

Coding tests have a venerable history in psychology. The tests are quite simple to produce and require little testing time. Furthermore, the task can be understood and performed by children and adults, as well as healthy and impaired individuals. In its simplest form, a participant is shown an array of paired symbols at the top of a sheet, such as the first nine letters of the alphabet paired with the digits 1 to 9. On the lower portion of the same sheet, one element of the pair is present and the participant is asked to write down the symbol that is paired with it in the symbol–digit array. For example, given the symbol *C*, the correct answer would be 3. The number of these codings, or symbol–digit substitutions, that a person can do in a set amount of time is his or her coding score.

Despite the simplicity of the task, coding tests are quite sensitive to cognitive impairments and are broadly used to assess drug and fatigue effects (e.g., Cameron, Sinclair, & Tiplady, 2001; Kaplan et al., 1998; Mattila, Aranko, Mattila, & Paakkari, 1994; Williamson, Feyer, Mattick, Friswell, & Finlay-Brown, 2001). The Digit–Symbol Substitution Test (DSST), a subtest of Wechsler intelligence scales, is one of several intelligence scale subtests on which survivors in longitudinal studies of aging had higher scores at initial testing than nonsurvivors (e.g., Botwinick, West, & Storandt, 1978). The DSST is also highly correlated with general intelligence (Matarazzo, 1972). Most pertinent for the present study, the DSST shows a rapid decline with age (e.g., Bak & Greene, 1980) after peaking at 18 to 21 years (Wechsler, 1958). Despite their extensive use and sensitivity to important behavioral and cognitive factors, there is not agreement as to what coding tasks actually measure.

Royer developed a method of analysis of coding tests that framed the task in information-processing terms (Royer, 1971b). Guided by Garner's (1966) principles of pattern perception, Royer (1971b) demonstrated that performance on coding tasks was related to the information load of the symbols in the test. Garner (1966, 1974) suggested that the perception of any pattern required the coding of sufficient information, bits, to differentiate the pattern from similar items. Garner (1966) coined a term, "equivalence set size (ESS)," to describe the number of elements implied by an individual symbol. While the implied set size is related in general to the confusability of patterns, Garner (1966) noted that if one worked with symbols drawn from a limited universe of elements, such as the horizontal and vertical segments composing a square with an internal cross, then a description of the ESS could be developed based solely on the number of unique exemplars produced from 90° rotations and mirror reflections of a pattern. For example, an *H* pattern would produce only two unique patterns and thus would be said to have an ESS of 2. A *T* pattern when rotated and reflected would have an ESS of 4. Given the popularity of information theory, the ESS was often transformed to bits ($\log_2$ [ESS] = bits). Royer and his colleagues (Gilmore, Royer, & Gruhn, 1983) demonstrated that performance on coding tests was directly related to the number of bits of information in the symbol array.

Gilmore et al. (1983) examined the coding test performance of a broad age range of adults by using a Symbol–Digit Substitution Test (SDST) that varied the information load of the test forms. An advantage of a symbol–digit coding task is that a well-learned response, the drawing of single digits, is used on each form. The

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common response controls for possible drawing differences that may result from the use of different symbols (Royer, 1971b). Gilmore et al. (1983) found that there was an interaction of age with the average information load of the symbols in the coding test. The symbol arrays composed of low ESS symbols elicited the most correct symbol–digit substitutions by each age group. However, the differences among the age groups were also greatest for these easy forms. While such a finding may be attributed to floor effects on forms, Gilmore et al. (1983) demonstrated that this interaction was not a floor effect but a simple product of the number of bits processed on each test form. That is, when the number of correct substitutions was multiplied by the average number of bits in each test form, it was shown that the rate of bit processing was the same on each of the test forms. Thus, the age differences on the coding tests were shown to be due to different information-processing rates.

Gilmore, Royer, Gruhn, and Esson (2004) have recently extended the decomposition of coding test performance by examining symbol–digit substitutions on 20 test forms by young adults. The symbols on the forms were varied to examine the separate contributions of encoding, memory, and visual search on coding performance. The symbol sets used in the original series of studies by Royer and his colleagues (Gilmore et al., 1983; Royer, 1971b) confounded these three factors. Gilmore et al. (2004) constructed symbol sets that permitted the factorial examination of the independent factors to separately demonstrate their impact.

It was shown in Gilmore et al.'s (2004) study that symbols containing diagonal line segments yielded fewer correct substitutions. This finding was interpreted in light of the psychophysical and neuroanatomical evidence on the difficulty in detecting diagonal lines as evidence that the presence of diagonal lines affected stimulus encoding (Appelle, 1972).

The influence of memory on performance was examined by varying the ESS of the symbols while holding constant feature composition and visual confusability. In information theory it is assumed that the memory load of a symbol is directly related to the number of bits of information needed to uniquely identify it (Garner, 1966). For example, the symbol *T* has a higher information load than the symbol *O*. The symbol *T* forms a four-item equivalence set created by 90° rotations or reflections of the symbol (upright *T*, *T* upside down, *T* rotated to the left or to the right), while the symbol *O* forms a unique equivalence set of one. Two bits ($\log_2 4 = 2$) of information are required to uniquely identify a symbol from the *T* set, while the unique *O* symbol requires 0 bits ($\log_2 1 = 0$). Royer (1971a) demonstrated that patterns with high ESS values are more difficult to recall. In a coding task, the participant is required to hold a symbol in memory while the symbol–digit array is searched. Gilmore et al. (2004) posited that symbols taken from large equivalence sets and consequently with high information loads would be more difficult to remember, thus resulting in fewer symbol–digit substitutions. As expected, ESS of the symbol arrays was negatively related to coding task performance in Gilmore et al. (2004).

Finally, Gilmore et al. (2004) manipulated visual search by varying the confusability of the symbols in each array. Confusable arrays contained symbols from the same equivalence set. For example, a highly confusable array may contain multiple exemplars from the symbol *T* four-item equivalence set while an array with low confusability would contain only one exemplar from the equivalence set (see Forms 2 and 1, respectively, in Figure 1). Coding test performance was found to be negatively related to the number of symbols identical by rotation or reflection that were included in the array. Thus, Gilmore et al. (2004) have provided a tool for creating symbol arrays that may separately affect performance through the manipulation of encoding, memory, and visual search.

In addition to showing that the symbol array manipulations were effective in performance, Gilmore et al. (2004) provided construct validity for the contention that performance differences related to the level of visual confusability among the symbols were driven by the visual search efficiency of the participants. Gilmore et al. (2004) selected samples of participants whose coding performance demonstrated either large or small effects of visual confusability. The persons in one group, termed the "good searchers," had high scores on forms that did not contain visually confusable symbols and had relatively low scores on forms with high levels of visual confusability. The second group, "poor searchers," yielded the same low coding performance on forms with either high or low visual confusability symbols. When presented with a tachistoscopic visual search task, the reaction time performance of the participants showed that the groups analyzed nontarget elements to different depths. Following Wolfe's (1994) model of visual search behavior, the poor searchers could be characterized as having a low threshold of activation that led to the detailed analysis of nearly all of the nontargets. The good searchers had a high threshold of activation and only examined elements that were very similar to the target character. This description of the tachistoscopic search behavior of the participants suggests an interpretation of their symbol–digit substitution performance. Persons who show little effect of the manipulation of the visual confusability of symbols have set a low threshold of activation when searching for a target. This low threshold requires them to conduct an exhaustive analysis of each element in the array of symbols regardless of its absolute confusability with the target. The good searchers set a high activation threshold so that only symbols that are very similar to the target are examined. The high threshold permits the observer to quickly find the target symbol in the array by skipping nonconfusable elements.

It is interesting to note that the coding performance functions of the good and poor searchers were similar to the functions reported

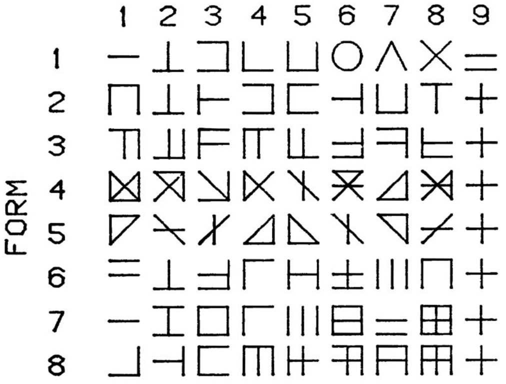

Figure 1. Symbols used on each of the eight forms in the symbol–digit substitution task.

by Gilmore et al. (1983) for young and older adults, respectively. That is, the older adult participants behaved like the poor searchers in that their performance did not improve with decreased visual confusability. The young adults performed like the good searchers and completed more substitutions on forms that contained few confusable symbols. Given this observation, it is tempting to argue that the poorer performance of older adults on coding tasks may be directly related to their inefficient visual search capabilities.

Consistent with the finding of Gilmore et al. (1983) of an age-related drop in the speed of bits of information processed, Salthouse (1992) in a correlation study of a number of elementary information-processing tasks concluded that adult age differences in coding tasks are due to a reduction in the rate of information processing and not deficits in memory. Furthermore, Salthouse (1992) argued that there was not an age-related change in the efficiency of specific information processes. The trend in recent studies has been to attribute adult age differences in cognition to general factors that may affect a broad class of sensory, perceptual, and cognitive factors (Salthouse, Hancock, Meinz, & Hambrick, 1996).

The present study used a subset of SDST forms created by Gilmore et al. (2004) to determine if a componential analysis of the SDST would yield evidence of the locus of the age-related differences in information processing. Three information-processing components were evaluated: feature encoding, memory, and visual search. A form was also included to estimate the motor speed component of the task. Hertzog and Bleckley (2001) have recently demonstrated that an independent measure of motor speed was highly correlated with information-processing ability. Tun, Wingfield, and Lindfield (1997) also reported that performance on a symbol copying task accounted for a portion of the age-related differences in digit–symbol substitution test performance. It was deemed important to be able to assess motor speed contributions to the coding task used here.

Given the parallels drawn above between the visual search styles of the participants in Gilmore et al. (2004) and the performance of young and older adults in Gilmore et al. (1983), it was expected that older adults would be less affected by manipulation of the visual confusability of symbols in the SDST. Following Salthouse (1992), differences between the groups were not expected to be related to the variation in the memory load. Finally, given the reported encoding deficits of older adults (e.g., Hines, Poon, Cerella, & Fozard, 1982; Simon & Pouraghabagher, 1978), it was anticipated that the manipulation of feature composition would yield a greater impact on the older adults. The use of the multiform coding task was expected to elucidate more fully the age-related differences on such tests.

Experiment 1

Method

Participants. The participants were 30 university students and 30 community-dwelling older adults. The mean age of the young adults was 19.7 (2.2) years while the older adults was 70.6 (4.7) years. The scaled Wechsler Adult Intelligence Scale vocabulary scores of the young and older adults were 14.1 (1.5) and 14.7 (3.2), respectively.

Design. Eight symbol–digit substitution test forms were used. These were a subset of the forms used by Gilmore et al. (2004). The symbols in the first form were drawn to be similar to those symbols used in the DSST subtest of the Wechsler Adult Intelligence Scale (Wechsler, 1958). The symbol sets are shown in Figure 1. An array of 9 symbols paired with single digits appeared at the top of the form. The symbols were arrayed in a random order in the lower portion of the form. There were 10 symbols, which were used for practice, followed by 90 symbol exemplars. The task of the participant was to record the digit that was paired with the symbol in the array at the top of the form. The use of a common response on each form controlled for possible differences in copying the symbols.

The first three forms were given in the order used by Gilmore et al. (1983) to permit comparison with that study of age effects. The order of the remaining five forms was randomly determined. The same order was given to all participants. An advantage of the fixed order was that it held constant within and between groups any carryover effects among the forms.

All forms except Form 1 have a constant symbol, with an ESS of 1 in Position 9. This constant was not used in the calculations of information load and visual confusability for these forms. To be consistent, we excluded symbol 8 (a symbol of ESS 1) in determining the information load and visual confusability of Form 1.

The eight symbols of Forms 1–3 carried 1.5, 2.0, and 3 bits of information, respectively. This enumeration of the information load is consistent with the usage of Gilmore et al. (1983, 2004) and Royer (1971b).

The remaining test forms were used to examine three factors: feature composition, memory load, and visual confusability, which were confounded within Forms 1–3. The stimulus specifications of the symbol arrays on each form are given in Table 1. Forms 6, 7, and 8 were used to determine the impact of memory load on information-processing speed when the factors of feature composition and visual confusability were held constant. Each of the forms was composed only of vertical and horizontal segments. These are referred to as *rectilinear forms*. The visual confusability of the symbols was defined to be zero because none of the forms had symbols that came from the same equivalence set. The memory load of the forms was determined by averaging the ESSs of the symbols in each form to yield the average bits of information. For example, a symbol with only vertical symmetry, such as *T*, has an ESS of 4. Expressed as bits of information, this value equates to 2 bits ($\log_2 4$). An asymmetric symbol has an ESS of 8, which is 3 bits of information. Forms 6, 7, and 8 had memory loads of 1.75, 0.875, and 2 bits, respectively.

Both the factors of feature composition and visual confusability could be evaluated with Forms 2, 4, 5, and 8. Information load was constant across the forms. Each of the forms was composed of symbols in the first eight positions, which had information loads of 2 bits. Forms 2 and 8 have rectilinear symbols. Forms 4 and 5 are composed of symbols with diagonal, vertical, and horizontal segments. These complex symbols are described as diagonalinear. Comparison of Forms 2 and 8 with Forms 4 and 5 provides a measure of the impact of the presence of the diagonal lines in the symbols independent of the information load and visual confusability.

The impact of visual confusability can be determined by contrasting the scores on Form 8 with Form 2 and on Form 4 with Form 5. Forms 8 and 4 were composed of eight unique symbols. Forms 2 and 5 were designed with the full equivalence sets of two symbols. That is, there were two confusable sets of four symbols in each test form. For example, Form 2 contains the symbol *T* in four orientations while Form 8 has only one exemplar of a *T*-like symbol. The multiple instances of the *T*-like symbol in Form 2 may be visually confusable during visual search. A factorial analysis of Forms 2, 4, 5, and 8 permits the evaluation of both feature composition and visual confusability independent of information load.

Motor speed was assessed with the ninth form, which was a simple digit copying task. This form did not have a symbol–digit array. It did follow the format of the other forms in that the lower portion of the form consisted of an array of 100 boxes with a single digit in each box. The task of the participant was to copy each digit into the empty frames.

Procedure. Participants were tested individually. All participants were tested in the same room and ambient luminance was held constant (shades drawn, all room lights on). Test materials were distributed in the form of

Table 1
Means and Standard Errors of the Number of Correct Items

				Experiment 1: Age group				Experiment 2: Contrast group			
Load (bits)				Young		Older		Normal		Degraded	
Form	Information	Visual	Feature	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
1	1.50	0.125	R	72.40	2.03	43.03	1.85	75.63	1.82	62.13	2.01
2	2	2	R	48.37	1.26	30.97	1.41	51.13	1.37	48.87	1.29
3	3	3	R	30.93	1.32	25.50	1.24	32.30	0.97	32.53	1.04
4	2	0	D	57.17	2.26	30.90	1.79	61.50	2.11	50.03	2.02
5	2	2	D	40.63	1.36	28.00	1.17	45.50	1.54	42.67	1.60
6	1.75	0	R	69.63	2.07	40.37	1.89	74.10	2.19	64.43	2.35
7	0.88	0	R	69.53	2.18	43.67	1.86	73.90	1.98	63.13	2.29
8	2	0	R	60.90	2.06	39.97	1.88	65.30	1.86	57.77	2.20
9				43.57	1.20	32.33	1.43	43.93	1.45	43.90	0.98

Note. All participants in Experiment 2 were young adults. Stimulus specifications of the symbol sets in the eight symbol–digit substitution forms are given for information and visual loads (bits) and feature composition. Form 9 assessed digit copying speed. R = rectilinear; D = diagonalinear.

a stapled packet, with one test form per page. Forms were ordered 1–9 for all participants. The test packet was given face down on the desk to the participant. Participants were told not to look at test forms until instructed to do so. The task was explained and an example of the test form shown. Participants then completed the 10 practice cells of Form 1. Participants were instructed to put their pencils down and turn the test packet face down when they had completed the practice cells. When told to start, participants were instructed to complete the array sequentially from left to right, without skipping any cells, and as accurately and as quickly as possible. Participants were given 90 s to complete as much of Form 1 as possible. Once time had elapsed, participants were instructed to stop working and turn their test packets face down. Forms 2–8 were administered in a similar manner.

Form 9 is a number copying task. Participants were instructed to simply write the number in the array below the printed number. As with Forms 1–8, participants were given 10 practice cells. The test form contained 90 cells. Participants were given 20 s to complete Form 9.

After testing, participants were debriefed and dismissed. Tests forms were scored for the total number of cells correctly coded.

Results

Errors in coding were rare for each age group. To compare the groups, the number of coding errors was summed across the eight coding forms. Form 9 had no errors. The young adults produced a total of 3.4 errors while the older participants yielded only 5.6 errors over the eight coding forms, $t(58) = 1.63, p > .10$. The level of errors did not warrant further investigation.

The correct symbol–digit substitution performance of the two age groups is given in Table 1. The results are presented by contrasting performance across specific forms to determine the separate information-processing contributions of motor speed, feature encoding, memory, and visual search components.

Motor speed. The digit copying speed of the young adults was 34% faster than the older participants on Form 9, $t(58) = 6.02, p < .01$. The means of the young and older groups were 43.57 and 32.33, respectively. It is clear that motor speed can be a major contributor to the age differences in general level of performance.

Forms 1, 2, and 3. An important comparison of the study was among Forms 1–3. Figure 2A shows the significant interaction for the mean number of correct substitutions by the two age groups across the three forms, $F(2, 116) = 68.83$, $MSE = 31.47$, $p < .01$. The steep drop in performance by the young group compared with the shallow slope of the older group as the number of bits increased is similar to the age-related performance pattern reported by Gilmore et al. (1983).

The copying scores on Form 9 were used as a covariate to estimate the true information-processing speed of the two age groups with motor speed extracted, $F(1, 57) = 32.23$, $MSE = 108.01$, $p < .01$. The scores adjusted for the copying speed covariate on Forms 1–3 are shown in Figure 2B. It is very interesting that the adjustment for motor speed resulted in the two groups yielding nearly the same score on Form 3, the most difficult symbol–digit substitution form. The differences between the age groups were evident on the easier forms. It appears that the motor speed adjusted information-processing rate of the two groups was the same on Form 3, which had maximum memory and visual confusability loads. In contrast, the easier forms that had less processing load as indexed by the bits of memory and visual confusability yielded faster processing scores for the younger adults. This pattern suggests that the older participants were less able to take advantage of the information load reduction.

As noted in the *Method* section, the forms were designed to permit independent examinations of feature composition, memory load, and visual confusability factors. It is important for our componential analyses that the age groups yielded virtually the same scores on one of the copying forms, Form 3, after the adjustment for motor speed. Because Form 3 had the highest memory load and visual confusability of the forms in the battery, it can be argued that when the participants were required to hold a very complex form in memory and to conduct an exhaustive search of the array, the age groups had the same slow processing speed. The age differences on Forms 1 and 2 must logically be due to the reductions in the memory and/or visual loads. The source of the age-related effect may be decomposed by analyses of the full set of forms.

Memory load. The number of correct substitutions was evaluated on Forms 6, 7, and 8, which varied in the average number of bits of information but were equated for feature composition and visual confusability. There was a significant interaction between

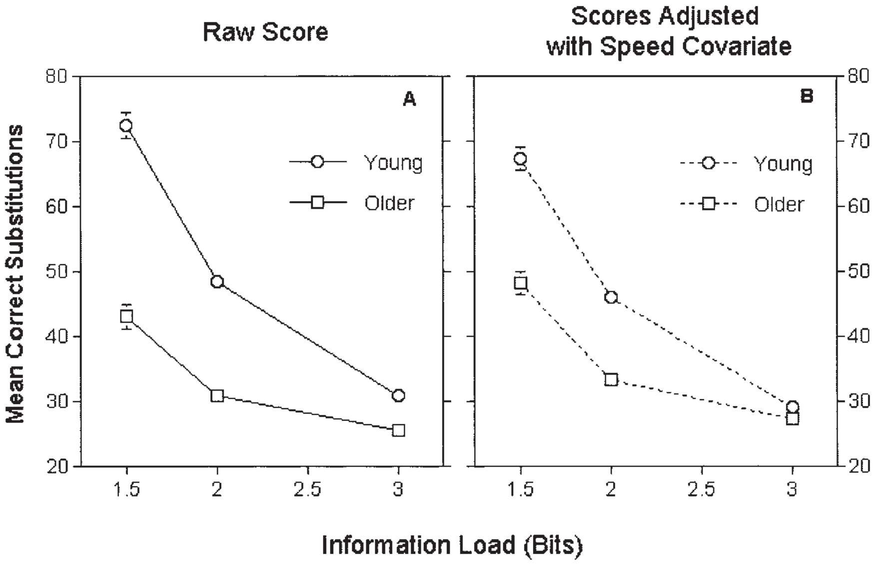

Figure 2. Performance of young and older adults in Experiment 1 on Forms 1–3 that varied the bits of information load. Mean number of correct substitutions reported as (A) raw scores and (B) adjusted for a motor speed covariate. Error bars (*SE*) are visible only where the size of the standard error exceeds the size of the datapoint symbol.

memory load and age group, *F*(2, 116) = 12.85, *MSE* = 20.5, $p <$ .01. Examination of the scores for both groups on Forms 6, 7, and 8 in Table 1 illustrates that at the range of information loads assessed here, from 0.875 to 2 bits, the impact on the symbol–digit substitution speed of the young adults was greater. The young adults yielded a range of substitution scores of 8.73 while the older participants had a range of only 3.7. The difference between the age groups suggests that a portion of the age effect among Forms 1–3 may be attributed to the complexity of the memory code held by the participants in each group. Young adults may be more efficient in memory coding as the bits of information are reduced for a symbol.

Feature composition. The comparison of the rectilinear, 2 and 8, and the diagonalinear forms, 4 and 5, assessed the additional encoding load of processing a diagonal feature independent of memory load and visual confusability. The rectilinear forms, 45.05, did yield a significantly higher level of performance when compared with the diagonalinear forms, 39.18, *F*(1, 58) = 76.31, *MSE* = 27.14, $p < .01$. The results demonstrate that the presence of diagonal lines does significantly slow information processing on coding tasks. The feature composition variable did not interact simply with age group. However, the impact of feature composition on the age groups did arise in an interaction with visual confusability.

Visual confusability. The comparison of forms that contained highly confusable symbols, Forms 2 and 5, with forms composed of unique symbols, Forms 4 and 8, permitted an evaluation of the visual search demands of the task independent of feature composition and information load. The forms with highly confusable symbols yielded a much lower level of correct substitutions, 36.99, as compared with the performance in the low confusability condition, 47.23, *F*(1, 58) = 144.64, *MSE* = 43.51, $p < .01$.

The older adults were affected less by the visual confusability manipulation. This finding was evident in both the interaction between age group and confusability, *F*(1, 58) = 25.40, *MSE* = 43.51, $p < .01$, and the triple interaction of feature composition, visual confusability, and age group, *F*(1, 58) = 12.82, *MSE*= 29.83, $p < .01$. The triple interaction was explored by conducting separate analyses within each age group. Young adults did not have a significant interaction between feature composition and visual confusability, *F*(1, 29) = 2.84, *MSE* = 42.22, $p = .10$. However, the older adults did yield a highly significant interaction between these variables, *F*(1, 29) = 16.01, *MSE*= 17.44, $p < .01$. Figure 3 illustrates that the older adults had shallower slopes of performance across visual confusability load particularly when the symbols were composed of diagonalinear elements.

The larger difference between the age groups occurred with the low confusability forms and was exacerbated by the presence of

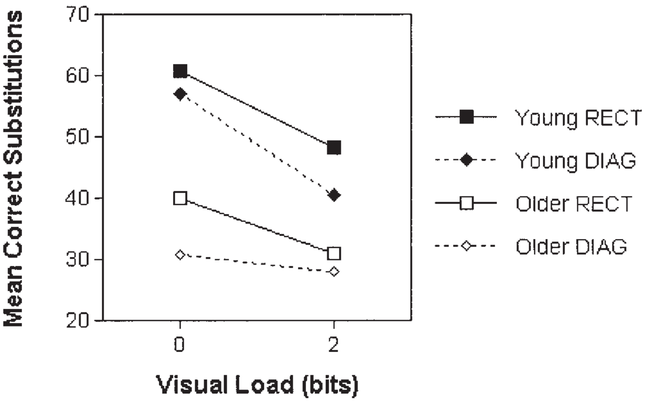

Figure 3. Mean correct substitutions by young and older adults in Experiment 1 on Forms 2, 4, 5, and 8 that varied in feature composition and visual confusability while holding information load constant at two bits. RECT = rectilinear features; DIAG = rectilinear and diagonal lines.

diagonal features. The older participants were less able than the young adults to take advantage of the low confusability of the forms to speed their visual search of the symbol array. This interaction suggests that the age effect on Forms 1–3 was driven in part by the different visual search demands of the forms. It appears that the older adults engaged in a detailed analysis of the elements in an array even when the symbols had very low confusability. The additional demand of processing diagonal lines made it more likely that the older adults would engage in an exhaustive analysis of the symbol arrays.

Correlations. Measures of the information-processing demands of feature composition, memory load, and visual confusability were derived by comparing performance on critical forms. A feature encoding measure of the impact of the diagonal lines on performance was assessed by taking the average of the difference between Forms 8 and 4 and Forms 2 and 5. These forms were chosen because they differed in the presence of diagonal lines but were equated for memory and visual confusability loads. By taking the difference between Forms 8 and 2 and Forms 4 and 5, a measure of the effect of visual confusability was determined. Finally, the impact of increasing the complexity of the memory load independent of feature composition and visual confusability was measured by looking at the difference between Forms 7 and 8. The derived information-processing measures were correlated with Forms 9 and 1. Form 9 was an independent measure of motor speed. Form 1 was chosen for two reasons. First, it has the same symbols as the DSST and thus offers generalizability to that important intelligence test. Second, Form 1 was not used in deriving the information-processing measures.

Table 2 presents the correlations among the selected variables. It is noteworthy that the derived information-processing variables yielded very low intercorrelations, thus supporting the assumption that these factors could be assessed independently. Performance on Form 1 was highly correlated with Form 9, the motor speed measure. It is not surprising when the participants include young and older adults that motor speed should be an important variable. The information-processing measures of the effect of both memory and visual confusability loads were also significantly related to the copying scores on Form 1.

A stepwise regression was conducted to determine the importance of each of the variables in predicting performance on Form 1. Not surprisingly, the motor speed measure was the most important predictor, accounting for 62.3% of the variability in Form 1. The visual confusability and memory load components each accounted for a small but significant portion of additional variance in Form 1, 4.8% and 5.6% variance, respectively. Feature encoding was not a significant contributor. The three contributing variables accounted for 72.7% of the variance on Form 1.

Discussion

The purpose of the experiment was to elucidate the information-processing locus of age differences in coding tasks. The experiment replicated and extended the findings of Gilmore et al. (1983). The difference in the coding performance of the young and older groups was inversely related to the number of bits of information in the array. The age groups were more similar in performance with the most complex set of symbols. Indeed, when motor speed was controlled statistically, it was shown that the coding speed of the age groups was the same on the most difficult form.

On the surface this finding seems to be counterintuitive given the well-described fall off in performance by older adults with more complex tasks (cf. Cerella, Poon, & Williams, 1980). Older adults are slower and less efficient in performing complex mental transformations. One might expect that the complex high ESS symbols in Form 3 would elicit a greater age difference than the simple low ESS symbols used in Form 1. However, the information-processing steps required to complete the coding task with each form are identical. The fundamental difference, we suggest, lies in the efficiency with which information processing, particularly visual search, is performed. The poorer performance by older adults may be characterized by a loss of efficiency in visual search. Visual search for the target symbol may involve either a detailed serial search of the symbol array or a more global analysis strategy (Gilmore et al., 2004). Form 3, because of the confusability of the symbols, requires each participant, regardless of age, to perform a detailed serial search of the items in the array to find the target. The symbols in Form 1 are not confusable, yet the search task may still be accomplished successfully with a serial analysis. An alternative and more efficient approach with an array of nonconfusable symbols would be to adopt a global analysis strategy or high activation threshold that can reject nontargets more quickly and consequently lead to the completion of more symbol–digit codings. We suggest that the age groups differed in their use of the latter, more efficient search strategy, particularly on Form 1. Thus, the findings are consistent with the complexity hypothesis in that the older adults did not utilize the more efficient search strategy as often as the younger adults.

Table 2

Pearson Correlations Among the Derived Information-Processing Factors for the 60 Participants in Experiment 1

Factor	Form 1	Motor speed[a]	Feature composition[b]	Memory load[c]	Visual confusability[d]
Form 1	—	.789***	.167	.415***	.652***
Motor speed[a]		—	.238	.279*	.605***
Feature encoding[b]			—	−.161	.084
Memory load[c]				—	.059
Visual confusability[d]					—

[a] Motor speed = Form 9. [b] Feature composition = [(Form 8 − Form 4) + (Form 2 − Form 5)]/2. [c] Memory load = (Form 7 − Form 8). [d] Visual confusability = [(Form 8 − Form 2) + (Form 4 − Form 5)]/2.

* $p = .03$. *** $p < .01$.

The componential analysis of performance permitted by the multiform symbol–digit substitution task produced evidence that there were age-associated differences in each information-processing component and in motor speed. These findings suggest that the age differences seen on coding tasks, such as Form 1 and on the DSST, which uses the same symbols, may be attributed to the impact of motor slowing, less efficient memory coding of symbols, and a more detailed visual search of the symbols in an array. The componential analysis supports the findings of a recent correlational study of the DSST (Joy, Kaplan, & Fein, 2004). Joy et al. reported that copying speed was the major factor in accounting for differences on the DSST followed by a small contribution of memory. The present componential analysis underlines the importance of visual search efficiency as a third contributor to coding task performance.

Experiment 2

In a series of studies, Lindenberger and Baltes (1994, 1997) have demonstrated that the age-related variance on the DSST is highly correlated with sensory acuity. Lindenberger and Baltes (1994) offered three hypotheses to explain this intriguing relationship. The first was that the relationship between intelligence and sensory factors is mediated by a third variable, a common cause. According to this hypothesis, the common cause, such as biological decrepitude, drives both the drop in intelligence and sensory acuity. The second hypothesis adapted from Sekuler and Blake (1987) was that the slow, inevitable decline in sensory function leads to a creeping sensory deprivation that eventually drives down intelligence. According to this hypothesis, the sensory factors were causing the decline, but only over a long period of time. The third hypothesis was that the reduction in sensory acuity actually caused the intelligence decline. Lindenberger and Baltes (1994) argued that the common cause hypothesis was the most logical contender as the correct explanation, but acknowledged that a direct test of the hypotheses was needed.

The hypothesis most amenable to test by behavioral scientists is the causal link between sensory factors and intelligence. Lindenberger, Scherer, and Baltes (2001) had young adults perform several cognitive tests while wearing glasses that optically reduced acuity to the level of an older adult. The investigators reported that the acuity manipulation did not impede performance. Indeed, there was evidence that the middle-aged adults responded to the sensory challenge by performing better in the low acuity condition. Thus, the sensory deficit hypothesis was not supported.

Schneider and Pichora-Fuller (2000) have provided an excellent review of the recent literature on the relationship between perceptual deterioration and cognitive performance. They make a strong case that the modification of stimuli by a deteriorated sensory system can impact perceptual and cognitive performance. In addition to acuity, an important sensory capability that diminishes with age is spatial contrast sensitivity (Owsley, Sekuler, & Siemsen, 1983). It may be argued that contrast sensitivity is more important than acuity, because the former is a better predictor of judging distances, night driving, and mobility (Rubin, Roche, Prasada-Rao, & Fried, 1994), as well as discriminating highway signs (Evans & Ginsburg, 1985). The present study was designed to examine the impact of stimulus contrast on coding test performance.

The study used a subset of SDST forms created by Gilmore et al. (2004) to investigate two questions. The first was whether the simulation of the spatial contrast sensitivity deficit of older adults may or may not affect performance on a coding task. This would be a direct test of the sensory deficit hypothesis of age-related declines in intelligence test performance. The second purpose was to determine if the componential analysis of the SDST would yield evidence of the locus of the age-simulated difference in information processing.

Method

Participants. The participants were young university students. There were 30 people in both the normal and the degraded contrast groups. The groups were matched on age, with means of 19.8 and 20.3 years in the normal and degraded groups, respectively. The near Snellen acuity for all participants was normal, with mean LogMAR acuities of .015 and .055 for the normal and degraded groups, respectively.

Materials. The normal and degraded versions of the symbol–digit substitution tests were printed with an HP LaserJet at 600 dpi on bright white resume paper. The printer had been calibrated so that the gray levels of the images could be adjusted to produce the appropriate levels of degradation. Each participant was presented with an original print of the test forms; no photocopies were used.

The normal contrast stimuli were digitally created to resemble the printed version of the symbols used in the DSST (Wechsler, 1958). As the digital printing process can produce a sharper image than the original Wechsler forms, the images were subjected to an antialiasing filter to simulate the original pen-drawn Wechsler images. The antialiasing filter is a loupes filter that produces a very slight blurring of edges.

The degradation of the forms was accomplished with a digital filter applied to the normal contrast stimuli. The spatial contrast sensitivity functions (CSF) of 20- and 80-year-olds were used to construct the filter (Owsley et al. 1983). Each function was described with a model developed by Thomas, Gilmore, and Royer (1993). The two mathematical models were combined to build the filter that was applied to the stimuli. The mechanics of combining the model for 20-year-olds with the model for 80-year-olds is straightforward and will be the topic in a separate manuscript that will include the computational routines.

In short, the filter combines the two CSF models (from 20-year-olds and 80-year-olds) so that the stimuli are either degraded or enhanced. The perceived stimulus can be related to the product of the actual stimulus image and the CSF of the participants. If either the stimulus or the CSF of the participants is degraded, the effect is a decrease in the quality of the perceived stimulus. Thus, the filtered stimuli seen by 20-year-olds can be made equivalent to the nonfiltered stimuli seen by 80-year-olds. Rather than degrade the 20-year-old vision directly, the stimuli are degraded to achieve the same result in the perceived stimuli, and the degradation is determined by the ratio of the two CSF functions used to define the filter. Similarly, if the 20-year-olds see the unfiltered stimuli, and the 80-year-olds see enhanced stimuli, the result is comparable to directly enhancing the visual signal in 80-year-olds within limits of display characteristics and not including temporal effects. Thus, the spatial contrast of the forms in the degraded condition simulated the reduction in spatial frequency contrast in the visual system of 80-year-olds.

Design and procedure. The eight symbol–digit substitution test forms and the number copying form described in Experiment 1 were used with the exception that one group received a degraded version of the forms.

The testing procedures were identical to those used in Experiment 1. Participants were tested in groups of 1–6 students per session. All participants were tested in the same room and ambient luminance was held constant (shades drawn, all room lights on). Near Snellen acuity was measured binocularly while participants wore their best correction for a distance of 18 cm.

Results

The symbol–digit substitution performance of the participants in the normal and degraded contrast conditions is given in Table 1. No substitution errors were produced by the young adults in this experiment. The results are presented by contrasting performance across specific forms to determine the separate information-processing contributions of motor speed, feature encoding, memory, and visual search components.

Motor speed. The digit copying speed of the participants on Form 9 was not affected by the contrast conditions. The means of the normal and degraded contrast groups, 43.93 and 43.90, respectively, were remarkably similar. The contrast manipulation had no effect on the time to encode and copy the digits.

Forms 1, 2, and 3. The critical comparison of the study was among Forms 1–3 in the normal and degraded contrast conditions. If the contrast manipulation was effective, then the age group by form pattern of results reported in Experiment 1 and by Gilmore et al. (1983) should be produced. Figure 4 shows the significant interaction for the mean number of correct substitutions by the two contrast groups across the three forms, $F(2, 116) = 21.06$, $MSE = 34.92$, $p < .01$. The steep drop in performance by the normal contrast group compared with the shallower slope of the degraded contrast group as the number of bits increased is similar in pattern to the performance of young and older adults, respectively, as reported in Experiment 1 and illustrated in Figure 2. Thus, the simulation of an age-related spatial contrast sensitivity difference did produce an age type effect in young adults on a coding task.

In Experiment 1 it was shown that the age effect in coding performance was not present in the most challenging coding condition, Form 3, when the scores were adjusted for motor speed (see Figure 2B). In Experiment 2, both groups of young adults yielded the same motor speed as indexed by the number of digits copied on Form 9. These young groups also completed the same number of symbol–digit substitutions with Form 3 (see Figure 4). The fact that the age groups in Experiment 1 could be matched in the same condition as the young groups subjected to different stimulus contrasts in Experiment 2 permits us to examine the group difference in Experiment 2 as exemplars of the age effects obtained in Experiment 1.

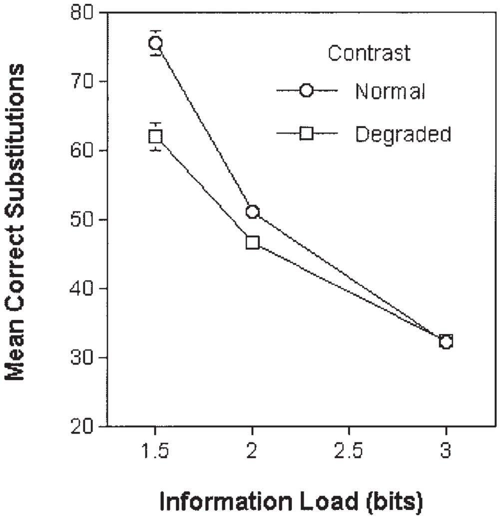

Figure 4. Mean number of correct symbol–digit substitutions by young adult participants in Experiment 2 who completed the coding task with normal contrast or age-simulated, degraded contrast forms. Error bars (*SE*) are visible only where the size of the standard error exceeds the size of the datapoint symbol.

There are two factors that allow us to make a strong case that the group differences in Experiment 2 are valid simulations of age effects in coding performance. First, the stimuli in the degraded condition were created specifically to represent the reduced proximal signal strength available to older adults. Second, the age groups in Experiment 1 and the contrast groups in Experiment 2 both showed no group difference in the most complex coding condition, Form 3, when the motor speed of the groups was matched (see Figure 2B and Figure 4). Thus, it is reasonable to argue that the magnitude of the differences in performance between the contrast groups in Experiment 2 is an index specifically of the age-simulated impact of reduced spatial contrast sensitivity on higher level information-processing components.

The source of the age-simulated effect may be decomposed by analyses of the full set of forms. As noted in the *Method* section, the forms were designed to permit independent examinations of feature composition, memory load, and visual confusability factors.

Memory load. The number of correct substitutions was evaluated on Forms 6, 7, and 8, which varied in the average number of bits of information but were equated for feature composition and visual confusability. The form with the highest memory load, Form 8, did yield the lowest level of performance, 61.53. The scores on Forms 6 and 7, 69.27 and 68.52, respectively, were significantly higher than on Form 8, $F(2, 116) = 39.53$, $MSE = 27.61$, $p < .01$. This pattern of results, which matches that obtained in Experiment 1, offers partial support for the hypothesis that coding task performance would be monotonically related to the average number of bits processed on a form.

The contrast groups did differ in their level of performance, with the normal group completing 71.10 items while the degraded contrast group had only 61.78 correct substitutions, $F(1, 58) = 10.82$, $MSE = 361.41$, $p < .01$. However, the contrast condition did not interact with the memory load, $F(2, 116) = 1.47$, $MSE = 27.61$, $p > .23$. This result implies that the simulated age effect on Forms 1–3 was not driven by the memory demands of the higher information load.

Feature composition. The comparison of the rectilinear (Forms 2 and 8) and the diagonalinear forms (4 and 5) assessed the additional encoding load of processing a diagonal feature independent of memory load and visual confusability. While the rectilinear forms, 55.27, did yield a significantly higher level of performance when compared with the diagonalinear forms, 49.93, $F(1, 58) = 81.44$, $MSE = 21.02$, $p < .01$, the contrast groups did not interact with feature composition, $F(1, 58) = 1.12$, $MSE = 21.02$, $p > .29$.

The results demonstrate that the presence of diagonal lines does significantly slow information processing on coding tasks. However, because feature composition did not interact with the contrast condition, it appears to be unlikely that the simulated age effect was related to feature encoding differences.

Visual confusability. The comparison of forms that contained highly confusable symbols (Forms 2 and 5) with forms composed of unique symbols (Forms 4 and 8) permitted an evaluation of the visual search demands of the task independent of feature composition and information load. The forms with highly confusable symbols yielded a much lower level of correct substitutions, 46.54, as compared with the performance in the low confusability condition, 58.65, $F(1, 58) = 161.25$, $MSE = 54.56$, $p < .01$.

Figure 5 shows the significant interaction between visual confusability and contrast group, $F(1, 58) = 9.74$, $MSE = 54.56$, $p < .01$. The larger difference between the normal and degraded contrast conditions occurred with the low confusability forms. The young participants in the degraded condition were less able than the participants in the normal condition to take advantage of the low confusability of the forms to speed their visual search of the symbol array. This interaction suggests that the simulated age effect on Forms 1–3 was driven by the different visual search demands of the forms.

Correlations. Table 3 presents the correlations among the derived information-processing variables and the scores from Forms 1 and 9. As in Experiment 1, the derived information-processing variables were shown to be independent of one another. Because Form 1 yielded the largest difference between the participant groups, it would be expected that the correlations with Form 1 would reflect the contributions of the factors to group differences. Given the results reported above, it is not surprising that only the visual confusability factor correlated significantly with performance on Form 1. Indeed, in a stepwise regression only the visual confusability factor contributed to predicting Form 1 performance, accounting for 31.1% of the variance. While this amount is less than the 42.5% variance accounted for by the visual confusability factor in Experiment 1, it is still striking because it is the only significant predictor here of performance on Form 1. These analyses support the finding that the contrast-defined groups differed specifically in their visual search analysis of the symbol–digit forms.

Discussion

Multiple symbol–digit substitution forms were used to determine if an age simulation of spatial contrast sensitivity differences could be directly linked to age-associated performance on a task that is highly related to intelligence. A sensory deficit in spatial contrast sensitivity was simulated in the production of the test forms. The coding forms were reduced in spatial frequency amplitude in the specific ranges in which 20- and 80-year-olds differ in their spatial contrast sensitivity. The simulation of the age-related sensory deficit markedly reduced the number of items that could be completed in the coding task. This finding offers direct support for the hypothesis that sensory deficits influence coding task performance.

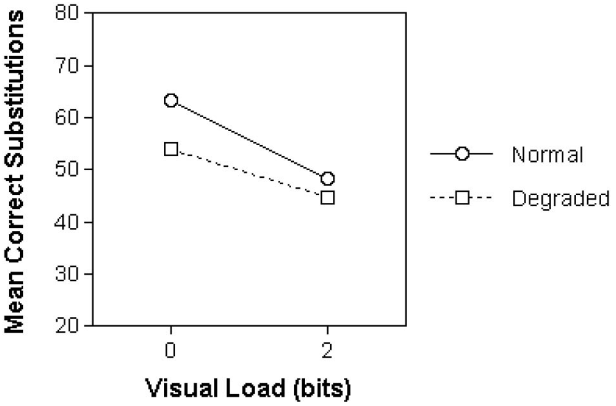

Figure 5. Mean number of correct symbol–digit substitutions in Experiment 2 on forms that varied in the degree of visual confusability among the symbols. Participants completed the coding task with normal contrast or age-simulated, degraded contrast forms.

It is noteworthy that the contrast reduction did not lead to a constant reduction in performance across all forms. The contrast manipulation had a selective effect on forms that were low in the number of bits of information that had to be encoded to complete the symbol–digit substitution. This pattern of results was seen in Experiment 1 and has been reported by Gilmore et al. (1983) for normal contrast coding tasks given to a broad age range of participants. The Age × Information Load interaction reported by Gilmore et al. (1983) and in Experiment 1 for Forms 1–3 was replicated in the present study by young participants viewing stimuli that simulated the spatial contrast reduction of older adults. The parallel findings suggest that the Age × Information Load interaction is directly linked to age-related changes in spatial contrast sensitivity.

The information-processing locus of the age-related differences was investigated through the comparison of multiple versions of the coding test. The multiple forms permitted the separate evaluation of the impact of encoding speed, memory load, and visual search on the age-simulated differences in coding task performance. Consistent with the report by Gilmore et al. (2004), each of these factors was shown to be a significant contributor to coding speed. The presence of diagonal features reduced coding performance, indicating a reduction in encoding speed. The number of bits of information carried by a symbol was also shown to be an independent contributor to coding task performance. Finally, the visual confusability of the symbols affected coding speed, thus suggesting that the visual search of the arrays was easier in the low confusable arrays. Only one of these factors was shown to be related to the age-simulated coding task performance.

Because the contrast groups did not differ in their digit copying speed and the feature composition did not interact with contrast, it appears that the age-simulated effects were not due to simple differences in encoding speed for features. This may be a surprising finding because on the surface it would seem reasonable that the adjustment of stimulus contrast would influence encoding speed factors. Since the work of Sternberg (1967) on the effect of stimulus degradation on memory search speed, it has been accepted that the product of the encoding stage is an abstract representation of the physical properties of a stimulus. In Sternberg's model, degraded stimuli were normalized to a standard abstract representation. Sternberg demonstrated in the memory search task that the impact of stimulus degradation was on the encoding stage and not on higher level processes such as comparisons in memory.

The absence of evidence for an encoding level effect associated with the stimulus degradation used in the present study suggests that there is not a normalization of stimulus contrast during initial encoding in the coding task. It appears that these stimuli with relatively small degradations are passed in raw form to the higher stages of processing in which the degradation does have an impact on processing efficiency.

Table 3
Pearson Correlations Among the Derived Information-Processing Factors for Participants in the Normal and Age-Simulated Degraded Contrast Conditions in Experiment 2

Factor	Form 1	Motor speed[a]	Feature composition[b]	Memory load[c]	Visual confusability[d]
Form 1	—	.142	−.036	.070	.557***
Motor speed[a]		—	.256**	−.068	−.063
Feature encoding[b]			—	−.209	−.183
Memory load[c]				—	−.077
Visual confusability[d]					—

[a] Motor speed = Form 9. [b] Feature composition = [(Form 8 − Form 4) + (Form 2 − Form 5)]/2. [c] Memory load = (Form 7 − Form 8). [d] Visual confusability = [(Form 8 − Form 2) + (Form 4 − Form 5)]/2.
** $p = .05$. *** $p < .01$.

The manipulation of information load independent of other factors also did not interact with contrast, thus suggesting that memory was not a source of the age-simulated effects. This finding is consistent with a report that did not find that contrast of stimuli had an influence on recall (Koss & Braunschweig, 2000).

The confusability of the symbols was related to the contrast of the forms. Participants performed much better on the low confusable forms when the contrast was normal. Given the link of this variable to visual search performance (Gilmore et al., 2004), it may be argued that the age-simulated performance differences in the low confusable forms were due to faster visual search operations in the high-contrast conditions.

Applying the principles of the guided visual search behavior model developed by Wolfe (1994), it may be suggested that the primary difference between the normal and degraded contrast conditions was the level of feature activation. In the normal contrast condition, the participants used a high threshold for feature activation when searching for a symbol among the array of symbols. Only the features associated directly with the target symbol were activated, permitting the distinctive symbol to pop-out in the arrays composed of nonconfusable elements. In the visually confusable arrays, the pop-out would not occur and a more detailed serial search would be conducted. In the degraded contrast condition, the participants set a low threshold of feature activation. The multiple-feature activation, including elements not directly associated with the target symbol, would make it less likely that a target symbol would pop-out and be quickly detected in the array. Instead, the participants in the degraded condition were more likely to use a detailed serial search with symbol arrays composed of both confusable and nonconfusable symbols. Thus, the interaction between the contrast of the symbol arrays and the visual confusability of the symbols was due to differences in visual search efficiency.

It is interesting that the present study did provide support for the sensory deficit hypothesis, whereas Lindenberger et al. (2001) did not. The difference in results may lie in the methods used to induce age-simulated sensory deficits. One possibility is that the two methods may have elicited different cognitive resource adjustments by the participants. The subtle nature of the degradation of the stimuli in the present study may not have compelled the young adults to make an adjustment. The use of obvious manipulations to degrade stimuli, such as masks (e.g., Sternberg, 1967), may elicit compensatory processing that changes the character of the processing event. The imposition of glasses in the Lindenberger et al. (2001) study that blurred the entire testing scene as well as the forms may have driven the participants to normalize the stimuli before processing to higher levels. That is, all stimuli whether degraded or not were encoded abstractly before storage in memory and visual scanning. When major, obvious stimulus changes are used, the differences in performance of young and older adults may be related more to the access to and the utilization of compensatory processes than to fundamental differences in information-processing ability. Further work is needed to determine the range and type of stimulus alteration that will elicit older adult-type coding performance. Additionally, when stimulus degradation does not degrade performance, it will be important to characterize the nature of the compensatory action that is taken by the processor.

The second reason that this study found an impact of stimulus quality on performance may be that the spatial contrast manipulation is a more ecologically valid factor. Indeed, it may be argued that a decline in high spatial frequency contrast sensitivity has a causal link to reductions in visual acuity. As such, the manipulation of spatial contrast would be a cleaner and more direct intervention whose influence would be easier to detect. Clearly, further studies investigating the specific forms of sensory deficit and their relationship to cognitive performance will be needed to determine the valid sensory variables.

Conclusions

This article has introduced a method for investigating group differences in information processing on coding tasks. It is an extension of a method pioneered by Royer (1971a). Multiple symbol–digit substitution forms were created by Gilmore et al. (2004) that permitted independent evaluation of the impact of motor speed, feature encoding, memory load, and visual confusability on coding performance. The multiform method was used here to investigate the age differences reported on the DSST (Wechsler, 1958) and specifically the Age × Information Load interaction reported by Gilmore et al. (1983).

In addition, we introduced a method for investigating the direct impact of reductions in spatial contrast sensitivity on a paper-and-pencil test. Using a digital filter, the spatial frequency amplitudes were modified to simulate the reduction in proximal signal strength experienced by older adults. This method permitted a direct test of the hypothesis that coding test performance was impaired by an age-related sensory deficit. An advantage of this method is that it permits the examination of an age-sensitive specific sensory factor in young adults and thereby avoids the potential confounds of other changes in cognition and biological status. The method may be useful in investigating other forms of age-related information-processing differences.

The componential analysis permitted by the multiform coding test was shown to be effective in both Experiments 1 and 2 in illustrating the independent contributions of information-processing factors. In Experiment 1, it was shown that motor speed was a major contributor to adult age differences in coding performance. The depth of visual analysis was demonstrated to be different between the age groups. Finally, it was demonstrated that the memory load of the symbols contributed to age effects.

Experiment 2 isolated the visual search component as the only process that was affected by the simulated age-related reduction in spatial contrast sensitivity. The reduction in signal strength was sufficient to produce a pattern of performance across Forms 1−3 (see Figure 4) in young adults that was very similar to that seen for older adults (see Figure 2 and Gilmore et al., 1983). This finding suggests that a portion of the age-related decline in performance on coding tasks is due directly to a reduction in spatial contrast sensitivity. To put it more broadly, a sensory deficit directly impairs performance on a task that is highly related to general intelligence.

There are three major conclusions from the study. The first two are methodological. A multiform coding test may be used to examine not only group but also individual differences in information processing. Using test forms that simulate reductions in spatial contrast sensitivity permits an evaluation of this sensory factor on information processing and individual differences. Finally, the evaluation of the cognitive capabilities of older adults must take into account their sensory deficits. Even subtle deficits, such as reductions in spatial contrast sensitivity, can impair performance on tests that are highly related to intelligence.

References

Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: The “oblique effect” in man and animals. *Psychological Bulletin, 78,* 266–278.

Bak, J. S., & Greene, R. L. (1980). A review of the performance of aged adults on various Wechsler Memory Scale subtests. *Journal of Clinical Psychology, 37,* 186–188.

Botwinick, J., West, R., & Storandt, M. (1978). Predicting death from behavioral test performance. *Journal of Gerontology, 33,* 755–762.

Cameron, E., Sinclair, W., & Tiplady, B. (2001). Validity and sensitivity of a pen computer battery of performance tests. *Journal of Psychopharmacology, 15,* 105–110.

Cerrela, J., Poon, L., & Williams, D. M. (1980). Age and the complexity hypothesis. In L. W. Poon (Ed.), *Aging in the 1980s* (pp. 332–340). Washington, DC: American Psychological Association.

Evans, D. W., & Ginsburg, A. P. (1985). Contrast sensitivity predicts age-related differences in highway-sign discriminability. *Human Factors, 27,* 637–642.

Garner, W. R. (1966). To perceive is to know. *American Psychologist, 21,* 11–19.

Garner, W. R. (1974). *The processing of information and structure.* Oxford, England: Erlbaum.

Gilmore, G. C., Royer, F. L., & Gruhn, J. J. (1983). Age differences in symbol–digit substitution task performance. *Journal of Clinical Psychology, 39,* 114–124.

Gilmore, G. C., Royer, F. L., Gruhn, J. J., & Esson, M. J. (2004). Symbol–digit substitution and individual differences in visual search ability. *Intelligence, 32,* 47–64.

Hertzog, C., & Bleckley, M. K. (2001). Age differences in the structure of intelligence—Influences of information processing speed. *Intelligence, 29,* 191–217.

Hines, T., Poon, L. W., Cerella, J., & Fozard, J. L. (1982). Age-related differences in the time course of encoding. *Experimental Aging Research, 8,* 175–178.

Joy, S., Kaplan, E., & Fein, D. (2004). Speed and memory in the WAIS-III Digit Symbol-Coding subtest across the adult lifespan. *Archives of Clinical Neuropsychology, 19,* 759–767.

Kaplan, G. B., Greenblatt, D. J., Ehrenberg, B. L., Goddard, J. E., Harmatz, J. S., & Shader, R. I. (1998). Single-dose pharmacokinetics and pharmacodynamics of alprazolam in elderly and young subjects. *Journal of Clinical Pharmacology, 38,* 14–21.

Koss, E., & Braunschweig, H. M. (2000, April). *The effect of contrast differences on recall of high frequency word lists in Alzheimer’s patients.* Poster session presented at the Cognitive Aging Conference, Atlanta, GA.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong correlation. *Psychology and Aging, 9,* 339–355.

Lindenberger, U., & Baltes, P. B. (1997). Intellectual functioning in old and very old age: Cross-sectional results from the Berlin aging study. *Psychology and Aging, 12,* 410–432.

Lindenberger, U., Scherer, H., & Baltes, P. B. (2001). The strong connection between sensory and cognitive performance in old age: Not due to sensory acuity reductions operating during cognitive assessment. *Psychology and Aging, 16,* 196–205.

Matarazzo, J. D. (1972). *Wechsler’s measurement and appraisal of adult intelligence* (5th ed.). Oxford, England: Williams & Wilkins.

Mattila, M. J., Aranko, K., Mattila, M. E., & Paakkari, I. (1994). Effects of psychotropic drugs on digit substitution: Comparison of the computerized symbol–digit substitution and traditional digit–symbol substitution tests. *Journal of Psychopharmacology, 8,* 81–87.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23,* 689–699.

Royer, F. L. (1971a). Information processing of visual figures in the digit symbol substitution task. *Journal of Experimental Psychology, 87,* 335–342.

Royer, F. L. (1971b). Spatial orientation and figural information in free recall of visual figures. *Journal of Experimental Psychology, 91,* 326–332.

Rubin, G. S., Roche, K. B., Prasada-Rao, P., & Fried, L. P. (1994). Visual impairment and disability in older adults. *Optometry and Vision Science, 71,* 750–760.

Salthouse, T. A. (1992). What do adult age differences in the Digit Symbol Substitution test reflect? *Journals of Gerontology: Psychological Sciences and Social Sciences, 47,* P121–P128.

Salthouse, T. A., Hancock, H. E., Meinz, E. J., & Hambrick, D. Z. (1996). Interrelations of age, visual acuity, and cognitive functioning. *Journals of Gerontology: Psychological Sciences and Social Sciences, 51B,* P317–P330.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 155–219). Mahwah, NJ: Erlbaum.

Sekuler, R., & Blake, R. (1987). Sensory underload. *Psychology Today, 21,* 48–51.

Simon, J. R., & Pouraghabagher, A. R. (1978). The effect of aging on the stages of processing in a choice reaction time task. *Journal of Gerontology, 33,* 553–561.

Sternberg, S. (1967). Two operations in character recognition: Some evidence from reaction-time measurements. *Perception & Psychophysics, 2,* 45–53.

Thomas, C. W., Gilmore, G. C., & Royer, F. L. (1993). Models of contrast sensitivity in human vision. *IEEE Transactions on Systems, Man, and Cybernetics, 23,* 857–864.

Tun, P. A., Wingfield, A., & Lindfield, K. C. (1997). Motor-speed baseline for the digit–symbol substitution test. *Clinical Gerontologist, 18,* 47–51.

Wechsler, D. (1958). *The measurement and appraisal of adult intelligence.* Baltimore, MD: Williams & Wilkins.

Williamson, A. M., Feyer, A. M., Mattick, R. P., Friswell, R., & Finlay-Brown, S. (2001). Developing measures of fatigue using an alcohol comparison to validate the effects of fatigue on performance. *Accident Analysis and Prevention, 33,* 313–326.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review, 1,* 202–238.

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