Cognitive Efficiency Modes in Old Age: Performance on Sequential and Coordinative Verbal and Visuospatial Tasks

Paul Verhaeghen, John Cerella, Silvie C. Semenec, Melissa A. Leo, Kara L. Bopp, and David W. Steitz
Syracuse University

In an experiment using a large set of verbal and spatial tasks requiring low or high degrees of executive control, 3 distinct age-related effects were found. The smallest effect (no slowing) was tied to lexical tasks with low executive involvement, the largest deficit (age-related slowing factor of 2.2) was tied to visuospatial tasks with high executive involvement, and an intermediate level of deficit (slowing factor of 1.7) was found for visuospatial tasks with low executive load and verbal tasks with high executive load. These age-related dissociations were incompatible with any "common cause" formulation. The mechanism responsible for the dissociation between verbal and visual tasks, and between low and high executive load remains to be determined. The latter may reflect capacity limits.

How many deficits are needed for an adequate account of age differences in cognition? The number suggested in the literature varies from “one” to what seems to be “as many as there are processes” (see Kausler, 1991, and Salthouse, 1991, for an enumeration of deficits raised in the literature). Intuitively, the many-deficits position makes perfect sense. After all, neither the brain nor the mind is unitary; psychologists have spent over a century teasing apart different structures and processes involved in cognitive functioning. Empirically, though, the single-deficit position seems to hold up surprisingly well.

The single-deficit position grew out of early attempts at describing regularities in young-old reaction-time data by using Brinley plots (e.g., Brinley, 1965; Cerella, Poon, & Williams, 1980). A Brinley plot is a scatter plot with mean performance of younger adults on the x-axis and mean performance of older adults on the y-axis. The early plots typically showed that a single straight line, and hence a single linear equation, could describe data drawn from multiple conditions or tasks quite well. A straightforward interpretation of this functional relationship is in terms of speed of processing: Older adults are slower than younger adults by a certain constant multiplicative factor, regardless of task (see Cerella, 1990, for a theoretical model that derives slowing factors from linear Brinley functions). This factor defines what we term the efficiency of adult information processing.

In more recent studies, however, distinct age-related slowing functions have emerged for different types or domains of tasks (Hale & Myerson, 1991; Kliegl, Mayr, & Krampe, 1994; Lima, Hale, & Myerson, 1991; Mayr, Kliegl, & Krampe, 1996; Myerson & Hale, 1993; Sliwinski & Hall, 1998). Such bifurcations have been termed dissociations (Perfect & Maylor, 2000). Although age-related dissociations can often be described by a set of linear equations, one for each task type or task domain, the most general case is simply a violation of monotonicity in the Brinley plot (Cerella, 1994). For example, if distinct lines are present in the Brinley plot, and the data points are connected according to their rank order on the x-axis, the resulting configuration will be jagged or saw-toothed rather than smooth and continuously increasing. Cerella has shown that if a single information-processing mechanism drives the performance of both age groups, then the resulting plot of points in Brinley space is by necessity monotonic. Dunn and Kirsner (1988) have proven analytically that the inverse is also true: Monotonicity in two variables (older adults’ mean latency and younger adults’ mean latency) implies that a third variable (general cognitive efficiency) can be constructed to which both are monotonically related. Conversely, a nonmonotonic Brinley plot implies, by mathematical necessity, distinct underlying age-sensitive mechanisms, one for each distinct line in Brinley space.

Two qualifying remarks must be made here. The mapping from Brinley configurations to efficiency levels is valid only if the relative accuracies of the two age groups are unchanged across the points (Cerella, 1990). For instance, in a simulation study, Li, Lindenberger, and Frensch (2000) have shown that learning curves with different age levels of asymptotic accuracy can lead to dissociations, even though they are driven by a single learning mechanism. A second qualification is that no statistical test of monotonicity has been proposed in the aging literature (but see Faust, Balota, Spieler, & Ferraro, 1999). Given measurement error, it is unlikely that any plot will be strictly monotonic. It may be best to evoke distinct mechanisms only for clear deviations from monotonicity; admittedly, this calls for judgment on the part of the observer. Thus, Brinley plots may be more suited to detect relatively large-scale dissociations, those associated with major age-related declines.

The monotonicity failures cited earlier were resolved by their discoverers by separating tasks into subsets, such that the Brinley...
points within each subset were monotonic. The boundaries of these task domains are of key theoretical importance. The dissociation found by Hale, Myerson, and colleagues (e.g., Hale & Myerson, 1996; Jenkins, Myerson, Joerding, & Hale, 2000; Lima et al., 1991; Myerson & Hale, 1993) was resolved by distinguishing between lexical and nonlexical (or what we call “visuospatial”) tasks. Lexical tasks yielded smaller age differences than visuospatial tasks, as assessed by the slopes of the resulting Brinley functions (for other studies showing small age differences in lexical access, see Allen, Madden, Weber, & Groth, 1993; Madden, Pierce, & Allen, 1993). The dissociation found by Mayr, Kliegl, and colleagues (e.g., Kliegl et al., 1994; Kliegl, Mayr, & Oberauer, 2000; Mayr & Kliegl, 1993; Mayr et al., 1996; Verhaeghen, Kliegl, & Mayr, 1997) was resolved by distinguishing between sequential and coordinative tasks, with coordinative tasks yielding the larger age difference. Sequential tasks involved processing that proceeded in a chainlike fashion, in which intermediate results were used immediately in the next step. Coordinative processing occurred when intermediate results had to be stored in working memory while additional processing was carried out concurrently. For instance, Verhaeghen et al. found no age difference in mental arithmetic for chainlike sums (e.g., $5 + 2 + 1 - 3 - 4 + 2$) but a rather large age difference for sums with concurrent storage-and-processing requirements that were due to the introduction of brackets (e.g., $[6 - (2 + 1)] + [8 - (4 + 2)]$).

Two properties of the aging dimensions revealed by these two types of dissociations are notable. First, they are binary valued rather than graded; within any one dimension, the age deficit is uniform. Second, the dimensions appear to be orthogonal; one can devise, at least prima facie, lexical tasks that are sequential or coordinative and visuospatial tasks that are sequential or coordinative. The dimensions can therefore form the basis of a $2 \times 2$ experimental design, crossing stimulus type (lexical and visuospatial) and processing type (sequential and coordinative).

In this article, we report results from just such an experiment, spanning eight tasks that were designed to fall into the four categories of lexical-sequential, lexical-coordinative, visuospatial-sequential, and visuospatial-coordinative. As in the Hale and Myerson (1996) study, each task was implemented at several levels of difficulty (two, three, or four, depending on the task), so as to yield enough data points for Brinley analysis using multiple regression techniques.

What are the expected results? The simplest outcome would be a configuration of two lines in the Brinley plot. Two lines would be obtained if lexical and sequential tasks were governed by one small slowing factor; visuospatial and coordinative tasks were governed by another larger factor. Although possible, the two-line outcome seems to us unlikely. Our impression is that the prototypical tasks for the lexical-visuospatial dissociation have been sequential in type, and that the prototypical tasks for the sequential-coordinative dissociation have been visuospatial in content. If this characterization of the published studies is correct, the possible outcomes are further constrained. At least three lines would emerge in the Brinley plot: one reflecting the small deficit tied to lexical-sequential tasks, one reflecting the medium deficit tied to spatial-sequential tasks, and one reflecting the large deficit tied to spatial-coordinative tasks. The result from the fourth cell of the design, lexical-coordinative tasks, is undetermined, given the lack of data in published studies. Note, however, that one of the sequential-coordinative dissociations was obtained for mental arithmetic (Verhaeghen et al., 1997). If mental arithmetic is taken as an instance of lexical processing, then the lexical-coordinative deficit in our hypothetical experiment is likely to be greater than the lexical-sequential deficit.

To resolve and interpret these possible dissociations, we applied multiple regression analysis to four subsets of the data. First and foremost, a classical Brinley analysis was performed on the average data—older participants’ means versus younger participants’ means. The full-sample Brinley analysis was repeated by using an individual $z$ transformation of the raw latency, to remove the influence of a general slowing factor from the Brinley plot (Faust et al., 1999); additionally, analyses of variance (ANOVAs) were conducted on the transformed data.

Three additional rounds of analysis were performed to test the limits and interpretation of the primary analysis. In the first of the additional analyses, a subsample of fast older participants was regressed against a subsample of slow younger participants. The motivation for this analysis comes from Salthouse (1996). He argued that dissociations may be due to a loss of information from working memory in memory-dependent conditions. As Salthouse pointed out, this can be caused by a decline in processing speed, even without age change in memory function. With slower processing, intermediate results must be retained over longer intervals and will hence be lost more frequently, despite equal decay rates. This necessitates recomputation of intermediate results. A higher frequency of recalculation would lead to a disproportionate increase in older participants’ response times. A Brinley analysis on subsamples of younger and older adults matched for overall speed provides a test of Salthouse’s theory. If a dissociation were due to slowing-induced loss of information, it should disappear in samples matched for speed (Hale & Myerson, 1996). If a dissociation reemerges in this context, it would refute not only Salthouse’s speed-retention theory, but also any other reductionist account that sought to explain higher order deficits in terms of the compounded effects of a lower order deficit. If (selected) older adults perform better than (selected) younger adults in a lower order condition, then they cannot perform worse in a higher order condition, unless the second condition draws on a cognitive function not operating in the first condition, and unless that function is negatively affected by age. Indeed, the technique of selection on average performance may help to surmount the more general interpretation problems that arise with ordinal interactions in group comparison research (Faust et al., 1999; Loftus, 1978; Verhaeghen, 2000).

The second round of additional analysis addressed a second corollary of the speed-retention theory. If the theory is correct, then the higher order deficit is caused not by age, but by slow processing speed. This implication was tested on our data by comparing not younger and older adults, but faster and slower adults within each age group. If a dissociation were due to being slower (as opposed to being older), then it would be no more than a focusing of individual differences in processing speed already existing in the young, respectively in the old. Hence, a young-old dissociation should replicate as a fast-young/slow-old dissociation and as a fast-old/slow-old dissociation.

The third round of analysis addressed a concern raised by Perfect and Maylor (2000), who argued that dissociations in a
Brinley plot may arise as an artifact of data averaging and may not characterize individuals. We conducted additional analyses at the level of individuals. The data of each older adult were regressed on the group data for the younger adults. If the dissociations are an averaging artifact, they should not be observed at the individual level.

Method

Participants

Participants were 30 younger adults (19 women), all undergraduate students at Syracuse University who received course credit for participating, and 30 older adults (24 women) recruited through newspaper advertisements and recruitment at community centers, who received $20 for participating. The younger adults were on average 18.6 years old (SD = 0.80) and had completed 12.6 years of education (SD = 0.86); the older adults were on average 70.8 years old (SD = 5.3) and had completed 15.03 years of education (SD = 2.43).

Tasks

Eight different tasks were included, originally thought to fall into the categories of lexical–sequential (category judgment, lexical decision, and anagrams), lexical–coordinative (lexical decision plus and anagrams plus), visuospatial–sequential (visual search and matrices), and visuospatial–coordinative (matrices plus) processing.

The category-judgment task was based on a task used by Hale and Myerson (1996). Participants judged whether two nouns presented side by side were from the same semantic category (e.g., dog horse versus ear couch). Two levels of difficulty were implemented: In the easy condition, both exemplars were highly typical of their category (e.g., dog horse); in the hard condition, both exemplars had low typicality (e.g., skunk panther). Category typicality was determined according to the Battig and Montague (1969) norms. In this set of norms, the number of items in each category varies considerably; we chose highly typical words from the top third of the items listed under each heading (i.e., words that were frequent responses when the category label was presented) and words with low typicality from the bottom third of the list (i.e., words that were infrequent responses when the category label was presented).

In the lexical-decision task, participants were presented with three- or four-letter strings and had to determine whether each letter string was an English word. Three conditions representing different levels of difficulty were implemented: (a) three-letter strings of high-familiarity words, (b) four-letter strings of high-familiarity words, and (c) four-letter strings of medium-familiarity words. High familiarity was defined as a value of 500 or more on the 700-point familiarity scale used in the MRC Psycholinguistic Database (http://www.dci.clrc.ac.uk/Projects/Psych/index.asi); medium familiarity was defined by values situated between 300 and 499.

Nonwords were constructed from sets of newly chosen words by randomly forming to a virtual square three, four, or five cells wide (for an example, see the top part of Figure 1); in negative items, none of the Xs could be configured as the corner points of a square. The participant’s task was to decide whether such a virtual square was present. Four conditions representing different levels of difficulty were implemented: (a) zero distractors, (b) three distractors, (c) five distractors, and (d) seven distractors. The zero distractor, or copy condition, gave participants a preview of the possible configurations of Xs before attempting the distractor conditions.

The matrices-plus task was similar to the matrices task, with two differences. Instead of Xs, arrowheads were printed (the symbols $<$, $>$, $V$, or an upside down $V$; see the bottom part of Figure 1 for examples). The participant was required to take into account not the location of the arrowhead, but the location it was pointing to, and was instructed to “Imagine an X in the box that the arrow is pointing to.” The arrow grids also differed in the number of distractors employed in each condition—0, 1, 2, and 3 rather than 0, 3, 5, and 7—in order not to overtax participants. For an example, see the bottom part of Figure 1.

Procedure

All tasks were presented on a computer, and reaction times were recorded to the nearest millisecond using a timing routine for Turbo Pascal developed by Brysbaert, Bovens, d’Ydewalle, and Van Calster (1989). Participants positioned the monitor at their most comfortable viewing distance. For each task, 40 items were presented. The first 6 were considered practice items; reaction times and error rates were calculated from the last 34 trials. All items were presented in a verification (yes–no) format; that is, participants had to judge whether a target was present, whether a string unscrambled into a word, and so forth. Decisions were indicated by pressing the / key for yes (marked with green tape) or the z key for no (marked with red tape). Participants were instructed to be both fast and accurate. Trials were participant initiated by pressing the space bar, and the stimulus remained on the screen until a response was made. For the verbal tasks, a trial began with a 100-ms fixation cross, followed by a 100-ms blank screen, followed by the presentation of the stimulus. For visual search, the fixation cross remained on the screen for 250 ms, followed by a blank screen for 250 ms. For the matrices and matrices-plus tasks, the stimulus grid appeared immediately after pressing the space bar.

Testing was conducted individually over two sessions on consecutive days in quiet and light-controlled testing rooms. In the first session, lexical-decision, lexical-decision-plus, matrices, and matrices-plus tasks were presented, in that order; the second session was devoted to anagrams, anagrams-plus, category judgment, and visual search tasks, in that order. Within each task, conditions were presented in increasing level of difficulty.
Results

Error rates and mean response times were calculated for each participant for each condition. Response times for items answered correctly were averaged across participants in several ways, and the resulting mean values were assembled in Brinley plots. Figure 2, top row, shows plots for the full sample; Table 1 reports the means and standard deviations used for Brinley plotting, as well as proportion correct. In the left panel of Figure 2, data points are connected by task, generating eight more-or-less linear traces.

Simple inspection of the figure shows that our original a priori classification of tasks into four distinct categories, yielding different Brinley lines, is incorrect. Multiple regression analyses showed that, technically speaking, our original classification fits the data well ($R^2 = .967$ when four intercept and slope parameters were included; $R^2 = .954$ when only significant terms were retained), but only two significantly different lines emerged: one for the tasks originally conceived as being lexical–coordinative (anagrams and anagrams plus) and one for the other tasks. This lexical–coordinative line had a negative intercept that was impossibly large (viz., $-13,653$ ms). Therefore, we decided to use a more exploratory approach to resolve the lines in Brinley space. In principle, multiple linear regression can be used to determine how many Brinley lines are needed to describe these traces. There are, however, 255 ways that eight tasks can be partitioned into equideficit classes, and effects can occur in intercept, slope, or both. This combinatorial explosion seems to us to rule out the use of multiple regression as a discovery procedure. Given that a particular partition has been proposed, multiple regression analysis is well suited to confirming it, but the partition must be uncovered by some other means.

We devised the following set of heuristics to partition task traces into equideficit classes. The three rules may or may not be universally successful. They worked well in our case (i.e., they matched our “eye-ball” solutions), perhaps because the task intercepts were close to the origin. Thus, all the traces were close to radius vectors and could be characterized primarily by their slope or angular orientation. This led to Rule 1: If the angle for Task B is greater than the angle for Task A, then Task B is placed into a higher deficit class. Under Task 1 alone, classes proliferated counterintuitively (e.g., lexical decision plus yielded a smaller angle than lexical decision). Rules 2 and 3 crimped this behavior. Rule 2: The coordinative version of a task cannot be placed in a lower deficit class than the sequential version of the task. Rule 3: Within a task, easier conditions cannot be included in a higher deficit level than more difficult conditions.

The right panel of Figure 2 shows the partition generated by Rules 1, 2, and 3. The eight task traces were reduced to three classes. Three tasks displayed a small (or no) deficit (categories,
lexical decision, and lexical decision plus), three tasks displayed a
moderate deficit (anagrams, anagrams plus, and matrices), and two
tasks displayed a large deficit (visual search and matrices plus). To
test whether the three levels thus constructed were reliably differ-
ent, we conducted a regression analysis including interaction
terms. The regression equation was the following:

\[ L_0 = a + b \times L_y + c \times \text{dummy1} + d \times \text{dummy1} \times L_y + e \]
\[ \times \text{dummy2} + f \times \text{dummy2} \times L_y \]  

(1)

\( L_y \) represents the mean response time of younger participants in a
condition, and \( L_0 \) represents the response time of the old; the
variable \( \text{dummy1} \) was coded 0 for the three low-level tasks, 1 for
the moderate-level task, and 0 for the high-level task; the variable
\( \text{dummy2} \) was coded 1 for the high-level task and 0 for the tasks
making up the two other levels. Thus, Equation 1 specified a trio
of lines, one for each of the three deficit levels. The parameters \( a, b, c, d, e, \) and \( f \) were estimated freely. This equation fit the data
well (\( R^2 = .981 \)), and significantly better than a model with a
single regression line for all data points (\( \Delta R^2 = .151 \)), \( F(4, 19) = 38.68 \). The coefficients associated with the multiple inter-
cept terms (i.e., \( c \) and \( e \)) were not significant. Refitting the model
after deleting these terms did not worsen the fit (\( R^2 = .980 \)), and
both the Level 2 and Level 3 interaction terms (i.e., \( d \) and \( f \))
remained significant. Thus, three lines were needed to describe the
data (as illustrated in the figure), and these lines differed significan-
tly in slope only. For Level 1, latency of the old was given by
\( L_0 = 66 + 1.02 \times L_y \); for Level 2, \( L_0 = 66 + 1.66 \times L_y \); and for
Level 3, \( L_0 = 66 + 2.18 \times L_y \). Note that the slowing factor of 1.02
for the first level is not different from 1, denoting equal perfor-
mance of younger and older adults; the two other slowing factors
were reliably larger than 1, as indicated by 95% confidence inter-
vals of the parameters.

Cerella (1990) has stressed that \( L_0 \times L_y \) plots can be meaning-
fully interpreted in terms of slowing factors only if younger and
older accuracy levels are comparable; otherwise, latency differ-
ences will be confounded with speed–accuracy trade-off differ-
ences. Across the 25 conditions, older participants were about 2%
more accurate than younger participants (viz., .86 vs. .84). Figure

Figure 2. Brinley plots of the latency data. The top row plots mean latencies of all older participants as a
function of mean latencies of all younger participants; the top row plots the data of the fastest 15 older
participants versus those of the 15 slowest younger participants (median splits on the average latency across all
tasks). The left-hand graphs connect data points of conditions within tasks; the right-hand graphs show the data
organized by level of efficiency, including the freely estimated regression line for each level. C = coordinative;
L = lexical decision; L+ = lexical decision plus; A = anagrams; A+ = anagrams plus; M = matrices; M+ = matrices
plus; V = visual search.
3 shows the full $A_o \times A_y$ plot (accuracy-old vs. accuracy-young). A regression analysis showed that one line fit the data well ($R^2 = .936$), $A_o = 0.114 + 0.90 A_y$. Adding interaction terms and dummy intercept variables did not reliably increase the fit of the function ($\Delta R^2 = .010$), $F(4, 19) = 0.48$. Thus, a single linear equation was sufficient to describe the age effect in accuracy. The bottom line here is that the dissociations in the $L_o \times L_y$ plot cannot be attributed to accuracy differences between levels.

Recently, Faust et al. (1999) have advocated a $z$ transformation for eliminating the effects of general slowing in between-groups designs. This transformation is calculated for each individual separately. Condition means are standardized on each individual’s own performance by subtracting the overall mean for an individual from each of his or her condition means, and dividing the result by the standard deviation of the condition means for the individual. Because rescaling is done at the level of the individual, it factors out the effects of general slowing from the age comparison. If the distinct lines in the original plot express only general slowing common to all conditions, the $z$-transformed points should collapse along the diagonal of the transformed plot (see Figure 8 in Faust et al. for an example). The $z$-transformed plot for our data is depicted in Figure 4. This plot shows the same pattern of dissociations as the raw-latency plot. While removing the general-slowing effect reoriented the curves to straddle the diagonal (a reorientation similar to that effected by the fast-old vs. slow-young analysis), the three efficiency levels reemerged in the transformed data.

The $z$ transformation has the additional advantage that it allows for planned comparisons between levels of complexity, taking the repeated-measures nature of the data into account, an analysis impossible in classic Brinley analysis. We conducted two series of planned contrasts on our lexical-decision (lexical-decision-plus), anagrams (anagrams-plus), and matrices (matrices-plus) tasks.

The first series of planned contrasts focused on the sequential versus coordinative complexity manipulation, separately in each of the three task families. Three repeated-measure ANOVAs were conducted with complexity (sequential vs. coordinative) and difficulty (the three levels for the lexical-decision [lexical-decision-plus] and anagrams [anagrams-plus] tasks, and with the four levels for the matrices [matrices-plus] tasks) as the within-subject variables and age group as the between-subjects variable. The relevant

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Table 1
Means and Standard Deviations for Latency and Proportion Correct for All Tasks, Split by Age Group
The $F$ value associated with the Complexity × Age interaction, indicating that age differences vary with the sequential–coordinative manipulation. This statistic was not significant for the anagrams (–plus) tasks, $F(1, 58) = 0.17$, $MSE = 0.24$. The effect was significant, but in the opposite direction than predicted for lexical-decision (lexical-decision-plus) tasks, $F(1, 58) = 35.19$, $MSE = 0.30$, with an average age difference (in $z$ units) of $-0.10$ in the lexical-decision tasks and $0.79$ in the lexical-decision-plus tasks (positive differences denote better performance in older adults than in younger adults). The effect was significant and in the predicted direction for the matrices (–plus) tasks, $F(1, 58) = 17.42$, $MSE = 0.30$; the age difference averaged $-0.05$ for matrices and $-0.46$ for matrices plus. Thus, in agreement with the Brinley analysis, the coordinative manipulation yielded larger age differences in the matrices task only.

The second series of planned contrasts focused on the different task types: lexical decision versus anagrams and anagrams versus matrices. Because the previous analyses did not show the complexity dissociation predicted by sequential–coordinative theory for lexical decision and anagrams, we collapsed all lexical-decision and lexical-decision-plus and all anagrams and anagrams-plus tasks in the first contrast, conducting a repeated-measures ANOVA with task type (lexical decision [lexical decision plus] vs. anagrams [anagrams plus]) and difficulty level (the six conditions within each task type) as the within-subjects variable and age group as the between-subjects variable. The Task Type × Age interaction was significant, $F(1, 58) = 30.63$, $MSE = 0.39$, indicating that age differences were more negative in the anagrams (anagrams-plus) tasks (viz., $-0.07$) than in the lexical-decision (lexical-decision-plus) tasks (viz., $0.45$). The anagrams task contained three levels of difficulty; the matrices task contained four levels. Therefore, we tested the anagrams versus matrices contrast twice: once using difficulty Level 1 to Level 3 of the matrices task and once using difficulty Level 2 to Level 4. In both repeated-measures ANOVAs, the Task Type × Age interaction proved nonsignificant, $F(1, 58) = 2.44$, $MSE = 0.48$, and $F(1, 58) = 3.60$, $MSE = 0.66$, indicating that age differences were identical for the anagrams and matrices tasks.

Summarizing the results from the $z$-transformed data, these analyses show that (a) the predicted sequential–coordinative dissociation was significant only for the matrices tasks, and (b) lexical-decision (lexical-decision-plus) tasks yielded smaller age differences than anagrams (anagrams-plus) tasks, but the matrices tasks did not yield larger age differences than the anagrams tasks. These results are in agreement with our exploratory Brinley analysis, with the exception of an age difference favoring the old in the sequential–coordinative comparison within lexical-decision tasks (an effect going against any reasonable aging hypothesis).

The bottom row of Figure 2 shows plots derived from the fastest older participants and the slowest younger participants (viz., 15 younger and 15 older participants, who were selected via a median split on their average latency for all tasks). As can be seen, these plots demonstrate the same pattern of dissociations as the full-sample plot, even though the young–old slopes are dramatically different from the slopes found in the total sample: these exceptional old were slowed by a factor of $1.25$ in Level 3, but were faster than these exceptional young in Level 2 (slope of $0.85$) and in Level 1 (slope = .73).

Figure 5 shows the plot comparing slower younger adults with faster younger adults, using a median split on the average latency (top panel), as well as a plot comparing slower older adults with faster older adults, using a median split on the average latency.
faster older adults (bottom panel), using a median split on the average latency. For the younger adults, a single regression line fit the data well ($R^2 = .919; L_{\text{slow}} = -219 + 1.52 L_{\text{fast}}$), but including interaction and intercept dummy terms significantly increased the fit ($\Delta R^2 = .070$), $F(4, 19) = 29.63$. The only added term that was significant was the interaction associated with Level 2, resulting in two regression lines: one spanning Level 1 and Level 3 ($L_{\text{slow}} = -130 + 1.28 L_{\text{fast}}$) and one specific to Level 2 ($L_{\text{slow}} = -130 + 1.76 L_{\text{fast}}$). Thus, the deficit structure found for older participants of small, moderate, and large deficits must derive from something more than age-amplified individual differences already present in younger adults. Slower young showed moderate and large deficits compared with faster young, but the moderate deficit of the young was an amalgam of the small-deficit conditions and the large-deficit conditions found for the old. For the older adults, a single regression line fit the data well ($R^2 = .959; L_{\text{slow}} = -1,820 + 1.89 L_{\text{fast}}$); including interaction and intercept dummy terms did not significantly increase fit ($\Delta R^2 = .015$), $F(4, 19) = 2.73$. Note that the nonsignificant trend present in the data from the older adults was for Level 2 and Level 3 to dissociate in an equal amount from Level 1.

Because Brinley plots are derived from group averages, the resulting configuration of points may not represent the performance of typical individuals, or indeed, of any individual. To test for this, we analyzed the data of each older participant separately. Three simple linear regressions were performed: The Level 1 conditions for an older participant were regressed onto the corresponding Level 1 averages of the full sample of younger adults, the Level 2 conditions for the participant were regressed onto the Level 2 young-participant averages, and the Level 3 conditions for the participant were regressed onto the Level 3 young-participant averages. Because individual data are more subject to error than group data, and because the Brinley analysis showed that the regression lines are close to radius vectors, all individual regression analyses were forced through the origin. We then extracted the slopes of these single-participant/single-level Brinley lines. In 23 out of 30 cases, the slopes were ordered as they were in the average data: Level 1 $< $ Level 2 $< $ Level 3. Thus, the performances of individual older adults by and large mirrored the effects found in the group means.

For 17 of the 30 older participants, slopes for the Level 1 regression lines happened to be smaller than unity, indicating that these older adults were faster than the average younger adult and enjoyed an age advantage rather than an age deficit on Level 1 tasks. The 17 participants so circumscribed constitute a select subsample of “fast” older adults. We examined whether these participants crossed over from a slope smaller than 1 to a slope larger than 1 in passing from Level 1 tasks to Level 2 or Level 3 tasks. This is the same logic underlying the fast-old/slow-young comparison, applied now to individual participants. A crossover in slope was found in 16 of these 17 fast participants. Thus, virtually all of the older adults who showed an advantage in Level 1 showed a deficit in Level 2 or Level 3. These cases make it particularly clear that Level 2 or Level 3 deficits cannot be attributed to basic deficits in Level 1.

Discussion

In the present study, we examined age differences in reaction time and error rates in eight cognitive tasks, each presented at a number of difficulty levels, 25 conditions in total. The main analysis consisted of mapping the relation between performance of older adults and performance of younger adults in a Brinley plot (Brinley, 1965; Cerella et al., 1980). In the analysis of reaction-time data, and a series of follow-up analyses, we found evidence for the existence of three tiers, or levels, of age-related dissociations. No such young–old dissociations were found in error rates. Therefore, these levels were taken as indicators of age differences in efficiency of processing; that is, of age differences in the speed at which a stable age difference in accuracy is reached. The stratification of points in the Brinley plot suggested qualitative, all-or-none jumps in processing ability, to the exclusion of intermediary values. For example, the same cognitive operation, letter transposition, seemed to be conditioned by different age-related slowing factors, depending on the level in which it was embedded (discussed later). To underscore the quantal character of the deficits, we label these levels efficiency modes.

Broken down by task, the first and most efficient processing mode (showing no age deficit in the present sample) consisted of
lexical decision with and without concurrent transformations and category judgment. The medium efficiency mode (with an age-related slowing factor of about 1.7) consisted of anagram solving with and without concurrent transformations and of the detection of target configurations of Xs amid X distractors (pattern detection). The least efficient mode (with an age-related slowing factor of about 2.2) consisted of visual search for Ys amid X distractors and of pattern detection with concurrent transformations. The three modes emerged at both the group level and at the individual level. The modes were definitely age related, in that they did not surface in the same way from a comparison of slow-versus-fast younger adults or of slow-versus-fast older adults.

It is worth noting that prior to the experiment described here, we conducted a paper-and-pencil pilot study on 47 younger and 48 older adults, with the anagrams and anagrams-plus conditions and a variant of the matrices and matrices-plus tasks (in this variant, apart from virtual squares, the stimuli also included virtual diamonds). These tasks contained only positive items, and participants indicated their answers by writing down the unscrambled words or connecting points to form a square or diamond. Forty-eight items were used for each task, time was limited, and time per item was computed. Results from this pilot study were entirely consistent with the levels found in the main experiment: anagrams, anagrams plus, and matrices formed one level (i.e., the intermediate level in the main experiment) and matrices plus (i.e., the large-deficit level in the main experiment) reliably dissociated from the other tasks. The data are shown in the Brinley plot of Figure 6, with the dissociations clearly evident. (More details of the pilot study can be obtained from the authors.)

How are our findings to be understood? Before undertaking any new interpretation of the data, we first review existing theories—those that have been formulated, or can be reformulated, around the configuration of points in a Brinley plot. These theories may be organized under two headings: single deficit and dual deficit. The preeminent single-deficit theory is, of course, general slowing, succinctly embodied in the claim that every component process is extended with age by a constant factor (e.g., Cerella, 1990; Cerella et al., 1980). Assuming that the component processes are sequential, and that age differences in accuracy are constant (as they were in our experiments), then a young-versus-old plot of the resulting latencies will be linear, with a slope equal to the slowing factor. As explained in the introduction, any theory that posits a single processing deficit predicts by mathematical necessity a monotonic locus in a Brinley plot (Cerella, 1994; Dunn & Kirsner, 1988). Given that we found three distinct loci, the strong prediction of general slowing was violated.

The information-processing mechanism underlying general slowing theory is extraordinarily simplistic, a single stream of processing steps; it is hardly surprising that the observed outcomes exceeded the model. Salthouse’s (1996) dual-mechanism model doubles the information-processing components, adding to the processing stream a working-memory store. Salthouse pointed out that even without a specific age change in working memory, a speed reduction will lead to disproportionate deficits in tasks that require intermediate storage. Because of slower processing, all retention intervals will be lengthened and stored information will be more likely to decay. Assuming that accuracy is maintained, information will have to be recomputed (Assuming also that information decays rather than be displaced.) The theory, therefore, rests on two information-processing mechanisms: a processing stream and a memory store, only one of which shows an age-related deficit (the processing stream). The theory has received correlation-based support from hierarchical regression analyses, showing that reaction times in a memory-free task can explain reaction times in memory-dependent version of the same task (e.g., Salthouse & Coon, 1994). For multitask experiments like ours, predictions can be extended to the group means; memory-free tasks should show small deficits and memory-dependent tasks should show large deficits.

This two-mechanism/one-deficit theory, with its predictions of dissociations in the Brinley plot, clearly makes closer contact with our data than a one-mechanism/one-deficit theory. There seems to be no reason why multiple efficiency modes (i.e., more than two) cannot be countenanced. Detailed predictions, however, have

![Figure 6. Brinley plots of the latency data from the pilot experiment, plotting mean latencies of all older participants as a function of mean latencies of all younger participants. The left-hand graphs connect data points of conditions within tasks; the right-hand graphs show the data organized by level of efficiency, including the freely estimated regression line for each level. A = anagrams; A+ = anagrams plus; M = matrices; M+ = matrices plus.](image)
never been developed. One would have to factor together the amount of processing and the amount of intermediate storage required by a task; such task modeling would, we think, be fruitful to pursue (cf. Byrne, 1998, for a step in that direction).

One immediately testable prediction of general-slowing theory is that age deficits in the more complex levels should be conditional on age deficits in less complex levels. If no age deficit exists in the execution speed of the simple memory-free task, then no age difference should emerge in the memory-dependent version. This was the rationale for our fast-old/slow-young comparisons. We found that simple-task/complex-task dissociations reemerged for samples of older participants selected to be, on average, equally fast as the younger adults. In this subsample, older adults were actually faster than younger adults on the simpler tasks, and hence, given the slowing/retention logic, the age effect should have been reversed in the harder tasks. This was not the case.³

We tested another corollary of the slowing retention theory. The theory is not tied to the effects of age per se but to the effects of individual differences in speed, whatever their cause. The pattern of effects obtained by comparing older with younger individuals (i.e., the full-sample age comparison) ought then to be replicated in a comparison of slow-young versus fast-young subsamples and in a comparison of slow-old versus fast-old subsamples. In our data, the tripartite old-young dissociation did not reemerge in these samples. The failure to dissociate was particularly telling because the overall slowing factor for the slow-young compared with the fast-young was about 1.5, and the overall slowing factor for the slow-old compared with the fast-old was about 1.9, factors that were quite comparable to the overall old-young slowing factor of 1.8.

The two-mechanism/one-deficit notion is appealing for its parsimony, and one may imagine other models of this type, in which the consequences of a single, low-level defect are compounded at higher levels of processing complexity. Cerella and Hale’s (1994, Figure 18) distinction between uni- and bimedial lattices is another example. These models all seem capable of predicting dissociations, although the boundaries will vary with the details of the model. All, however, would seem to succumb to the demonstrations we provide here, of higher level deficits in the face of lower level surfeits.

Continuing the survey of existing theories, we turn to those richer versions that interpret patterns of age loss in terms of two deficits rather than one. Hale, Myerson, and colleagues (e.g., Hale & Myerson, 1996; Jenkins et al., 2000; Myerson & Hale, 1993) have argued that lexical processes are circumscribed by one small deficit, and visuospatial processes by a second moderate deficit. Theirs, then, is a two-mechanism/two-deficit theory, encompassing a lexical process and a spatial process, each with its own deficit. Three of our tasks paralleled ones used by those investigators to establish their theory, and our results replicated theirs—lexical decision and category judgment together showed a small age deficit, and visual search showed a larger deficit. However, results from our other tasks cut across the lexical–visuospatial boundary. Two ostensibly lexical sets of tasks dissociated: lexical decision and category judgment on one side and anagrams and anagrams plus on the other side; two visuospatial sets of tasks dissociated: matrices on the one side and visual search and matrices plus on the other. Finally, two sets of tasks failed to dissociate that were ostensibly lexical on the one side (anagrams and anagrams plus) and visuospatial on the other (matrices). (In the following section, we concede that this last finding may be a coincidence.) Consequently, this dual-deficit theory needs to be extended for a full understanding of our data.

Kliegl and colleagues have also advanced a dual-deficit theory (e.g., Mayr & Kliegl, 1993; Verhaeghen et al., 1997). These authors argued that age deficits are tied not to the content of processing (lexical or spatial), but to the type of processing: sequential or coordinative. Sequential processing proceeds in a chainlike series of steps and is associated with a moderate age deficit; coordinative processing involves the storage of intermediate results in working memory while additional steps are carried out concurrently and is associated with a large age deficit. Essentially, this theory seems to call on the same mechanisms as the Salthouse theory, a processing stream and a memory store, but now attaches a deficit to both processes.

The application of Mayr and Kliegl’s (1993) distinction between sequential and coordinative processes to our tasks was less straightforward than the application of the Hale–Myerson theory, as none of our tasks matched those of Kliegl closely. We relied on his definitions to classify the tasks. In agreement with the theory, the lexical-decision deficit matched the categorization deficit (both sequential), and anagrams matched matrices (again both sequential). Similarly, matrices showed a moderate deficit, and matrices plus showed a large deficit (one sequential and one coordinative). However, other outcomes were not in agreement with the theory. Visual search and matrices dissociated, although both were ostensibly sequential; visual search and matrices plus failed to dissociate, although one was sequential and the other coordinative; nor did lexical decision and lexical decision plus dissociate; nor did anagrams and anagrams plus. Here we classified anagrams solving plus as a sequential process: a permutation of the stimulus string must be generated and the result checked against the lexicon; if no match is found, another permutation is executed, and so forth, until a match succeeds. On this analysis, the anagrams task may have required many more steps than the simple lexical-decision task, but because those steps were merely sequential, the two tasks should be executed in the same high-efficiency age mode. Thus, anagrams and lexical decision should not dissociate, but they did; similarly, anagrams plus and lexical decision plus should not dissociate, but they did.

Mayr (2000) recently reassessed the sequential–coordinative distinction, and suggested that a coordinative level of processing may be induced by the need to simultaneously maintain two or more mental task schemas. This theory is able to explain the dissociation between lexical decision and anagrams: Anagrams require the activation of, and alternation between, both a permutation schema and a lexical-decision schema. Furthermore, anagrams plus, with its additional letter-transposition schema, should not have dissociated from anagrams if the latter was already

³ The reader may note that selecting these subsamples creates a possible confound. If general ability is correlated with speed, and relative speed is stable within a birth cohort, then we are comparing a group of older adults positively selected for general ability with a group of younger adults negatively selected for general ability.
matrices are sequential visuospatial tasks. Category judgment, lexical decision, and lexical decision plus are replicated dissociation between verbal and visuospatial processing: not the deep structure of the stimulus (which may be verbal) but "material"

authors concluded that backward recall (which is a form of per-
stimuli affect backward letter recall, but not forward recall. The manipulations that alter the visuospatial characteristics of the series of five experiments on memory span, Li and Lewandowsky (Davies, 1987; Gavurin, 1967). Second, and more generally, in a second possibility is more provocative; it may be that both task the colinearity of the effects is no more than a coincidence. The produced by the two kinds of tasks are theoretically distinct, and that interpret this mixture. The first is that the efficiency modes in-
duced by the two kinds of tasks are theoretically distinct, and that the colinearity of the effects is no more than a coincidence. The second possibility is more provocative; it may be that both task sets are, in actuality, spatial.

There are data that point in the direction that anagram solving may be a spatial rather than a verbal task. First, there is correla-
tional evidence that anagram solving loads onto a spatial factor (Davies, 1987; Gavurin, 1967). Second, and more generally, in a series of five experiments on memory span, Li and Lewandowsky (1995; see also Li & Lewandowsky, 1993) demonstrated that manipulations that alter the visuospatial characteristics of the stimuli affect backward letter recall, but not forward recall. The authors concluded that backward recall (which is a form of permutation) "relies on a visual-spatial representation of the study material" (p. 837). Thus, what makes a task visuospatial may be not the deep structure of the stimulus (which may be verbal) but rather the type of operations needed to decode or extract that deep structure (which can be visuospatial). If this is so, then the two first levels found in our Brinley plot can be taken to reflect the well-replicated dissociation between verbal and visuospatial processing: Category judgment, lexical decision, and lexical decision plus are verbal–lexical tasks; anagrams, anagrams plus, and matrices are visuospatial tasks.

Although appealing in its parsimony, this interpretation of Level 2 creates a difficulty for Level 3. If both anagrams and matrices are sequential–visuospatial tasks, we cannot explain why the element-transposition manipulation carried matrices to Level 3 but not anagrams. This difficulty seems serious enough to return to the first interpretation of Level 2, and to allow that the colinearity of anagrams and matrices in the Brinley plot may be no more than a coincidental alignment of a coordinative verbal task (anagrams plus) and a sequential visuospatial task (matrices).

Waiting additional data, we conclude provisionally that there are four efficiency modes. Two modes are visible as distinct lines in our data, verbal–sequential with an efficiency level of about 1.0, and visuospatial–coordinative with an efficiency level of about 2.2; the other two are collapsed onto the same Brinley line in the present data, verbal–coordinative and visuospatial–sequential, both with an efficiency level of about 1.7. This structure can be accounted for by a three-mechanism/three-deficit theory. The theory assumes that there is a verbal process and a visuospatial process, and that these processes run in a sequential mode (which can be regarded as a kind of default that does not entail a distinct mechanism) and in a coordinative mode; each process is conditioned by a distinct age deficit.

A question left open is the nature of the coordinative process deficit, which has been attributed alternately to working-memory involvement (Mayr & Kliegl, 1993) and to attentional control (Mayr, 2000). Both mechanisms would seem to be involved in the tasks that we have identified herein as being coordinative, and our data do not allow us to decide between them. We offer the following speculations. A recent meta-analysis has shown that the age deficit in divided attention, as measured in dual task performance, is additive, and does not depend on task complexity (Verhaeghen, Steitz, Sliwinski, & Cerella, 2000). In that meta-analysis, the Brinley line for the dual-task conditions (those involving complex control operations) was parallel to the line for the single-task conditions, reflecting an intercept difference and not, as found in our data, a slope difference. This finding tends to rule out executive demand as the dimension underlying the coordinative "failure" in older adults.

This tips the seesaw toward Mayr’s (2000) earlier formulation, toward an age difference in storage capacity. We prefer to frame this hypothesis in the context of Cowan’s (1997) embedded-process model of working memory. That model makes a distinction between items activated and residing in the focus of attention (with a limit of three to five items) and items activated but not in the focus of attention. Limitations in working memory arise from (a) a capacity limit of the focus of attention and (b) a time limit of memory activation, and not from any executive mechanism. Given an age limitation in (a) or (b), we would expect an exacerbation of age differences whenever items (or information about items) could not be accommodated in the focus of attention and had to be temporarily housed in a short-term cache awaiting subsequent retrieval for further processing. Thus, the working memory deficit is ascribed to the memory requirement of the task, and not to the working or manipulative requirement.

In this model, the nature of the processing that takes place in the time frame between storage and retrieval is not critical. Hence, age differences can occur even if a task has no process-switching requirements. Likewise, a task can have switching requirements, yet not show any age difference, because all items stay in the focus of attention. This can explain why lexical decision and lexical decision plus do not dissociate: The stimulus content can all be accommodated within the focus of attention, including the transformation. The extra demands of anagram solving compared with lexical decision (including permutation generation and tracking previous permutations to avoid duplicate processing) may exceed the attentional focus, and hence trigger a dissociation. Similarly, our visual search task used a large number of distractors, far in
excess of focal storage; moreover, previously processed locations may need to be tracked; again triggering a dissociation, this time in the visual-spatial mode. Our reading of the literature, then, leads us to favor working memory demand as the critical aspect of coordinate-mode processing, rather than executive functioning, but this conclusion can be no more than provisional.

We would like, last of all, to raise, and to rule out, a more complicated account of our findings. Our model assumes that a given task engenders a single homogenous process, verbal or spatial, and that that process may be uniformly transformed by the coordinative modifier. (Of course, this simple view is framed to capture only the age effects in the processing stream; it ignores sensory-motor processes, which must be added for a complete model.) The assumption of processing homogeneity is what allows the Brinley slopes to be read directly as efficiency levels. One could, though, suppose that the processing stream spans heterogeneous subprocesses, some of them verbal, and some of them spatial; some of them sequential, and some of them coordinative. In that case, the observed Brinley slope would be a composite equal to the weighted average of the various component efficiencies.

The design of two of our tasks allowed a test of the homogeneity assumption. The test revolves around the efficiency of a particular component, that of letter transposition. In lexical-decision-plus condition, that component occurred in a verbal—sequential context. In anagrams-plus condition, the same component occurred in a verbal—coordinative context. Assuming that the component adds to the processing stream, its duration in the first case can be calculated by subtracting latencies in the lexical-decision conditions from latencies in the lexical-decision-plus conditions, and in the second case by subtracting latencies in the anagrams conditions from the anagrams-plus conditions. One can then compute the average old-young ratio for letter transposition in both tasks. The obtained age ratios were different in the two cases and were quite close to the slopes of the Brinley lines associated with the tasks; namely, 0.98 for the transposition component in the lexical tasks and 1.54 for the transposition component in the anagram tasks. Thus, the same component showed a differential deficit according to the context in which it was performed. This suggests that the whole task, with all its components, was performed at a uniform level of efficiency—a level given by the slope of the Brinley line.

In summary, we found evidence that in older adults at least three modes of efficiency in processing could be distinguished. The first mode, with an age-related slowing factor of about 1.0 (i.e., no slowing), consisted of low-complexity lexical processing. The second mode, associated with a slowing factor of about 1.7, consisted of (depending on how the tasks were interpreted) either low-complexity processing in a visuospatial mode, regardless of whether the input materials were verbal or spatial in nature or a mixture of verbal/high-complexity processing and visuospatial/low-complexity processing. The third mode, with a slowing factor of about 2.2, consisted of visuospatial processing of high complexity. This evidence goes against any common-resource theory of aging, but the exact desiderata driving the dissociation between verbal and visual tasks, and between low and high complexity, remain to be determined.

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