Universität Potsdam

Ulrich Mayr, Reinhold Kliegl

Sequential and coordinative complexity : age-based processing limitations in figural transformations

first published in:
Journal of Experimental Psychology 19 (1993) 6, S. 1297-1320,
ISSN 1939-1285, DOI 10.1037/0278-7393.19.6.1297

Postprint published at the Institutional Repository of the Potsdam University:
In: Postprints der Universität Potsdam
Humanwissenschaftliche Reihe ; 163
http://opus.kobv.de/ubp/volltexte/2010/4041/
http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-40416

Postprints der Universität Potsdam
Humanwissenschaftliche Reihe ; 163

Sequential and Coordinative Complexity: Age-Based Processing Limitations in Figural Transformations

Ulrich Mayr and Reinhold Kliegl

Dimensions of cognitive complexity in figural transformations were examined in the context of adult age differences. *Sequential complexity* was manipulated through figural transformations of single objects in a multiple-object array. *Coordinative complexity* was induced through spatial or nonspatial transformations of the entire array. Results confirmed the prediction that age-related slowing is larger in coordinative complexity than in sequential complexity conditions. The effect was stable across 8 sessions (Experiment 1), was obtained when age groups were equated in accuracy with criterion-referenced testing (Experiment 2), and was corroborated by age-differential probabilities of error types (Experiments 1 and 2). A model is proposed attributing age effects under coordinative complexity to 2 factors: (a) basic-level slowing and (b) time-consuming reiterations through the processing sequence due to age-related working memory failures.

The assumption that complex skills can be reduced to a set of simple skills or processing components has guided much cognitive research in the past (e.g., Hunt, 1978; Sternberg, 1977). More recently, the interest has shifted to a consideration of working memory functioning and its contribution to complex cognition (e.g., Baddeley, 1986; Carpenter, Just, & Shell, 1990; Kyllonen & Christal, 1990). In this article, we want to further the integration of the two lines of research by proposing and validating two dimensions of task complexity. The first dimension, called *sequential complexity*, represents individual differences in speed of simple information processing steps; the second dimension, called *coordinative complexity*, is linked to individual differences in the coordination of processing steps in working memory. We attempt to demonstrate this dissociation for an important class of individual differences, those between young and old adults. Specifically, we propose that age effects in coordinative complexity conditions cannot be reduced to, or accounted for, by age differences in sequential complexity conditions. In contrast, dominant models in cognitive aging research attribute age effects in cognition to a single, general factor (e.g., Cerella, 1990; Salthouse, 1985). Thus, the field of cognitive aging is a particularly interesting test case for any model that proposes a dissociation between two or more constraints on cognitive processing.

The research reported in this article was conducted in the context of the project "Functional Limits in Cognitive Development." Experiment 1 as part of Ulrich Mayr's dissertation work was supported by a stipend of the Max Planck Society.

We would like to thank Paul B. Baltes, Neil Charness, Sandra Hale, Jutta Heckhausen, Ralf T. Krampe, Leah Light, Ulman Lindenberger, and an anonymous reviewer for helpful comments, as well as Annette Rentz, Jörg Ricklinhart, Anne Tschida, and Laurie Galvan for their technical assistance.

Correspondence concerning this article should be addressed to either Ulrich Mayr or Reinhold Kliegl, Max Planck Institute for Human Development and Education, Lentzeallee 94, H14195 Berlin, Germany.

In two experiments and using two different variants of a figural transformation task (i.e., rule verification and rule identification) we test the prediction that age effects in time demands are more pronounced in coordinative than in sequential complexity conditions. In Experiment 1 there is an added focus on the effect of the proposed complexity dimensions across practice. In Experiment 2 we investigate the generality of the theoretical distinction across processing domains and address the problem of age-differential performance characteristics (i.e., speed vs. accuracy) by using a novel assessment technique based on criterion-referenced testing. Finally, within both experiments we analyze the probability of different types of errors to validate the notion of coordinative demands and their relation to age effects.

Complexity and General Slowing

Before we present our main argument, it is useful to consider the way task complexity is treated in current developmental research. In particular in research on aging (e.g., Cerella, 1990; Salthouse, 1985), but also in research on child development (Kail, 1991), task complexity has often been operationalized simply in terms of the amount of time required by young adults to solve a task, that is, without any reference to the specific mental operations involved. Two critical assumptions for this approach are that (a) young and old adults (or young adults and children) do not differ in the kind and sequence of mental operations (i.e., the correspondence assumption), and (b) a general characteristic of the cognitive system (such as slowing of information processing speed) is responsible for age differences. If these assumptions are valid, the amount of time needed by old adults should be monotonically related to general complexity indexed by young adults' time demands. Support for this line of reasoning comes from meta-analytic summaries of age-comparative response-time data comprising a large variety of cognitive tasks. In these studies, means of old adults were plotted against those of young adults from corresponding task conditions (Brinley, 1965). The relation between old and young adults is usually referred to as the *slowing function*. Linear functions accounted for at least 90% of the variance (e.g., Cerella, 1985, 1990); the slope of the function reflects the proportional factor with which old adults were slowed compared with young adults. Slightly better fits were provided by nonlinear functions suggesting that proportional age effects may increase somewhat with complexity (Cerella, 1990; Hale, Myerson, & Wagstaff, 1987). The highly regular patterns usually found in the old–young plots suggest that information about particular task conditions was not necessary to account for the age effects, rather general task complexity seemed to be the only critical aspect (Salthouse, 1985). The finding of a single complexity dimension has been interpreted as a general slowing of information processing speed that affects most nonlexical cognitive processing in a highly similar way (Cerella, 1985, 1990; Lima, Hale, & Myerson, 1991; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Salthouse, 1985).[1]

The present research challenges the notion of a uniform pattern of age effects in nonlexical tasks caused by one general mechanism. We argue that at least two slowing functions can be identified, representing (a) age effects in sequential complexity conditions related to a basic slowing of processing speed and (b) additional age effects in coordinative complexity conditions related to working memory deficits.

Sequential and Coordinative Complexity

Central to the distinction between sequential and coordinative complexity is that task conditions differ in their demands on coordination of information exchange between processing steps. Sequential complexity refers to any task manipulation that leads to a variation in the number of independent processing steps but does not increase the amount of information exchange between single steps. In particular, no simultaneous storage and processing demands should be involved in these tasks so that working memory load is low. An example for such a task variation is an increase in the size of the search set within a visual scanning paradigm (e.g., Madden & Nebes, 1980; Schneider & Shiffrin, 1977). A general decline in mental speed affecting each processing step in a similar way (e.g., Cerella, 1985; Salthouse, 1985) is proposed to be the main source of age differences in task variations on this dimension. The assumption of a uniform slowing of each processing step leads to the prediction of purely proportional age effects in sequential complexity conditions. In other words, absolute age effects increase with sequential complexity, but the old–young ratio remains invariant.

Coordinative complexity refers to the amount of coordinative processing required to regulate and monitor the flow of information between interrelated processing steps. Coordinative activities are constrained by the capacity to process and to retain information simultaneously in working memory and should be particularly pronounced when results from earlier processing steps are required later (e.g., Baddeley, 1986; Daneman & Carpenter, 1980; Salthouse & Mitchell, 1989). Coordinative processing demands have been proposed as a central dimension for categorizing tasks in individual differences research (e.g., Snow, Kyllonen, & Marshalek, 1984). Most psychometric tests of reasoning (e.g., Carpenter et al., 1990; Kyllonen & Christal, 1990), and also complex spatial processing (e.g., Just & Carpenter, 1985; Lohman, 1988), are assumed to put high demands on coordinative activities. Theoretically one could argue that processing speed should be a critical factor for working memory functioning: the slower the processing the higher might be the probability of losing information from intermediate storage. For one particular subsystem of working memory, the articulatory loop, such a relation was found (e.g., Baddeley, 1986). However, there seem to be only small to moderate correlations between mental speed (measured through perceptual speed measures) and the coordinative components of working memory (e.g., Kyllonen & Christal, 1990; Snow et al., 1984). Thus, at least in age-homogeneous samples, central aspects of working memory functioning and speed of processing seem to relate to different sources of interindividual variability.

The proposal that coordinative complexity constitutes an age-relevant task dimension rests on the assumption that aging is accompanied not only by a loss in speed but also by a decline in the efficiency of working memory processes. In particular, loss of critical information during task solution could incur costs in terms of additional processing, such as rechecking or reiterations through the algorithmic sequence required for task solution. Therefore, we expect proportional age effects in terms of time demands to be larger in coordinative complexity than in sequential complexity conditions. There is a bulk of evidence suggesting age-related decline in aspects of working memory functioning (for recent reviews see Light, 1991; Salthouse, 1990). Old adults exhibit lower performance than young adults on almost every task that theoretically involves working memory, such as reasoning (Welford, 1958), language production and comprehension (Kemper, 1987), mental calculation (Charness & Campbell, 1988), or mental rotation (Hertzog & Rypma, 1991). Moreover, old adults seem to lose task-related information during processing with higher probability than do young adults (e.g., Arenberg & Robertson-Tchabo, 1985; Salthouse, 1990). Also, in reasoning tasks, loss of information has been shown to lead to more redundant processing for old adults than for young adults (e.g., Arenberg, 1974). We favor the hypothesis that such age effects are produced through deficits concerning the coordination of simultaneous storage and processing (e.g., Salthouse, 1990; Welford, 1958). Note, however, that so far it has been difficult to attribute age effects in working memory tasks unambiguously to deficits in storage, processing, or the coordination of both (e.g., Gick, Craik, & Morris, 1988; Salthouse, Babcock, & Shaw, 1991; Salthouse & Mitchell, 1989).

Do age effects in working memory functions represent deficits that are independent of age-related slowing? Psy-

[1] Evidence has been reported that limits the validity of the general slowing model to nonlexical processing: There seems to be less slowing in lexical tasks (e.g., lexical decision) than in nonlexical tasks (Lima et al. 1991).

chometric research has shown that a large proportion of age effects in complex psychometric tasks (e.g., Hertzog, 1989) and in working memory tasks (e.g., Salthouse, 1991) can be explained by statistically controlling for speed of processing (using measures of perceptual speed). In most cases, however, a small but reliable amount of age-related variability remained after controlling for speed. The importance of these residual age effects and the factors producing them are unclear. What seems to be missing are experimental studies assessing time demands in task conditions that differ widely in terms of working memory demand. Such research would be necessary to evaluate the role of age differences in working memory from the perspective of recent general slowing models (e.g., Cerella, 1990; Myerson et al., 1990).

The critical prediction of the model proposed in this study is a discontinuity in the size of proportional age effects between sequential and coordinative complexity. This assumption can be tested against the general, proportional slowing model by showing that old–young ratios are larger in coordinative complexity than in sequential complexity conditions (e.g., through a significant age-by-type-of-complexity interaction using log-transformed latencies; Kliegl & Mayr, 1992). However, even when a simple proportional model can be rejected, it needs to be shown that other monotonic but nonlinear functions cannot account for the pattern of age effects in the old–young plot (Dunn & Kirsner, 1988). This is important because some variants of the general slowing model suggest that the ratio between old and young adults' time demands increases in a nonlinear way with complexity (as indicated by young adults' time demands). For example, in their information loss model, Myerson et al. (1990) assumed that old adults take more time than young adults for every processing step because loss of information needs to be compensated. As compensation is incomplete, time demands increase in a nonlinear way with the number of processing steps. A two-parameter power function describes the relation between young and old adults' time demands predicted by the information loss model. A second nonlinear model is Cerella's (1990) overhead model. Here the critical assumption is that with every processing step an "organizational overhead" increases linearly for old but not for young adults. This model leads to a one-parameter quadratic function to account for old adults' time demands as a function of young adults' time demands. Each of these two nonlinear slowing models predicts that proportional age effects for complex tasks (probably most tasks involving working memory processes) are larger than those for simple information processing tasks. Thus, to distinguish nonlinear models from a model proposing two or more condition-specific functions, it is critical to include sequential and coordinative complexity conditions that are of similar "general complexity" in terms of young adults' latencies. Only then can proportional, complexity-specific age effects be interpreted in terms of a true dissociation.

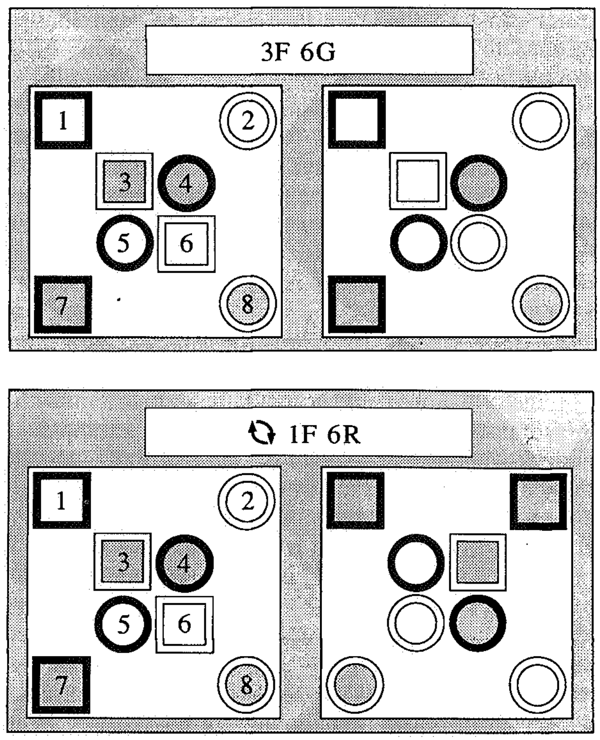
Experiment 1

To test the general hypothesis about age-differential effects of sequential versus coordinative complexity, we designed a figural transformation task that comprised conditions varying on both dimensions. In the task, participants indicated whether a transformation rule described the difference between two arrays of geometrical objects. Two types of transformations occurred: (a) transformations affecting single objects (e.g., a change of an object's form) and (b) transformations affecting the spatial arrangement of the entire array (e.g., a 90° rotation). The two arrays were always identical except for the change described by the transformation rules; in "no" items one transformation was applied incorrectly.

Sequential complexity was manipulated by varying the number of object transformations. Items with zero, one, or two transformations could occur. In the sample item with two object transformations shown in Figure 1a, participants had to check whether the color of object 3 (3 F) and the shape of object 6 (6 G) differed between the two arrays.[2] (As can be seen, both transformation rules describe the differences between arrays correctly.) It is critical to the operationalization of sequential complexity that object transformations can be checked independently. Thus, no results of earlier steps are needed for further processing except knowing which transformations had already been checked. We expect that proportional age effects are not affected by the variation of the number of object transformations.

Coordinative complexity was implemented by adding a spatial transformation to each of the three sequential complexity conditions. This actually provided two contrasts of coordinative complexity: First, spatial transformations of complex stimuli per se can be assumed to require coordinative processes (e.g., Hertzog & Rypma, 1991; Just & Carpenter, 1985). To verify a spatial transformation, objects defined by three features must be retained in working memory while their spatially transformed counterparts are identified in the right array. Loss of relevant information forces reiterations through the processing sequence (Just & Carpenter, 1985). Old adults' particular problems here would be evident in larger proportional age effects in all spatial transformation conditions compared with conditions containing object transformations only. Second, the design contained conditions in which information from spatial and object transformations had to be integrated to arrive at a solution (for a related approach, see Yee, Hunt, & Pellegrino, 1991). For example, in the item shown in Figure 1b, the indicated rotation needs to be checked first. To do this one must consider that objects that were used to verify the spatial transformation could themselves be affected by object transformations (e.g., object 1 in Figure 1b). At the same time the nature of the spatial transformation is critical for verifying object transformations. For example, to verify the postulated change of the margin of object 6 (6 R), its new position after the rotation must be considered as well. (The sample item is a no item as object 6 has changed its form instead of its margin.) The need to consider spatial and object transformations simultaneously should produce a considerable bur-

[2] An instructed participant would know the meaning of the transformation symbols (F = *Farbe*: German for *color*; G = *Gestalt*: German for *form*) in the rectangle above the two arrays.



a)

b)

Figure 1. (a) Sample item with two object transformations (sequential complexity). Object 3 must change the color of its inside (3 F) and object 6 must change the form (6 G). Both transformations are applied correctly. (b) Sample item with one spatial and two object transformations (coordinative complexity). The right array must be rotated by 90° clockwise, object 1 must change the color of its inside (1 F) and object 6 must change the color of its margin (6 R). The last transformation was applied incorrectly (i.e., there was a change of form instead of the margin's color).

den in terms of coordinative processing that affects old adults' processing more than that of young adults. Thus, we expect proportional age effects in spatial-plus-object transformation conditions to be even larger than in the condition with a single spatial transformation.

From the above account of processing in spatial-plus-object transformation conditions we can also derive more specific predictions concerning age effects in particular items: Coordinative demands should be particularly large whenever an object that is used to verify the spatial transformation is also affected by an object transformation. Participants were instructed to use objects 1 and 2 in the first line to check the spatial transformation. Therefore, a pronounced age effect in those items containing (a) a spatial transformation and (b) an object transformation of a line-1 object would validate the notion of age-related limitations due to coordinative demands.

As a further critical feature of this experiment, performance was assessed across eight practice sessions. In age-comparative research, there are strong methodological reasons for focusing on the range of functioning across levels of experience (i.e., instruction and practice) and levels of difficulty or complexity (e.g., Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989). The important question in the current context was whether complexity-specific age differences (i.e., sequential vs. coordinative) would be obtained even after eight sessions of practice. This amount of practice may not suffice to reveal ultimate limits of performance. However, it would substantiate the interpretation that complexity-specific effects are linked to definite age-related limitations in cognitive capacity rather than being a product of transient, capacity-extraneous performance factors or cohort effects.

To summarize, we proposed sequential and coordinative complexity as two general task dimensions with differential relevance for adult age effects. We expected that age differences in response latencies would be larger under coordinative than under sequential complexity conditions throughout practice. This general hypothesis was complemented by the more specific prediction that particular types of items in the spatial-plus-object transformation conditions (i.e., those with transformations of line-1 objects) would produce especially large coordinative demands.

Method

Participants

Twenty old adults (M = 74.9 years, SD = 5.7) and 20 young university students (M = 23.2 years, SD = 2.0) participated in 14 to 16 experimental sessions. There were 15 women in each age group. Young participants responded to announcements posted at the campus of the Free University Berlin. Old adults were recruited by newspaper advertisement. On a 5-point scale, participants in both age groups reported being in good health, $t(38) = .04$, $p > .5$. Old adults reported less years of formal education than did young adults, $t(38) = 4.91$, $p < .01$. On a short form of the Hamburg-Wechsler Intelligenztest für Erwachsene (HAWIE) Vocabulary subtest (after Wechsler, 1955), old adults scored marginally lower than young adults, $t(38) = 1.97$, $p = .06$. Age differences comparable to those typically reported for healthy subjects were obtained for the Digit Symbol Substitution (old: M = 45.3, SD = 9.8; young: M = 63.2, SD = 6.1), $t(38) = 6.92$, $p < .01$. All participants had normal or corrected-to-normal vision. Each participant was paid 20 deutsche mark (DM), about $13, per session.

Apparatus

Macintosh II computers were used for stimulus presentation and response collection. Stimuli were presented on a 13 in. (33.3 cm) color monitor (16-color mode) with white background. All responses were entered on the normal Macintosh keyboard using the right-arrow key for *yes* and the left-arrow key for *no* responses. Timing was in "tick" accuracy (1 tick = 16.6 ms).

General Task Characteristics

The figural transformation task required participants to verify the correspondence between symbolic transformation rules and transformations of figural objects (see Figures 1a and 1b). In each item, participants were presented with (a) one or more symbols representing figural transformation rules and (b) two square arrays, side by side, containing eight geometric objects each. The task was to check as quickly as possible whether the symbolic rules described the difference between the two arrays of objects. Participants were to press the yes key in case of complete agreement between suggested and actual transformations; otherwise, they were to press the no key. In case of more than one symbolic rule per item, the answer yes was correct only when all of the rules displayed corresponded to a figural transformation. The probability that all applications of indicated rules were correct within one item was 50%. If the response to an item was incorrect or if the available response time had expired, a short error tone sounded. Between items there was an interval of 1 s during which the frames of the two blank arrays remained on the screen.

Stimuli and Transformations

The two square arrays measured 8 cm per side, and each object measured 1.5 cm per side. Locations of the objects within the array were defined by a 4 × 4 matrix within which the eight objects were always located on the two diagonals of the matrix. The symbolic transformation rules were presented in a rectangle above the two object arrays. Objects were defined by three dimensions: form (square or circle), color of object margin (red or black), and color of the object's inside (blue or yellow). This specification yielded eight (i.e., 2^3) different objects. The left array was identical throughout the experiment. The right array differed according to (or in violation of) the transformation rules. In addition, objects in the left array were numbered from 1 to 8 to facilitate identification of objects to be transformed.

Spatial transformations. Spatial transformations applied to the stimulus array as a whole. Three types of spatial transformations could occur: The array could be rotated (i.e., each object was moved 90° clockwise), reflected on the horizontal axis, or reflected on the vertical axis. The sample item in Figure 1b contains a rotation. Spatial transformations were indicated by graphic symbols (i.e., arrows indicating the directions of the spatial transformation). In distractor items, the "faulty" transformation was either not performed at all or was replaced by one of the other two spatial transformations. Each of these three possibilities occurred with equal probability.

Object transformations. The second set of transformations referred to attribute changes of individual objects. Each object could change in form, color of the margin, and color of the inside. Object transformations were designated by the first letter of the relevant dimension (G for *Gestalt* [form], F for *Farbe* [color], R for *Rahmen* [margin]) and by an additional number between 1 and 8 indicating the object of the left array to which the transformation referred. The corresponding objects in the right array were not numbered; participants had to determine them through their locations. When no spatial transformation was present, the object was at the same location in both arrays. Otherwise, the locations of corresponding objects were specified through the type of the spatial transformation. Three distractors for suggested object transformations occurred with equal probability: The indicated object was affected by one of the other two object transformations or no transformation at all. Each single-object transformation occurred equally often across items within a particular task condition.

Identity transformation. Within the experimental design there was one condition in which neither a spatial nor an object transformation was present. Here, the identity transformation had to be checked. It was symbolized by an "=" sign and, if correct, the two arrays were similar in terms of all features. As distractors, each of the three spatial transformations was used with equal probability. This particular condition is equivalent to a physical match between the two arrays.

Task conditions. The number of spatial transformations (spatial factor) and the number of object transformations (object factor) were varied to manipulate both sequential and coordinative complexity. Experimental conditions were constructed by combining orthogonally (a) zero or one spatial transformation per item and (b) zero, one, or two object transformations per item. This design led to the following six conditions (i.e., spatial–object): 0–0, 0–1, 0–2, 1–0, 1–1, 1–2. Sequential complexity was expected to increase from zero to two object transformations in the absence of a spatial transformation; coordinative complexity was assumed to be low in these three conditions. Within sequential complexity conditions, the identity transformation (0-spatial–0-object) was to serve as the design-inherent baseline condition representing minimal processing requirements. Coordinative complexity was assumed to be high in items containing a single spatial transformation and even higher in items containing both spatial and object transformations.

Baseline response-time task. As an additional indicator of baseline response speed, the figural transformation task was modified into a simple physical match task. Instead of eight objects per array, only one object was presented in the middle of each of the two arrays. The participants had to indicate as quickly as possible whether both arrays contained the same object. Across items, objects could vary on the three object dimensions. In distractor items, objects differed from each other in one of these attributes. The probability of a distractor was 50%. This task is easier than the design-inherent baseline condition because one instead of eight objects was displayed in the array. It was used in certain analyses instead of the design-inherent baseline condition (0-spatial–0-object), which did not suffice as a baseline condition at the beginning of practice.

Procedure

Participants were trained and tested in groups of 1 to 4 people. The entire experiment required 14 to 16 days (1 to 3 days per week) with each session lasting from 45 to 90 min.

Day 1. Participants were informed about the general aspects of the study and took the Vocabulary and the Digit Symbol Substitution tests. Then they were introduced to the figural transformation task by means of an instruction booklet that explained the transformations and showed sample items. Finally, they worked through the booklet under the guidance of a tutor.

Day 2: Baseline assessment and learning-to-criterion. After solving sample items in a second instruction booklet, baseline performance was assessed in the six conditions of the figural transformation task. In the second part of this session, a tutor-guided learning-to-criterion phase was started. The goal was to ascertain that each participant was able to perform all six conditions of the figural transformation task. Starting with the easiest condition (0-spatial–0-object), blocks of 12 items were presented until, in two out of three blocks in a row, not more than one incorrect yes response and one incorrect no response occurred. This procedure was repeated for each of the other five conditions of the practice task in a roughly ascending order of complexity (spatial–object: 0–0, 0–1, 1–0, 1–1, 0–2, 1–2). Items were presented under the liberal time constraint of 60 s. After an incorrect response, the display remained on the screen and the tutor provided feedback. Also, the tutor instructed participants to work through items rule by rule and to use the two objects from the first line of the array to verify spatial transformations. When the criterion for the six complexity levels was not met during the 1st day, the instruction phase could be extended to a maximum of 2 more days. All participants met the criteria but old adults needed significantly more training blocks than young adults in all conditions except for the 0-spatial–0-object condition, all $ts(36) > 2.4$, $p < .05$. Age effects were particularly pronounced in conditions containing spatial transformations. Here old adults required up to three times more blocks of practice than young adults to reach the criterion.

Days 3, 4, 13, and 14. On these days performance in transfer tasks was assessed that are not of concern in this article. These contained highly complex transfer conditions that were included to test hypotheses about age differences in learning.

Days 5 to 12 (Practice Sessions 1 to 8). The experimental task was presented during eight practice sessions. In each session, participants answered six blocks of 12 items for each of the six experimental conditions (72 items per session and condition). Thus, across sessions, participants were exposed to 576 items per condition. Conditions were presented in the following sequence (spatial–object): 0–0, 0–1, 1–0, 1–1, 0–2, 1–2. This sequence led to more complex conditions being presented later in the session, but also avoided a complete confound between sequence of presentation and low versus high coordinative complexity. After a wrong response the items remained on the screen so that participants could check the error. At the end of each session, two blocks (24 items each) of the baseline response time task were administered.

Presentation times of items were regulated by an adaptive procedure that was implemented independently for each of the six experimental conditions. Presentation time per item was adjusted for each block according to the number of correct items in the preceding block of the same condition. If the criterion of not more than one incorrect yes item and one incorrect no item was met, presentation time was reduced in the following block. If accuracy remained below the criterion, presentation time was increased. Increases and reductions of presentation times occurred on a fixed scale in discrete steps (i.e., 10% downward and 11.1% upward, using 60 s as a starting point). In the first block of the first session, a presentation time of 60 s was used. In the following sessions, for the first block of each complexity level, the presentation time from the last corresponding condition of the preceding session was used as a starting time. Participants were informed about the adaptive assessment procedure and the criterion value. After each block, feedback about the number of correct items, mean response time for correct items, and the presentation time for the next block was provided. Participants were instructed to try to reduce the presentation time by working as quickly as possible while staying below the error criterion.[3]

Results

Analysis of results focuses on (a) effects of the experimental complexity manipulations using raw latencies, (b) complexity-specific age differences as reflected in log latencies and errors, (c) the detail-level analysis of the effects of coordinative demands, and (d) an analysis of the relationship between old adults' and young adults' response times. Two old female participants who were considerably slower than the rest of their age group (in some conditions three to four standard deviations) were taken out of the sample to allow for conservative tests of age-specific predictions. Analyses based on the complete sample led to an increase in the reported age differences with respect to errors and response latencies but without substantial changes in the results reported later. Thus, all of the following analyses were based on 20 young and 18 old adults. The criterion for statistical significance was $p < .05$.

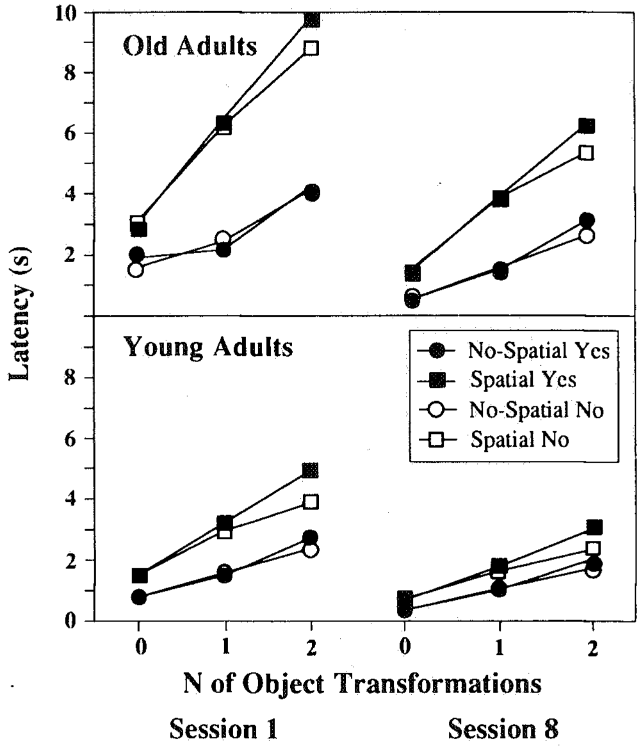


Figure 2. Old and young adults' raw response latencies as a function of the spatial and the object factors, separately for yes and no items in Sessions 1 and 8.

General Task Effects: Raw Latencies from Sessions 1 and 8

As an initial step, general information about the complexity factors will be provided at the level of raw latencies. Old and young adults' response latencies from the six experimental conditions are presented in Figure 2. Here and in all following analyses, response latencies will be based on correctly answered items only. A large variation in latency was produced by the two task factors, between 0.50 and nearly 10 s for old adults and between 0.30 and nearly 5 s for young adults. Data were analyzed using an Age (2) × Spatial (2) × Object (3) × Yes–No (2) × Session (2) analysis of variance (ANOVA) specifying the last four factors as repeated measures. Here and throughout, orthogonal contrasts were specified for the object factor. The first contrast, object (1), tested conditions with zero object transformations against conditions with one or two object transformations. The sec-

[3] Using an adaptive procedure, Baron and Matilla (1989) demonstrated that time pressure had a performance-enhancing influence on old adults, leading to a decrease in age differences. The authors concluded: "An important implication for the study of response slowing is that procedures that do no more than to instruct old subjects to respond rapidly (by far, the most common procedure) may not reveal the individual's true capability" (Baron & Matilla, 1989, p. 70). Thus, measuring response times under time limits can be regarded as a conservative method of assessing age-differential performance.

ond contrast, object (2), tested conditions with one against conditions with two object transformations.

The main effects associated with the two experimental factors were highly significant, spatial: $F(1, 36) = 159.81$, $MS_e = 4.96$; object (1): $F(1, 36) = 326.40$, $MS_e = 2.89$; object (2): $F(1, 36) = 259.36$, $MS_e = 1.30$. The slope of response latencies as a function of the number of object transformations was steeper for spatial than for no-spatial conditions (see Figure 2), Spatial × Object (1): $F(1, 36) = 102.72$, $MS_e = 1.18$; Spatial × Object (2): $F(1, 36) = 11.02$, $MS_e = 0.75$. This nonadditive effect of the two task factors indicates that time demands in the spatial-plus-object transformation conditions were larger than expected on the basis of an additive combination of constituent task components. This result is consistent with the expectation that additional processing requirements emerge when both spatial and object transformations need to be coordinated.

Except for the Spatial × Object (2) interaction, all of the aforementioned effects were qualified by a higher-order interaction with session, all $Fs(1, 36) > 16.20$. Also, the session main effect was highly significant, $F(1, 36) = 151.92$, $MS_e = 2.72$. All task effects were attenuated through practice. In a separate analysis of raw latencies at the end of practice (i.e., Session 8), however, the task effects reported earlier were still highly significant.

The yes–no factor had additional moderating effects that could be traced to one major source. In items with at least two transformations, no responses required less time than yes responses, Object (2) × Yes–No: $F(1, 36) = 147.2$, $MS_e = .09$; Object (1) × Spatial × Yes–No: $F(1, 36) > 36.5$, $MS_e = .09$. This effect was consistent with the assumption of a self-terminating mode of processing, that is, processing stopped as soon as a wrong transformation was encountered (e.g., Mulholland, Pellegrino, & Glaser, 1980; Sternberg, 1977).

Finally, with respect to age-differential effects, 16 of the 18 possible interactions with age were significant; except for the Age × Object (1) × Session and the Age × Spatial × Object (2) × Session effects, all $Fs(1, 36) > 4.20$. As can be seen in Figure 2, old adults exhibited longer response times in every condition, and age differences increased with the complexity of the experimental conditions. The significant Age × Spatial and Age × Spatial × Object interactions could be interpreted in terms of the predicted age-specific processing constraint related to coordinative complexity. However, this pattern of Age × Condition interactions could also be consistent with the assumption of a proportional complexity effect due to general slowing. To demonstrate specific age-differential effects of sequential and coordinative complexity, methods of analysis are required that permit a delineation of general (presumably slowing-based) and condition-specific age effects (Cerella, 1991; Kliegl & Mayr, 1992; Salthouse, 1992).

Age × Complexity Effects: Log Latencies and Errors

Data from Session 8 are of central interest for the evaluation of age-specific effects as these reflect age differences

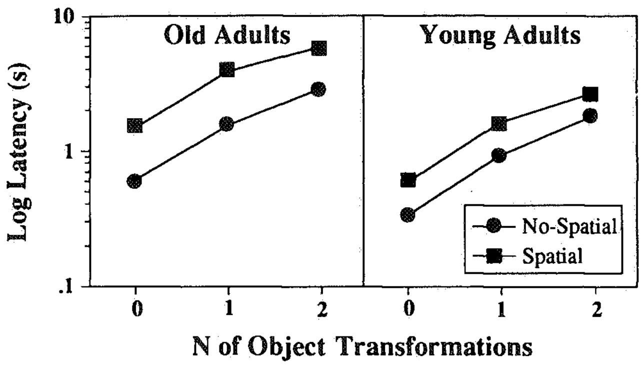


Figure 3. Old and young adults' log latencies as a function of the spatial factor and the object factor in Session 8.

that resisted extensive practice. A prime question here is whether the current data can be accounted for by a single proportional age effect often attributed to general slowing: If in old age each processing step is slowed down by a certain proportion, the ratio between age groups should remain stable across levels of complexity even though age effects increase in absolute terms. One method for taking the proportional complexity effect as a baseline for specific effects is the analysis of log latencies (Cerella, 1990). In logarithmic space, only Age × Condition effects that correspond to a change in the ratio between old and young adults will become significant. Thus, the hypothesis that age effects in coordinative complexity are larger than in sequential complexity conditions would be reflected in the Age × Spatial and the Age × Spatial × Object interactions. Consistent with predictions, the Age × Spatial interaction, $F(1, 36) = 28.46$, $MS_e = .09$, was highly significant. As can be seen in Figure 3, old adults were slowed to a larger degree in conditions containing a spatial transformation than in no-spatial conditions. Contrary to predictions, however, neither of the two contrasts for the Age × Spatial × Object interaction was significant, $F(1, 36) < 1.30$, $p > .26$. Figure 3 shows that slopes of log latencies across age groups and conditions were largely parallel. This pattern suggests (a) that age effects were particularly pronounced in all conditions containing spatial transformations and (b) that the relative costs of coordinating information from both spatial and object transformations were as high as when a single spatial transformation had to be performed—but not higher.[4]

The effects just described were qualified by an Age × Spatial × Yes–No effect, $F(1, 36) = 6.02$, $MS_e = .01$, and an Age × Spatial × Object (1) × Yes–No interaction, $F(1, 36) = 4.39$, $MS_e = .004$. Old adults took disproportionately longer to terminate their processing (i.e., to respond

[4] To examine whether this central effect was affected by sample characteristics, the following set of additional analyses was performed: (a) controlling for the vocabulary score, (b) dropping all old adults performing below the old-adults' median on the Digit Symbol Substitution, and (c) dropping all old adults above the median age of their age group. The relevant Age × Spatial interaction was highly significant in each of these control analyses.

Table 1
Mean Error Percentages and Standard Deviations as a Function of Age Group and Task Condition

	Conditions (Spatial–Object)											
	0–0		0–1		0–2		1–0		1–1		1–2	
Age	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Young	17.8	5.3	17.4	6.7	14.9	3.9	15.9	5.3	18.0	5.8	16.5	4.8
Old	18.8	5.1	16.1	4.7	14.2	3.2	17.5	7.0	26.5	5.2	24.2	5.7

Note. Underlined values denote significant age effects ($p < .05$).

no) in task conditions containing both object and spatial transformations. To determine to what degree the theoretically important Age × Spatial interaction was affected by this aspect, the above analysis was repeated using yes items only. The effect was still highly significant, $F(1, 36) = 21.8$, $MS_e = .05$.

To what degree did proportional age effects in the spatial and no-spatial conditions change with practice? To answer this question, the session factor (i.e., session 1 vs. session 8) was included in the ANOVA of log latencies. Significant interactions including age and session would indicate changes in the ratios between old and young adults' response times across sessions. The critical Age × Spatial effect was again highly significant, $F(1, 36) = 15.02$, $MS_e = .09$; however, the Age × Session interaction was not, $F(1, 36) = .01$, $MS_e = .07$. In addition, the Age × Session × Spatial interaction, $F(1, 36) = 14.2$, $MS_e = .02$, and the Age × Session × Spatial × Object (1) interaction, $F(1, 36) = 5.7$, $MS_e = .03$, were significant. Inspection of the data indicated that these effects were due to the fact that old adults needed a surprisingly large amount of time for the design-inherent baseline condition (0-spatial–0-object) in Session 1 (see Figure 2). This baseline condition apparently did not function as intended at the beginning of practice.[5] Therefore, here and in the following analyses of data from the entire practice procedure, it will be either excluded or replaced by the simple response-time measure that was administered in each practice session. When dropping the 0-spatial–0-object condition from the analysis so that the remaining two no-spatial conditions were contrasted with the three spatial conditions, the only significant age-specific effect was the Age × Spatial interaction, $F(1, 36) = 29.2$, $MS_e = .07$; the Age × Session × Spatial interaction was only marginally significant, $F(1, 36) = 3.9$, $MS_e = .01$, $p = .06$. The same pattern emerged when using the simple baseline response-time measure instead of the 0-spatial–0-object condition: The Age × Spatial interaction was the only age-relevant significant effect, $F(1, 36) = 24.9$, $MS_e = .09$, and again the Age × Session × Spatial interaction was only marginally significant, $F(1, 36) = 3.9$, $MS_e = .01$, $p = .06$. The marginal Age × Session × Spatial interactions in these two alternative analyses indicate that, if anything, ratios between old and young adults increased between Session 1 (old–young ratio = 2.10) and Session 8 (old–young ratio = 2.28) in spatial conditions, and decreased somewhat for no-spatial conditions (old–young ratio [Session 1] = 1.59; old–young ratio [Session 8] = 1.50). In summary, with the exception of the 0-spatial–0-object baseline condition, the above results suggest that the dominant age-differential effect was only marginally affected by practice.

The main focus of the experimental conditions was on response latencies. Errors had to be considered, however, to examine whether age-differential speed-accuracy tradeoffs limit interpretability of latencies. Table 1 contains errors for all conditions in Session 8.[6] In an Age (2) × Spatial (2) × Object (3) ANOVA of errors an Age × Spatial, $F(1, 36) = 20.83$, $MS_e = 7.22$, and an Age × Spatial × Object (1) interaction, $F(1, 36) = 8.14$, $MS_e = 7.09$, were obtained. According to post hoc *t* tests, old adults exhibited higher error probabilities than young adults in the two spatial-plus-object transformation conditions only (see Table 1). Thus, different from the analysis of log latencies, there were distinct age-related costs of coordinating object and spatial transformations in terms of accuracy. This finding could account for the failure of obtaining the predicted, particularly large age effects in log latencies in these conditions (i.e., larger than in the condition with a single spatial condition). Also, the overall error probabilities were rather high. This was in part due to time-out errors incurred by the criterion-referenced assessment procedure regulating presentation times.[7]

[5] One reason for old adults' particularly long response times could be that the distractors for the physical match of the entire array consisted of spatially transformed arrays. As the results reported so far indicated, old adults had particular problems with spatial transformations and thus possibly also with quick decisions between physically identical and spatially transformed arrays. As this effect was restricted to the beginning of practice, it probably reflects less a stable deficiency than it does a temporal, capacity-extraneous phenomenon.

[6] Error probabilities in Session 1 showed a very similar pattern as in Session 8 except for a small overall reduction of errors across practice, which was similar for both age groups.

[7] A further differentiation of false responses and time-out errors showed that the negative age effects in the two spatial-plus-object transformation conditions were due to false responses (1-spatial–1-object: mean error percentage of old adults = 23.2%, $M_{young} = 12.6\%$, $t[36] = 4.83$, $p < .01$; 1-spatial–2-object: $M_{old} = 19.2\%$, $M_{young} = 10.4\%$, $t[36] = 4.09$, $p < .01$) and not due to the fact that old adults suffered more from the time constraints imposed by the adaptive procedure that would be reflected by age effects in time-out errors (1-spatial–1-object: $M_{old} = 3.3\%$, $M_{young} = 5.4\%$, $t[36] = 1.77$, $p = .09$; 1-spatial–2-object: $M_{old} = 4.9\%$, $M_{young} = 6.2\%$, $t[36] = 1.01$, $p > .3$).

Joint consideration of the analysis of latencies and errors suggests a twofold age-related effect of the sequential–coordinative complexity manipulation: (a) a uniform increase of proportional age effects in response latencies for all three conditions containing spatial transformations, and (b) an additional age effect in errors for the two spatial-plus-object transformation conditions.

Detailed Analysis of Latencies and Errors

In spatial-plus-object transformation conditions, coordinative demands should be largest when objects used to verify the spatial transformation are affected by an object transformation. In these cases, changes due to the object transformation need to be considered to verify the spatial transformation. Participants were instructed to use the two objects in the first line of the array to check the spatial transformation. Therefore, if one of these objects was affected by an object transformation, age effects in latencies and errors should be larger than when objects of the other three lines were transformed. Log latencies of correct responses and errors from the four conditions with either one or two object transformations were submitted to an Age (2) × Object (2) × Spatial (2) × Line (2) ANOVA. The prediction of particularly large age effects in spatial items with line-1 object transformations would be reflected in an Age × Spatial × Line interaction. For log latencies, the critical effect was not obtained, $F(1, 36) = .19$, $MS_e = .01$. However, the interaction was highly significant for errors, $F(1, 36) = 13.10$, $MS_e = .01$, and is shown in Figure 4. In no-spatial (sequential) conditions, old and young adults exhibited a similar increase in error rate as a function of object position; in spatial conditions, the general error level of old adults was higher than that of young adults. Moreover, old adults' error probabilities were higher for transformed objects in the first line compared with transformed objects in the three other lines, $t(17) = 3.79$, $p < .01$; this was not the case for young adults, $t(19) = -1.09$, $p = .29$. Thus, the error analysis confirmed the hypothesis that transformations of line-1 objects in the coordinative complexity conditions produce particularly large age effects.

Cognitive Slowing

In models of cognitive slowing, an attempt has been made to subsume age differences across a wide range of complexity under one single aging process. Age differences are assumed to increase in a continuous but nonlinear manner with task complexity (Cerella, 1990; Myerson et al., 1990). In contrast, the present research proposes a discontinuity with respect to age differences between task conditions that are low and high in coordinative complexity. The analysis of log-transformed latencies tested condition-specific age differences against effects of proportional slowing, but not against nonlinear (i.e., disproportional) slowing. As described in the introduction, the information loss model (Myerson et al., 1990) and the overhead model (Cerella, 1990) explicitly predict that old–young ratios increase continuously as a function of complexity. A straightforward evaluation of whether the current results are produced by more than one discontinuous slowing process or by a nonlinear, continuous process can be obtained by plotting old adults' latencies as a function of young adults' latencies (Brinley, 1965). If age effects across all task conditions are the product of a continuous process, the old–young relation should be described best by a two-parameter power function (Myerson et al., 1990) or a one-parameter quadratic function (Cerella, 1990). If, however, in conditions of coordinative complexity an additional processing limitation comes into play, at least two slowing functions—linear or nonlinear—should be obtained.

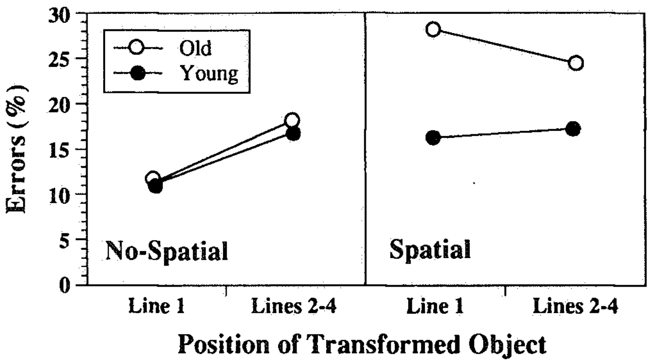


Figure 4. Old and young adults' error percentages as a function of the position of objects affected by an object transformation (i.e., line 1 vs. lines 2–4) in coordinative and sequential complexity conditions with at least one object transformation.

Figure 5 shows the results of plotting old adults' mean latencies of the six task conditions from each of the eight practice sessions (total: 48 data points) against young adults' latencies. As already shown in the ANOVA of latencies, old adults exhibited larger proportional slowing in no items from spatial conditions. Therefore, only latencies for yes items were used here to yield a conservative estimate of cognitive slowing. (The pattern of results changes only in a minor way when no items are added.) The external response time task was used instead of the 0-spatial–0-object transformation condition, which did not qualify as a design-inherent baseline condition (see footnote 5).

Obviously, data points fell along two linear functions. The one with the shallow slope represents conditions without spatial transformations. Conditions containing spatial transformations fell on the function with the steeper slope. Within each of these two domains, the 24 data points stemming from eight practice sessions and the three-level variation of the object factor fell on one function. Thus, aside from the no-spatial–spatial contrast, proportional age effects were invariant both across variations of the number of object transformations and practice sessions. This pattern is in agreement with the analysis of log-transformed latencies, where the Age × Spatial interaction was the only major effect.

The above observations were confirmed with a regression analysis in which the condition-specific hypotheses about age differences in coordinative complexity (spatial)

Table 2
Model Equations and Fit Statistics for Old–Young Functions

Type of model	Equation	R^2
Linear	$L_O = \mathbf{-.29} + \mathbf{2.11}\ L_Y$	.952
Bilinear	$L_O = .003 + \mathbf{1.57}\ L_Y + .12\ S + \mathbf{.51}\ L_Y \times S$	.990
Proportional	$L_O = \mathbf{1.99}\ L_Y$	.948
Bilinear proportional	$L_O = \mathbf{1.59}\ L_Y + \mathbf{.54}\ L_Y \times S$	.989
Power	$L_O = .85\ L_Y^{1.11}$	.954
+ S	$L_O = \mathbf{.48}\ L_Y^{\mathbf{1.16}} + \mathbf{.90}\ S$	.982
+ S + $L_Y \times S$	$L_O = \mathbf{2.40}\ L_Y^{.95} - .001\ S + \mathbf{.59}\ L_Y \times S$	.990
Quadratic	$L_O = L_Y + \mathbf{.0003}\ L_Y^2$	.904
+ S	$L_O = L_Y + \mathbf{.0002}\ L_Y^2 + \mathbf{1.18}\ S$	.967
+ S + $L_Y \times S$	$L_O = L_Y + \mathbf{.0002}\ L_Y^2 + \mathbf{1.09}\ S + .07\ L_Y \times S$	.967

Note. $N = 48$. Parameters printed in bold were significantly different from zero except for L_Y, where bold parameters indicate a significant difference from one ($p < .05$). S = spatial (0), spatial (1). (O = old, Y = young, and L = latency.)

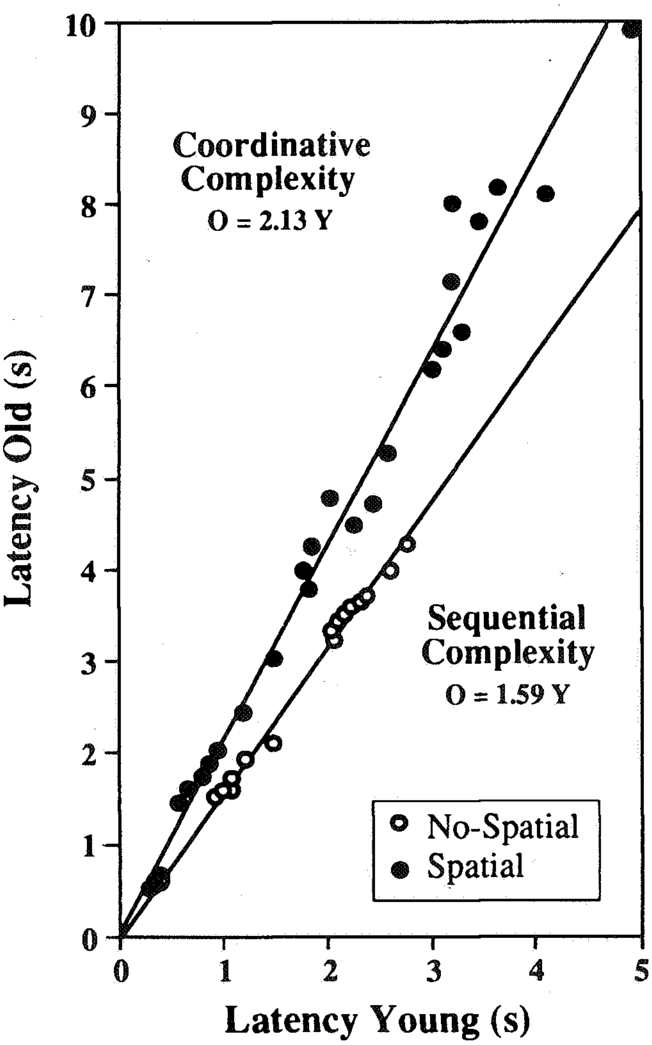


Figure 5. Old–young plot: Old adults' response latencies versus young adults' response latencies from all task conditions and all practice sessions separately for no-spatial (sequential complexity) and spatial (coordinative complexity) conditions. Data are fitted by the bilinear proportional model (see Table 2).

conditions were tested against the linear model.[8] As shown in Table 2, the bilinear model including general task complexity (indexed by young adults' latencies), the no-spatial–spatial contrast, and their interaction as predictors of old adults' latencies explained 99.0% of the variance, that is, significantly more than the linear model with young adults' latencies as the sole predictor (95.2%), or the model containing young adults' latencies plus the no-spatial–spatial main effect (98.1%; not shown in Table 2).

For the bilinear model neither the intercept, $t(44) = .3$, $p > .4$, nor the coefficient for the spatial factor were significant, $t(44) = .8$, $p > .7$. Thus, the data can be represented using a bilinear proportional model in which both the slope for the no-spatial and the slope for the spatial conditions pass through the origin of the coordinate system (see Table 2). This model was used to fit the data in Figure 5. With only two parameters it demands minimal information about task conditions, produces a substantive increment in explained variance over the proportional model, and with an R^2 of .989, leaves very little remaining variability to be explained (see Table 2). In no-spatial conditions the slowing factor was 1.59. As the spatial factor was dummy coded (no-spatial: 0, spatial: 1), the slowing factor for the spatial condition can be derived by adding the two coefficients for L_Y (1.59) and $L_Y \times S$ (.54), which is 2.13.

Does the bilinear proportional model fare better than the alternative nonlinear models? As shown in Table 2, the power function (i.e., the information loss model; Myerson et al., 1990) and the quadratic function (i.e., the overhead model; Cerella, 1990) do worse than the bilinear proportional model. As the nonlinear models and the bilinear proportional model are not nested within each other, direct comparisons are not possible. However, it can be tested whether parameters coding the complexity-specific effects (i.e., S and $L_Y \times S$) are

[8] The old–young plot technique has become common practice in cognitive aging research. It should be noted, however, that the regression analysis does not yield optimal statistical tests for such data (Fisk, Fisher, & Rogers, 1992; Kliegl & Mayr, 1992). The analyses were reported to allow comparisons with previous research (e.g., Cerella, 1990; Myerson et al., 1990).

significant when included in the equations of the nonlinear functions as additive terms. As shown in Table 2, for both the power function and the quadratic function at least one of the two task parameters was significant. Note also that the extended power function (including S and $L_Y \times S$) empirically reduced to a bilinear model as the power coefficient was not significantly different from one. Obviously, the two nonlinear models did not capture the particular characteristic of the present pattern of complexity-specific age effects. Therefore, these results validate the prediction of a dissociation between sequential and coordinative complexity represented by the bilinear proportional model.

Discussion

In this experiment we tested the hypothesis that two dimensions of complexity can be distinguished as sources of an important class of interindividual differences. The first dimension denotes manipulations of the number of processing steps that do not require coordinative processing; it was implemented through simple transformations of single geometrical objects. The second dimension refers to manipulations that not only increase the number of processing steps but also require coordinative processing in working memory. This aspect was operationalized through spatial transformations of a complex figural pattern. In line with the general expectation, adult age effects in figural transformations were shown to be a joint function of sequential and coordinative complexity. Throughout practice, old adults' performance in coordinative complexity conditions was particularly slow and in general also more error-prone than that of young adults. Analysis of log-transformed latencies and old–young functions indicated that age differences in response times could be represented by two proportional slowing factors. The first factor was found in sequential complexity conditions and had a value of about 1.6, which is similar to the amount of slowing typically reported in the literature (e.g., Cerella, 1985; Salthouse, 1985). The second slowing factor was obtained in coordinative complexity conditions (i.e., conditions including a spatial transformation), with a value of about 2.1. The general notion of age-specific limitations through coordinative demands was further substantiated by the detail-level analysis of error patterns. The coordinative burden was found to be particularly pronounced in those items in which object transformations affected objects that were used to check the spatial transformation.

Contrary to predictions there was no further increase of proportional age effects when both spatial and object transformations had to be coordinated. This implies that age-differential costs of coordination were involved in these complex conditions, but in terms of response latencies they were not larger than those observed when single spatial transformations had to be checked. The critical Age × Spatial × Object interaction, however, was obtained with respect to accuracy. On the one hand, this latter finding indicates that, in this experiment, we did not succeed completely in characterizing performance across the whole range of complexity with a single measure (i.e., response latency). On the other hand, it qualifies the failure of obtaining the critical Age × Spatial × Object interaction in terms of latencies.

Despite the clear outcome of this study with respect to the proposed distinction between complexity dimensions, there were some critical limitations. One is related to the fact that the present design contained a confound between type of processing (no-spatial vs. spatial) and complexity (sequential vs. coordinative). This confound could be problematic as spatial transformations produced the main age-specific effects. Contrary to expectations, the spatial-plus-object conditions did not lead to distinct additional processing constraints in old adults, at least not for log-transformed response latencies. Some researchers have suggested that mental transformations in the two- or three-dimensional space constitute a unique domain of analog processing governed by mechanisms differing from those underlying discrete, propositional processing (e.g., Shepard & Metzler, 1971). Moreover, neuropsychological evidence points to neurological subsystems involved in mental imagery and spatial processing (e.g., Farah, Gazzaniga, Holtzman, & Kosslyn, 1985). Thus, one could argue that spatial processing subsystems may be subject to a more pronounced age-related decline than other abilities. This would be an interesting finding in itself because, to our knowledge, there is little evidence for particularly large age effects in spatial processing. For example, in the meta-analytic research on cognitive slowing in nonlexical tasks (Hale et al., 1987), spatial tasks fell on the same old–young function as nonspatial tasks (but see the General Discussion of the present article). The dissociation between sequential and coordinative complexity, however, was proposed to capture general aspects of complex cognition not tied to particular domains of processing. Although there is a large body of research highlighting the coordinative aspects and working memory demands involved in complex spatial processing (e.g., Hertzog & Rypma, 1991; Just & Carpenter, 1985; Lohman, 1988), the ambiguity between a domain-specific and a complexity-based interpretation of the present pattern of results cannot be resolved in this experiment.

Another limitation refers to the fact that old adults not only were slower than young adults but also made substantially more errors in some of the coordinative complexity conditions. Thus, old and young adults worked on different points of the speed–accuracy curve (e.g., Wickelgren, 1977), complicating the estimation of age differences. A precise estimate would be desirable, for example, to identify the shape of the slowing function (Cerella, 1990; Myerson et al., 1990). Also, from the present data it is not clear whether old adults' higher error probability can be attributed to a performance factor (e.g., a more lenient response criterion) or a fundamental processing limitation. A second study was conducted to replicate the central outcome of Experiment 1 and to address some of the interpretational difficulties.

Experiment 2

The main goal of the second experiment was a test of the generality of the dissociation between sequential and coordinative complexity. To this end, coordinative complexity was implemented in two alternative ways: using a spatial transformation in one task condition and a nonspatial transformation in the other. Thus, the confound between processing domain and complexity dimension present in Experiment 1 was avoided here. Furthermore, an attempt was made to minimize age effects in accuracy and to map performance across a large complexity spectrum onto a single measure, namely time demands.

A rule-identification version of the figural transformation task was used in this experiment. The main reasons for changing the format were to arrive at (a) a task better suited to the particular assessment procedure used in this experiment and (b) a "purified" version that reduces the degrees of freedom for different strategies. The basic task condition required participants to compare two four-object arrays that were identical except for a transformation affecting one of the objects (see Figure 6a). Four transformations could occur (i.e., shape, size, shading of inside, or shading of margin); the correct transformation had to be indicated by pressing one of four keys. No coordination between processing components is required here, but rather a serial search of objects until the difference has been detected (which in the sample item is the inside shading). This condition represents a low sequential complexity baseline for three other conditions differing either in sequential or coordinative complexity. High sequential but low coordinative complexity was realized in a condition in which eight objects had to be checked (see Figure 6b). This task is more complex than the four-object condition in terms of the number of comparisons required. It does not, however, involve more coordinative processing.

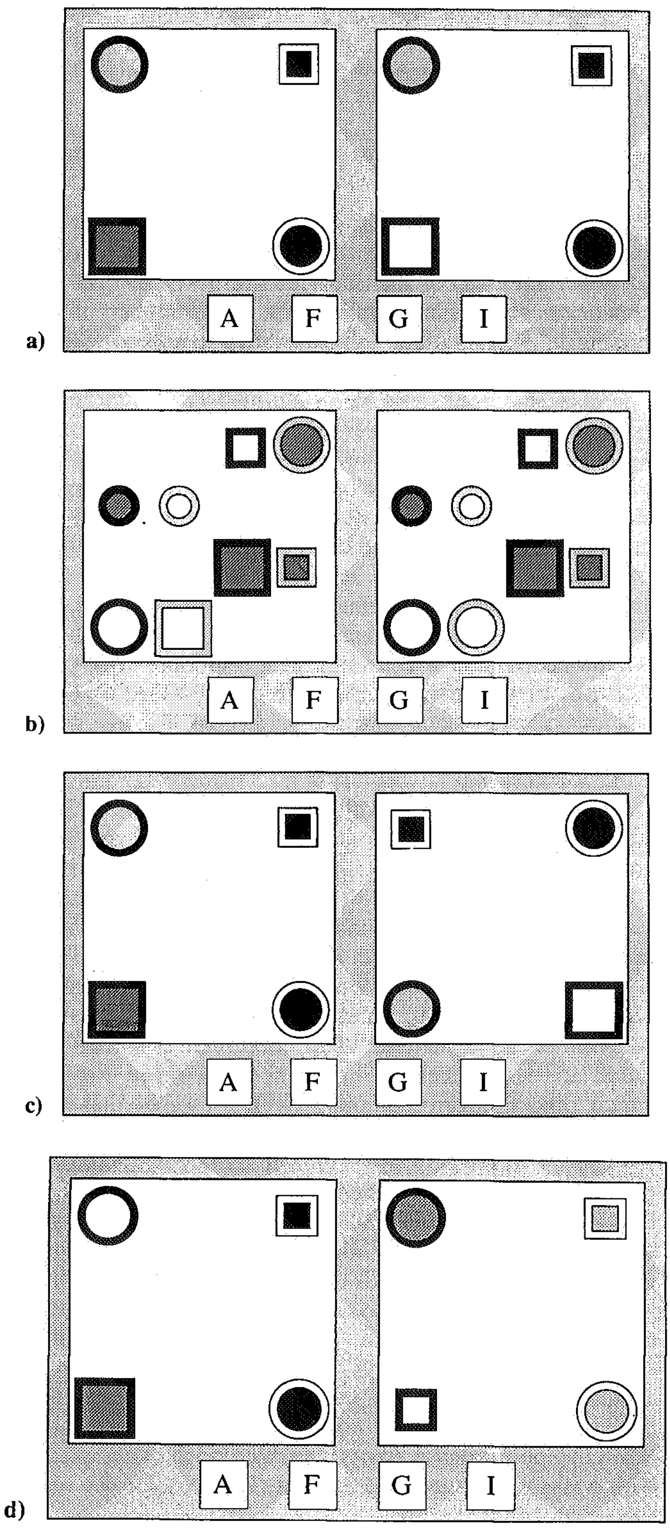
Coordinative complexity was manipulated in two ways. For the first coordinative complexity condition a spatial transformation of the entire array was added to the basic condition with four objects (see Figure 6c). To identify the one transformation affecting a single object, the spatial transformation affecting the entire array (which could either be a clockwise or a counterclockwise rotation) had to be considered.

In the second coordinative complexity condition, a global transformation of all objects within the array in one of the relevant features (shape, size, shading of inside, or shading of the margin) occurred in addition to the transformation affecting only one of the objects (see Figure 6d). The global transformation affecting all objects first had to be determined and then considered while searching for the single-object transformation. Thus, both the spatial and the global transformation added coordinative burden to the task without changing the general task format. The global transformation, however, clearly does not require spatial processing.

Figure 6 (opposite). Sample items from each of the four task conditions: (a) four-object condition (correct response is shading of inside [i.e., I]), (b) eight-object condition (correct response is form [i.e., F]), (c) spatial (correct response is shading of inside [i.e., I]), and (d) global (correct response is size [i.e., G]).

Criterion-Referenced Determination of Presentation Times

This experiment had an additional important feature. An assessment procedure was used in which presentation times required for solving the items of the four conditions were adaptively determined in a criterion-referenced way (see also



Kliegl & Lindenberger, 1993; Kliegl, Mayr, & Krampe, in press; Thompson & Kliegl, 1991). Specifically, the presentation time (not response latencies) needed to perform correctly on 6 (50%), 9 (75%), and 12 (100%) items out of blocks of 12 items, respectively, was estimated for each individual subject across multiple sessions. Note that chance rate was 25%, given that there were four possible responses. This assessment procedure has three advantages over traditional response time procedures.

First, the adaptive process regulating presentation times allows the assessment of central processing time demands without the contribution of a motoric response component. The critical dependent variable is the presentation time needed for an a priori specified accuracy criterion. Participants respond which of the four transformations affected one of the objects after an item was presented. The motoric component very often—as in this study—is not of much interest, but it is responsible for a large component in traditionally measured response latencies.

Second, the procedure avoids the problems created through differences in accuracy as a function of condition or age. Usually, with increasing complexity, accuracy decreases (see, e.g., Experiment 1) and, as a consequence, the validity of latency scores becomes questionable. With the present procedure both age groups are forced to the same accuracy levels. Thus, effects of task complexity and interindividual variance should be captured almost exclusively in the adaptively determined presentation times.

Finally, manipulation of accuracy criteria is in itself a variation of complexity or difficulty on a task-independent metric (see Myerson et al., 1990). Specifically, the 100% accuracy condition should be particularly demanding. Under coordinative complexity, old adults may exhibit considerable problems with achieving 100% accuracy and, as a consequence, may be pushed to very long presentation times.

To summarize, in this research two coordinative complexity conditions were contrasted with two sequential complexity conditions. In each condition presentation times were determined adaptively for three different accuracy criteria. The central prediction was that proportional age effects are similar for (a) the two sequential complexity conditions and (b) the two coordinative complexity conditions; however, the effects should be larger for the latter than for the former.

Method

Participants

Sixteen young ($M = 24.2$ years, $SD = 2.4$) and 16 old adults ($M = 72.0$ years, $SD = 3.7$) were recruited through a newspaper advertisement. On a 5-point scale participants in both age groups reported to be in good health, $t(30) = 1.50$, $p > .1$. Also, the two age groups did not differ significantly in years of formal education, $t(30) = .60$, $p > .5$, and on a short form of the HAWIE Vocabulary test (Wechsler, 1955), $t(30) = .94$, $p > .3$. However, old adults scored significantly below young adults on the Digit Symbol Substitution (young adults: $M = 58.8$, $SD = 7.1$; old adults: $M = 46.7$, $SD = 7.0$), $t(30) = 4.8$, $p < .01$.

Apparatus

Macintosh II computers were used for stimulus presentation and response collection. Stimuli were presented on a 13 in. (33.3 cm) monitor (black-and-white mode). All responses were entered on the extended Macintosh keyboard. Timing was in tick accuracy (1 tick = 16.6 ms).

Tasks and Stimuli

In all conditions of the figural transformation task participants were shown two square arrays (side length = 8 cm) containing four or eight objects. Objects were defined by four binary-value features: size, form (circle and square), shading of the inside (light and dark), and shading of the margin (light and dark). Besides the transformations to be described in the next paragraphs, the two arrays were identical. Object positions were defined by a 4 × 4 matrix. Within this matrix objects could appear in 12 different arrangements with either zero or two objects per line and column. All object arrangements preserved the same overall gestalt when the array was rotated by 90°, clockwise or counterclockwise. Across items, objects varied randomly in the four features with the constraint that each feature value had to be present at least once per array and that within an array, any two objects had to differ in at least one feature.

Sequential complexity: four objects. In this condition (see Figure 6a), participants had to identify a single transformation affecting one of the four objects in one of the object-defining features. Participants had to indicate the changed feature (and not the object). Across items each object position was affected equally often by each transformation. Responses were entered on four keys of the numerical key pad (4, 5, 6, and "-") labeled with the first letter of the possible transformations (A for *Aussen* [shading of the margin], F for *Form* [form], G for *Groesse* [size], I for *Innen* [shading of the inside]).

Sequential complexity: eight objects. This condition (see Figure 6b) was analogous to the four-object condition except that the arrays contained eight objects. Objects could appear in 12 different arrangements with either zero, two, or four objects per line and column.

Coordinative complexity: spatial. In this condition (see Figure 6c), the arrays contained four objects, and the right array was rotated with equal probability either 90° clockwise or counterclockwise. Again, only the transformation affecting a single object had to be identified. Solving an item, however, required the participant to detect the type of rotation and keep it in mind while searching for the change in one of the objects.

Coordinative complexity: global. In this condition (see Figure 6d), the arrays contained four objects and, again, the transformation affecting a single object had to be identified. In addition, all four objects had changed their value in one of the defining features. The global and the single-object transformation were never identical. In the example (Figure 6d), all objects changed their inside color and, in addition, one object changed its size. Thus, participants had to identify the global change and take it into consideration when searching the array for the single-object transformation.

Procedure

Participants were tested in groups of 1 to 6 people at a time. The whole experiment comprised 12 sessions. At the beginning of the first session, subjects received a short questionnaire as well as the vocabulary test and the Digit Symbol Substitution. The rest of the experiment was partitioned into four, structurally identical, three-session segments, one for each of the four experimental conditions. In the first session of each segment, participants performed two warm-up blocks of 12 items each with a self-paced response mode. They were instructed to search arrays line by line (starting in the upper left) and to use the objects in the first line to infer the spatial or the global transformation when present. Then they were exposed to 20 practice blocks of 12 items each with an adaptive criterion-referenced assessment procedure regulating presentation time per item. Within a block the same amount of presentation time was available per item. After the presentation time had elapsed, the item was covered with a random-dot mask. Only then could participants enter their response. Participants were instructed to strive for maximal accuracy. If fewer than 9 (75%) items of a block were correct, presentation time was increased for the successive block; if accuracy was above the criterion, presentation time was decreased. Increases and decreases of presentation times occurred on a scale of fixed steps (17.7% downward and 20% upward). During the 20-block practice procedure, presentation time was adjusted taking two steps at a time. Starting times in the first block were the same for both age groups but differed across task conditions (four objects: 5.2 s, eight objects: 8.9 s, spatial: 10.7 s, global: 22.2 s). The 20-block practice session served two purposes. First, the adaptive process had a chance to move into the adequate measurement region for each subject (i.e., those presentation times where the probability of reaching the criterion was close to .50). Second, participants received extensive experience with the task. In the second and third sessions within each segment the actual adaptive testing took place. For each of the two sessions, independent adaptive sequences were administered for three accuracy criteria: 9 (75%), 6 (50%), and 12 (100%) correct items per block. Each sequence comprised eight 12-item blocks. Presentation time was adjusted using 17.7% steps downward and 20% steps upward. In Session 2 of each segment, the starting time for the 75% condition was taken from the last block of the previous session. For the 50% criterion the starting time was three 17.7% steps below, and for the 100% criterion it was three 20% steps above the starting time of the 75% condition. In Session 3, the adaptive sequences from Session 2 were simply continued for each of the three criteria.

The same procedure was used for each of the four task conditions. Half of the participants in each age group started with the adaptive assessment of the four-object condition and then went on to the eight-object condition; for the other half the reverse sequence was used. For all participants the spatial condition was presented in the third segment and the global condition in the fourth.

Results

Results are presented in four parts. First, we document the process of criterion-referenced assessment. Second, complexity- and criterion-specific age differences are analyzed with log-transformed criterion-referenced presentation times based on the third session of each condition segment. Third, results of a detail-level analysis of errors are reported. Finally, presentation times are examined from the perspective of cognitive slowing using old–young functions.

Adaptive Testing

The first section focuses on the adaptive process regulating presentation times. The central question was whether age groups could be equated in terms of accuracy. Figure 7 shows presentation times for each age group, condition, and criterion across the practice and the two test sessions. Age groups began with a common initial presentation time for a criterion of 75%. Presentation times stabilized in the course of the 20 blocks of practice during Session 1. Overall, young adults needed less presentation time per item than old adults to achieve an accuracy of 9 of 12 items. Taking the average across the last eight blocks, there were no significant age differences in accuracy in any of the four conditions, all $ts(30) < 1.2$, $p > .2$.

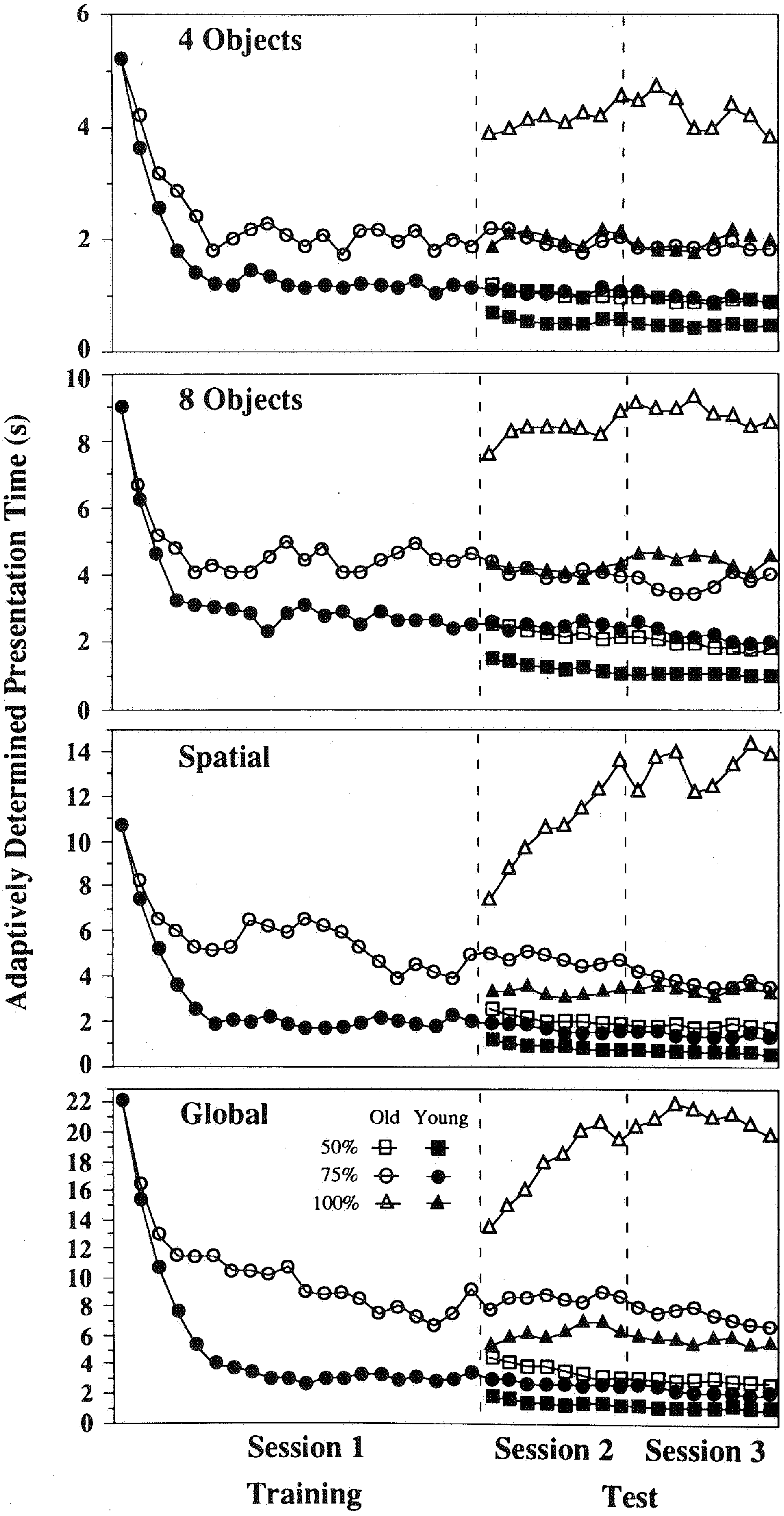
In the second session, the 50% and the 100% accuracy criteria were added. As described in the Method section, individual starting times were based on presentation times in the last block of Session 1. Although this procedure worked rather well in the standard condition and in the condition with eight objects, starting times for the spatial and the global conditions were not optimal. Specifically, old adults needed the first half of the second session until presentation times stabilized for the 100% criterion in these two conditions. Table 3 summarizes old and young adults' mean accuracies for each test session and each experimental condition. In Session 2 there were small but significant differences favoring young adults in the 50% four-object, the 100% spatial, and the 100% global conditions. In the third session, presentation times were stable for all conditions and criteria, and accuracies were similar for both age groups except for the 50% spatial condition. Therefore, to minimize the effect of age differences in accuracy, all subsequent analyses are based on this last session only. Inclusion of the data from both Sessions 2 and 3 would not change the pattern of results.

Presentation Times as a Function of Sequential and Coordinative Complexity

Figure 8 displays old and young adults' adaptively determined presentation times averaged for each individual across the eight blocks in the third session as a function of experimental condition and accuracy criterion. In addition, predictions for old adults' time demands are included that were based on a model assuming that a single proportional factor accounts for age effects across all conditions. These predictions were computed by multiplying young adults' times in each condition with the old–young ratio obtained in the most simple condition, that is, the 50% condition with four objects (old–young ratio = 1.95). As the figure shows, age effects were close to the predicted values in all sequential complexity conditions (i.e., all predicted values were within the 95% confidence interval of the observed values). However, age effects were substantially larger than predicted in all coordinative complexity conditions (i.e., predicted values were always outside the 95% confidence interval of the observed values). Also, absolute age effects increased as a function of criterion level.

Statistical tests of these observations were provided by subjecting log-transformed, adaptively assessed presentation

Figure 7 (opposite). Adaptively determined presentation times for each list, task condition, criterion level, session, and age group.



4 Objects
8 Objects
Spatial
Global
Old
Young
50%
75%
100%
Adaptively Determined Presentation Time (s)
Session 1
Training
Session 2
Session 3
Test

Table 3
Mean Accuracy Percentages and Standard Deviations for Each Task Condition and Age Group in Sessions 2 and 3

	4 Objects		8 Objects		Spatial		Global	
Criterion	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				Session 2, old				
50	<u>47.6</u>	3.7	<u>49.6</u>	<u>4.9</u>	51.5	4.6	51.7	4.0
75	71.8	4.7	70.1	4.6	72.0	4.2	70.4	5.1
100	92.9	3.1	92.4	2.3	<u>90.0</u>	4.2	<u>90.3</u>	3.5
				Session 2, young				
50	<u>50.9</u>	2.6	<u>52.6</u>	<u>2.6</u>	53.7	5.4	53.5	4.7
75	70.1	3.8	71.9	3.2	73.6	4.6	71.7	4.2
100	92.5	2.4	90.9	4.0	<u>93.4</u>	1.7	<u>93.1</u>	2.2
				Session 3, old				
50	49.1	5.1	48.1	5.5	<u>45.7</u>	4.3	47.5	4.7
75	71.2	4.1	69.0	5.0	71.7	5.4	72.5	4.7
100	94.6	2.8	94.4	2.0	93.9	1.7	93.8	2.2
				Session 3, young				
50	50.2	4.2	46.8	2.9	<u>50.9</u>	3.8	49.0	3.6
75	73.7	3.6	69.0	5.3	72.0	4.0	72.8	5.3
100	93.6	3.2	94.8	1.7	94.6	2.7	93.6	4.2

Note. Underlined values denote significant age effects ($p < .05$).

times to an Age (2) × Condition (4) × Criterion (3) ANOVA with repeated measures for the last two factors. The rationale for log-transformation was the same as in Experiment 1: it is the appropriate technique to use when the question is whether proportional age effects differ across conditions (e.g., Cerella, 1990, Kliegl & Mayr, 1992). According to the predictions concerning proportional age effects within and across complexity dimensions, three orthogonal contrasts were specified for the condition factor. The first contrast tested the two sequential against the two coordinative complexity conditions; the second contrast tested the four-object against the eight-object condition; and the third contrast tested the spatial against the global condition. The alpha level was set to $p = .05$.

Main effects for all factors and contrasts, $F(1, 28) > 131.8$, and the critical interaction between age and the sequential–coordinative contrast were highly significant, $F(1, 28) = 44.4$, $MS_e = .02$. The Age × Four Objects/Eight Objects interaction, $F(1, 28) = 1.01$, $MS_e = .01$, and the Age × Spatial/Global interaction, $F(1, 28) = .21$, $MS_e = .02$, were not significant. Thus, as predicted, proportional age effects were similar for the four-object and the eight-object conditions, they were larger for the two coordinative complexity than for the two sequential complexity conditions, and they were similar again for the spatial and the global coordinative complexity conditions.

This pattern of pronounced age effects across the two coordinative complexity conditions does not necessarily imply that they captured the same age-related variance. To address this issue, two hierarchical regression analyses were conducted. In the first step, log presentation times in the spatial and the global condition (averaged across the three accuracy criteria), respectively, were regressed on the log presentation times under sequential complexity (averaged across four and eight objects and the three accuracy criteria). This accounted for 79.3% of the variance in the spatial condition, $F(1, 30) = 115.15$, and 82.3% in the global condition, $F(1, 30) = 139.27$. In the next step, age was added as a dichotomous variable. It explained additional, highly reliable 6.2% variance for the spatial condition, $F(2, 29) = 12.6$, and 6.1% for the global condition, $F(2, 29) = 15.05$. After removing age again, the global condition was entered as a second predictor for time demands in the spatial condition, and vice versa. The global condition explained additional highly reliable 5.7% variance in the spatial condition, $F(2, 29) = 10.94$, leaving a marginally significant amount of 1.9% age-related variance, $F(3, 28) = 4.00$; the spatial condition explained highly reliable 4.9% variance in the global condition, $F(2, 29) = 10.95$, leaving a small but significant amount of 2.2% age-related variance, $F(3, 28) = 5.87$. Thus, a considerable proportion of the variance unique to age, beyond the variance shared with sequential complexity conditions, was common to the two different conditions representing coordinative complexity.

What does the variation of the accuracy criterion add to the pattern of age-specific effects? There was an interaction between age and the criterion factor, $F(2, 56) = 6.62$, $MS_e = .01$, and a triple interaction between age, the sequential–coordinative contrast, and criterion level, $F(2, 56) = 3.19$, $MS_e = .01$. To decompose these effects, two orthogonal contrasts were specified for the criterion factor. The first tested the 100% against the 75% and the 50% criteria; the second tested the 75% against the 50% criterion. Reliable age-related interactions were found for the first contrast in the spatial, $F(1, 30) = 10.33$,

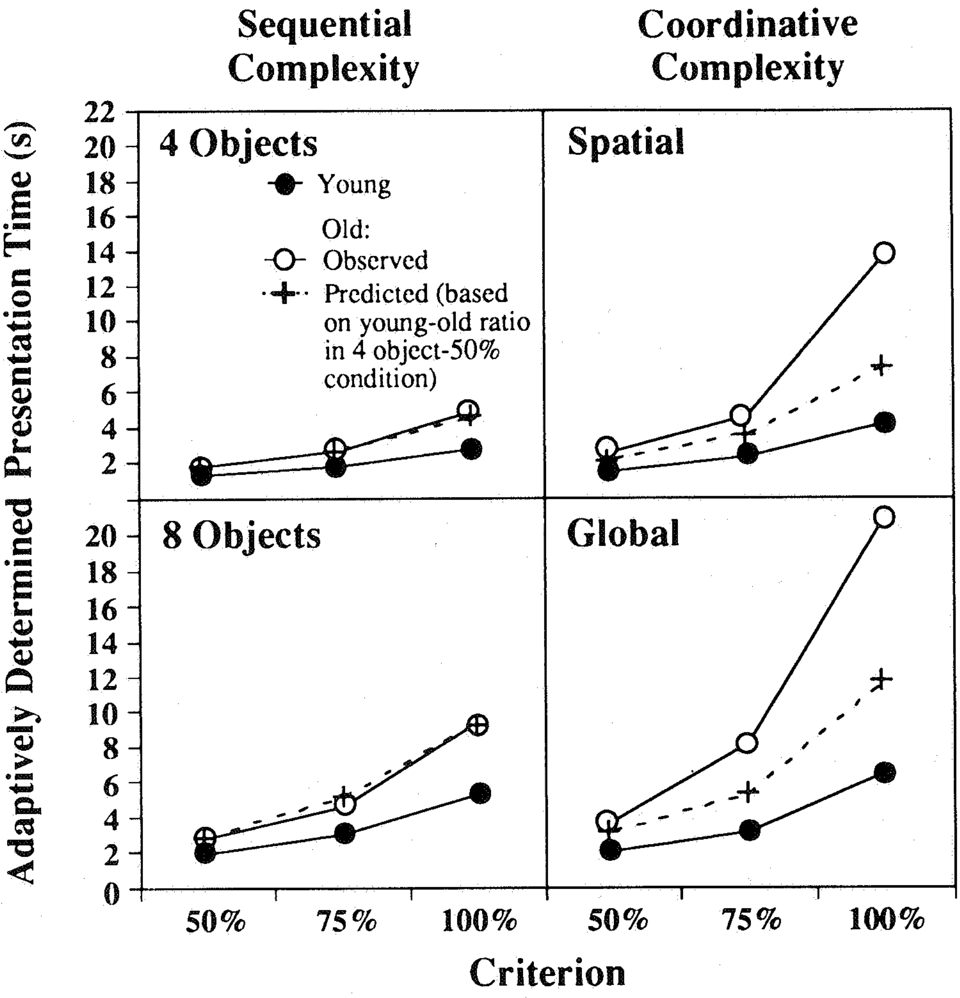


Figure 8. Adaptively determined presentation times from Session 3 as a function of task condition, criterion level, and age. Dashed lines indicate predictions of old adults' presentation times based on the old–young ratio in the four-object 50% condition.

MS_e =.01,[9] and in the global condition, $F(1, 30) = 4.15$, $MS_e = .01$. The second contrast in the global condition was marginally significant, $F(1, 30) = 3.54$, $MS_e = .01$, $p = .07$. All of these effects reflected an increase of proportional age effects for higher accuracy criteria. Thus, within each of the two coordinative complexity conditions, the higher accuracy criteria seemed to be particularly demanding for old adults. However, separate ANOVAs of log presentation times for each criterion level showed also that the general pattern of age- and complexity-specific effects could be replicated for each of the three levels of accuracy.

Detailed Analysis of Errors

Because of the adaptive procedure age groups were similar in terms of overall accuracy. Nevertheless, those errors that did occur may carry important information about age-specific processing constraints. As in Experiment 1 the central hypothesis of age-specific sensitivity to coordinative demands was submitted to a further test by analyzing age differences in specific error types. Coordinative demands were assumed to be particularly high whenever objects used to identify the spatial or the global transformation were also affected by a single-object transformation. In these cases, both changes need to be taken into account simultaneously. As participants were instructed to start their search in the first of the two lines of the array, we expected higher error probabilities for old adults than for young adults when one of the two line-1 objects was affected by the single-object transformation. In contrast, in the simple sequential complexity condition with four objects, error probabilities for both age groups should increase from line 1 to line 2.

Error probabilities from the four-object, the spatial, and the global conditions were submitted to an Age (2) × Task (3)

[9] As reported in the accuracy analysis, old adults were less accurate than young adults in the 50% spatial condition. However, the interaction between age and the first contrast in the spatial condition remained highly significant when accuracy was included as a covariate.

$\times$ Criterion (3) $\times$ Position (2) ANOVA. To keep the format comparable across conditions, the eight-object condition was not included in this analysis. The predicted Age $\times$ Task $\times$ Position interaction, $F(2, 60) = 4.86$, $MS_e = .01$, and an Age $\times$ Task $\times$ Criterion $\times$ Position interaction, $F(2, 60) = 6.74$, $MS_e = .01$, were significant. Separate Age (2) $\times$ Task (3) $\times$ Position (2) ANOVAs revealed that the critical interaction was only obtained for the 50% criterion, $F(2, 60) = 4.27$, $MS_e = .01$, not, however, for the 75% and the 100% criteria. Figure 9 displays the relevant data for the 50% criterion. Both old and young adults showed the predicted pattern of increasing error probability as a function of the position of the transformed object in the simple four-object condition. Interestingly, young adults exhibited this pattern throughout; simple comparisons revealed that error probabilities across the three tasks for line-1 object transformations did not differ statistically, all $ts(15) < 1.22$, $p > .2$. Thus, young adults' error scores were not affected by demands for coordinative processing. For old adults, however, error probabilities for line-1 object transformations in the spatial condition, $t(15) = 2.29$, $p < .05$, and in particular in the global condition, $t(15) = 3.90$, $p < .01$, were larger than in the four-object condition and also larger than the corresponding error probabilities of young adults, both $ts(30) > 3.10$, $p < .01$. In the global condition, the costs of coordination actually led to a reversal of the position effect in old adults. To summarize, for the 50% criterion condition, this analysis supports the hypothesis of large age effects due to coordinative demands. The fact that this effect was only obtained for the 50% criterion was most likely due to the strong time demands in this condition that probably precluded additional processes such as rechecking. The longer presentation times associated with 75% and 100% criteria may have allowed old adults to overcome these difficulties.

Cognitive Slowing

Can the present results be accounted for by a nonlinear slowing model? In an old–young function analysis, the relationship between old adults' criterion-referenced presentation times and those of young adults was examined. The old–young plot is displayed in Figure 10.

In line with predictions and with the results of the ANOVA of log-transformed presentation times, two linear functions emerged: a shallow one for sequential complexity conditions and a steeper one for coordinative complexity conditions. A regression model including young adults' raw presentation times, the sequential–coordinative contrast, and their interaction accounted for 99.4% of the variance. This bilinear model accounted for significantly more variance than the linear model (see Table 4). Inspection of the model coefficients revealed a very small intercept but a relatively large, though only marginally significant, negative main effect for the sequential–coordinative contrast. When eliminating the parameter representing the intercept, all coefficients in the resulting three-parameter model became significant (Table 4). This bilinear proportional function plus a sequential–coordinative main effect was used to model the data shown in Figure 10. The fact that in this model the sequential–coordinative main effect is negative implies a slight deviation from the pure proportional model for coordinative complexity conditions. In particular, data points from the low accuracy criteria were closer to the sequential complexity function than expected on the basis of a proportional model. This finding parallels the result of the ANOVA of log-transformed presentation times where the complexity-specific age effect was smaller (but still present) for lower accuracy criteria than for the 100% criterion. We return to this deviation from pure proportional slowing within tasks in the Discussion.

The two alternative nonlinear models, the power function (i.e., the information loss model; Myerson et al., 1990) and the quadratic function (i.e., the overhead model; Cerella, 1990), yielded much lower fits than the bilinear model. Analogous to the analyses for Experiment 1 we tested whether the sequential–coordinative contrast and its interaction with young adults' time demands are significant when added to the nonlinear models. For both the power function and the quadratic function at least one of the task parameters was significantly larger than zero (see Table 4). Moreover, the extended power function reduced to a bilinear model as

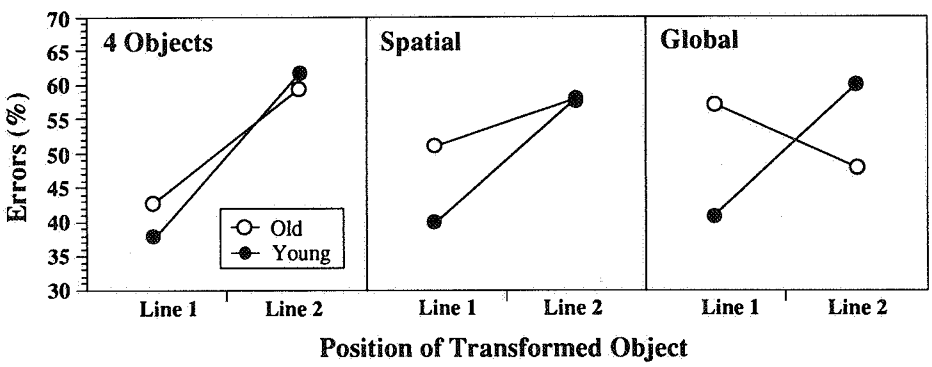


Figure 9. Old and young adults' error percentages as a function of the position of objects affected by an object transformation (i.e., line 1 vs. line 2) in the four-object, the spatial, and the global conditions with an accuracy criterion of 50%.

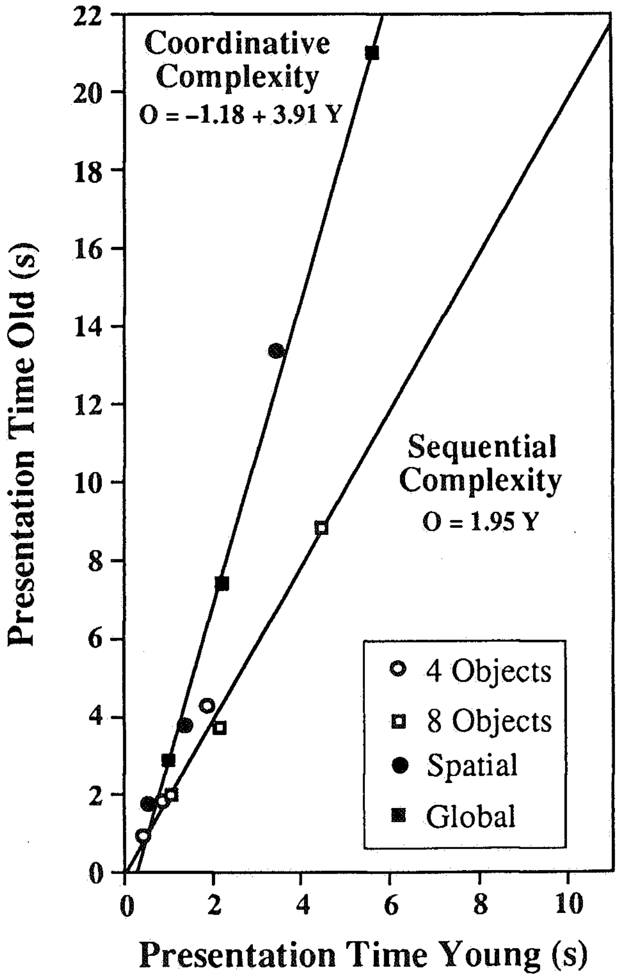


Figure 10. Old–young plot of adaptively determined presentation times including all task conditions from Session 3. Data were fitted by the bilinear proportional model plus the sequential–coordinative contrast (see Table 4).

the power coefficient was not significant. Thus, the present data, again, clearly support a dissociation with respect to age effects between sequential and coordinative complexity conditions rather than one continuous, nonlinear process.

Discussion

The results of Experiment 2 replicated the general pattern found in Experiment 1. We were able to confirm the central hypothesis of this research that age differences in figural transformations are determined by at least two complexity dimensions: sequential and coordinative complexity. The proposed distinction has proved to be fairly general (within the domain of figural transformations). Moreover, even though age groups were very similar with respect to accuracy and even though performance was assessed across a very large complexity spectrum, linear (or proportional) slowing functions across tasks were obtained for both complexity dimensions.

In sequential complexity conditions, an increase in terms of the number of self-contained processing steps (i.e., searching four to eight objects for a single-object change) led to an increase of both overall time demands and absolute age effects. However, there was no increase of proportional age effects. This finding is compatible with the assumption that age-related slowing affects speed of independent processing steps, regardless of the number of steps involved. However, with a value of 1.95, the ratio between old and young adults was somewhat larger than the ratio of 1.59 reported in the sequential complexity conditions of Experiment 1. We attribute this difference to the change in assessment procedure. The adaptive determination of presentation times leads to an estimate of central processing time demands; in contrast to traditional assessments of response times a motor response component is not involved. There is evidence that the more peripheral response component is less affected by aging than are central processes (e.g., Cerella, 1985; Salthouse & Somberg, 1982). Interestingly, traditional assessments of "pure" time demands (e.g., the search rate in a memory-scanning experiment) also revealed slowing ratios with a factor around 2 (Cerella, 1985). The age-related slowing determined in Experiment 2 may be closer to the true age effect in mental speed than what is typically obtained in standard response-time assessments (including Experiment 1).

In contrast to the sequential complexity variation, the addition of coordinative demands to the basic task did produce much larger proportional age effects. This effect was established in two different processing domains. In one condition coordinative complexity was produced through a spatial transformation of the entire array of objects. In the second condition a global change of every object in one feature served this purpose. Although the latter condition was somewhat more difficult than the former one for both young and old adults, the results in terms of proportional age effects were remarkably similar in both cases: the ratio between old and young adults was 3.43 for the spatial condition and 3.42 for the global condition (in both cases averaged across criterion levels). Also, regression analyses showed that the two conditions captured a largely similar proportion of the age-related variance not associated with the age effect in sequential complexity conditions. Thus, the sequential–coordinative complexity dissociation seems to be relatively general and not bound to spatial processing.

The old–young ratios for coordinative complexity conditions were much larger than those obtained in Experiment 1. To some degree this may be due to the fact that the response component is not contained in the adaptively determined presentation time. More important, however, the criterion-referenced procedure forced old adults to work at the same accuracy level as young adults at the expense of time demands. For the range of complexity studied, old adults' ability to comply with the 100% criterion implies a complete compensatory relation between time demands and accuracy. Although the tasks used in the two experiments are not directly comparable, this finding suggests that the high error rates in Experiment 1 may be more a reflection of a response bias than of a principle constraint on accurate performance for old adults.

Table 4
Model Equations and Fit Statistics for Old–Young Functions

Type of model	Equation	R^2
Linear	$L_O = -1.25 + \mathbf{3.37}\ L_Y$	.867
Bilinear	$L_O = -.08 + \mathbf{1.97}\ L_Y - 1.10\ S/C + \mathbf{1.94}\ L_Y \times S/C$	.994
Proportional	$L_O = \mathbf{2.99}\ L_Y$	.850
Bilinear proportional	$L_O = \mathbf{1.95}\ L_Y + \mathbf{1.65}\ L_Y \times S/C$	.986
+ S/C	$L_O = \mathbf{1.95}\ L_Y - \mathbf{1.10}\ S/C + \mathbf{1.94}\ L_Y \times S/C$	.994
Power	$L_O = 2.10\ L_Y^{1.26}$	.876
+ S/C	$L_O = 1.25\ L_Y^{1.50} + \mathbf{2.73}\ S/C$	.936
+ S/C + $L_Y \times$ S/C	$L_O = \mathbf{1.94}\ L_Y^{1.00} - \mathbf{1.17}\ S/C + \mathbf{1.96}\ L_Y \times S/C$	.994
Quadratic	$L_O = L_Y + \mathbf{.44}\ L_Y^2$	.852
+ S/C	$L_O = L_Y + \mathbf{.36}\ L_Y^2 + \mathbf{2.71}\ S/C$	.934
+ S/C + $L_Y \times$ S/C	$L_O = L_Y + \mathbf{.21}\ L_Y^2 + .25\ S/C + \mathbf{1.55}\ L_Y \times S/C$	.978

Note. $N = 12$. Parameters printed in bold were significantly different from zero except for L_Y, where bold parameters indicate a significant difference from one ($p < .05$). S/C = sequential (0), coordinative (1). (O = old, Y = young, and L = latency.)

An additional aspect of this study was the variation of accuracy criteria regulating the adaptive assessment of presentation times. With this technique performance from an exceptionally large complexity spectrum could be mapped unambiguously onto one measure (i.e., for old adults from about 1 s to about 21 s). In addition, three distinct points of the time–accuracy curve could be determined (e.g., Kliegl et al., in press). In coordinative complexity conditions a magnification of proportional age effects was obtained by increasing task difficulty through the accuracy criteria. Across the three accuracy criteria (50%, 75%, and 100%), old–young ratios were 2.8, 2.67, and 3.87 for the spatial condition and 2.59, 3.29, and 3.64 for the global condition, respectively. In the four-object condition, ratios were 1.97, 1.95, and 2.14; in the eight-object condition, 1.85, 1.71, and 1.95, respectively. This nonlinear increase of age effects within coordinative complexity conditions is incompatible with models assuming a uniform slowing of every processing step. It is also incongruent with extant nonlinear slowing models because such models would predict nonlinear increases of age effects not only within but also across task conditions. It is consistent, however, with the notion of recursions through the processing sequence due to working memory problems in old adults. Working memory failures can be assumed to be a probabilistic phenomenon. Therefore, the amount of additional processing in terms of reiterations should vary across items. As an example, assume that in the global condition the information about the type of the global transformation is lost from working memory while the single-object transformation is searched. In this case, additional time is required for rechecking the stimulus array. High-accuracy criteria (specifically 100%) are sensitive to those items within a block for which most additional processing is required to arrive at the solution. Thus, proportional age effects will be largest here. Krueger (1984; Krueger & Allen, 1987) made a similar argument with respect to the skewness of the latency distribution that was due to rechecking in the context of perceptual matching. To conclude, the increase of old–young ratios across accuracy criteria in coordinative complexity conditions is compatible with the assumption of old adults' working memory problems.

Finally, results from an analysis of error patterns corroborated the general idea that the quality of old adults' processing is particularly sensitive to coordinative demands. As in Experiment 1, old adults' error probabilities in contrast to those of young adults increased when the objects used to identify the transformation affecting the entire array were also affected by the single-object transformation. This effect was restricted, however, to the 50% criterion condition, where the least time for rechecking was available.

General Discussion

Two dimensions of complexity involving different types of cognitive processing (sequential and coordinative) and representing different sources of interindividual differences were proposed. The relevance of this distinction was demonstrated for the differences in cognitive functioning between young and old adults. Across variations in task format (rule verification vs. identification), assessment procedure (response time assessment vs. criterion-referenced testing), levels of experience (one to eight sessions), accuracy levels (50% to 100%), and processing domain (spatial vs. nonspatial), age effects in time demands were shown to be a joint function of sequential and coordinative complexity. In the remainder of this discussion, we relate this novel result to extant cognitive slowing models and to assumptions about age differences in working memory functioning.

General Slowing in Nonlexical Tasks?

On the basis of impressive empirical evidence, cognitive slowing models propose that age effects in nonlexical response-time tasks can be described as a function of a single, nonspecific complexity dimension (e.g., Cerella, 1990; Myerson et al., 1990; Salthouse, 1985). For lexical tasks, Lima et al. (1991) recently reported a second, more shallow slowing function. With respect to the nonlexical domain, some theorists make the additional claim that slowing increases in a nonlinear way with complexity (as indexed by young adults' latencies; Cerella, 1990; Myerson et al., 1990). Our results shed new light on these assertions. Two slowing factors instead of one were required to describe the present data and, in contrast to the models assuming a nonlinear slowing process, linear (proportional) slowing across task conditions was found both for sequential and coordinative complexity. Future research will need to show to what degree the bilinear model is generalizable across levels of complexity and types of tasks. It may very well be that additional functions will emerge when coordinative demands are manipulated across a larger spectrum than in the present research.

The fact that slowing in the sequential complexity conditions of Experiment 1 was of approximately the same magnitude as obtained in meta-analyses of studies on simple response time tasks (e.g., Cerella, 1985; Salthouse, 1985), agrees with the assumption of a relatively general slowing of processing speed (about 60% compared with young adults) as one important aspect of cognitive aging. Extant general slowing models cannot, however, account for the much more pronounced age effects obtained in coordinative complexity conditions. On an empirical level there are at least two possible reasons for the apparent divergence between the findings obtained in this study and previous meta-analyses. First, within the meta-analytic studies on age effects in response times, little information is available about tasks of moderate and high complexity. Across the four data sets reported by Cerella (1990), about 95% of the data points were derived from task conditions in which young adults needed less than 1.5 s, and 87% from conditions where young adults responded within less than 1.0 s. Moreover, as pointed out by Charness and Campbell (1988), data points from complex tasks were obtained from single-session experiments with minimal instruction and practice. Nonlinearity in slowing functions may be caused by age differences in strategies in unpracticed old and young adults. Thus, any inference from these data sets about slowing in more complex tasks needs to be considered with caution. Also, evidence for linear slowing across a wide range of complexity was demonstrated in a training study on mental calculation by Charness and Campbell (1988).

Second, in the one meta-analytic study that encompassed a considerable number of complex tasks (i.e., Hale et al., 1987), there was very little overlap between low-complexity reaction time tasks and mental rotation tasks in terms of latencies of young adults. Thus, it is possible that the nonlinear slowing obtained in this study actually is a mixture of two linear functions—a shallow function for low complexity conditions, and a steeper one for complex mental rotation conditions. In the present study, a similar confound was avoided by including sequential and coordinative complexity conditions that overlapped in terms of young adults' time demands. For example, young adults' response times in the condition with two object transformations of Experiment 1 were longer than those in the condition with a single spatial transformation; proportional age effects were, however, larger in the latter than in the former. Only with such constellations in the data is it possible to reject the assumption of a continuous slowing process (for related arguments, see Dunn & Kirsner, 1988; Fisk, et al., 1992).

Theoretically, the linear slowing function found for sequential complexity conditions suggests a simple proportional slowing of processing steps as one important factor in cognitive aging. One must keep in mind, however, that the assumption of some basic-level reduction of processing speed at this point is little more than a good guess about the actual mechanisms. Specifically, the correspondence assumption stating that old and young adults use the same basic-level processing algorithm with the same number of processing steps has never been tested explicitly (e.g., Cerella, 1990). The position advanced here is that the correspondence assumption may only be valid for sequential complexity conditions, not, as will be explicated later, for coordinative complexity conditions.

It is also useful to look at the present results from the perspective of psychometric studies in which measures of speed were used to explain age-related variance in complex tasks. In these studies, speed has been shown to account for large proportions of the age-related variability in complex cognition (e.g., Hertzog, 1989; Lindenberger, Mayr, & Kliegl, 1993) and working memory tasks (e.g., Salthouse, 1991). In Experiment 1 of the present study, 4.3%, and in Experiment 2, 6.2% of the residual variance in coordinative complexity performance was associated with age after controlling for speed (indexed through time demands in sequential complexity conditions). This may not seem like much. However, this age-related variability was found in addition to the 70.5% (Experiment 1) and 84.7% (Experiment 2) already accounted for by sequential complexity performance. In terms of mean age effects these specific age effects produced increases of proportional age differences between sequential and coordinative complexity from about 160% to 210% in Experiment 1, and from about 200% to 350% in Experiment 2. In future studies, it would be fruitful to combine the experimental and the psychometric approaches by including measures of working memory as predictors in order to evaluate our assertion that working memory processing is critical for coordinative-complexity age effects.

Slowing and Working Memory: A Tentative Model

What could be the reason for the particularly large age-related slowing in coordinative complexity conditions? We believe that the distinguishing characteristic of these conditions is that information processing does not occur in a sequence of self-contained steps. Rather a dynamic switching in working memory between processing, storing, and retrieving of information from an intermediate buffer is required. For example, to verify a rotation in Experiment 1 at least two objects, each defined by three features, had to be checked. Assuming that this is conducted in a single step, six features from objects in the left array had to be encoded and stored in working memory while identifying the rotated counterparts in the right array. When information was lost during this process because of working memory failure, the sequence had to be started over again.[10] For those items involving both spatial and object transformations, or the spatial and global condition from Experiment 2, the working memory demands in terms of coordinating information exchange between processing steps became even larger. In contrast, sequential complexity items in both studies could be solved in a sequence of independent steps without parallel retaining and processing of information.

There is converging evidence about the role of working memory in complex task performance. For example, spatial transformations of complex stimuli have been shown to require an elaborate sequence of working memory operations and rechecking (Just & Carpenter, 1985; see also, Lohman, 1988). In particular, longer response times of low-ability subjects could be attributed to reiterations through processes executed earlier. In a similar way old adults' low working memory capacity probably constrains their ability to process and store information in a fluent sequence. Consistent with this assumption, Hertzog and Rypma (1991) recently reported that old adults in a mental rotation task required much more postrotational processing than young adults. The authors attributed this to old adults' less reliable working memory representations. A more redundant way of processing for old adults as a consequence of information loss from working memory was also demonstrated in studies using complex problem-solving tasks (e.g., Light, Zelinski, & Moore, 1982; Offenbach, 1974; Young, 1966; see Salthouse, 1990, for an overview).

The present findings and the aforementioned evidence lead us to propose a new model describing the relation between old and young adults' time demands. Our assumptions are that (a) in coordinative complexity conditions information that is retained for later use is lost with a certain probability so that processing steps have to be repeated and (b) loss of information is experienced with larger probability by old than by young adults. Integrating such a view with the notion of a proportional and relatively general slowing, one can rewrite the well-known proportional slowing model

$$O = f*Y \qquad (1)$$

where O is the time for old adults, Y is the time for young adults, and f is the basic slowing factor, in the following way:

$$O = 1/p*f*Y \qquad (2)$$

where p is the probability of not having to repeat processing steps (relative to young adults) because of information loss from working memory.[11] The value for the basic slowing factor f would be fixed across conditions; the value for p would be 1.0 in sequential complexity conditions and considerably smaller in coordinative complexity conditions. The old–young function slopes in sequential complexity conditions can be used to represent the basic slowing value f (i.e., in Experiment 1, $f = 1.59$; in Experiment 2, $f = 1.95$; see Tables 2 and 4, bilinear proportional model). For $Y = 1$ and O equal to the slowing ratios in coordinative complexity conditions (i.e., in Experiment 1, $O = 2.13$; in Experiment 2, $O = 3.89$) values of p are .75 (Experiment 1) and .50 (Experiment 2). The difference in p values between experiments can be linked to variations in the assessment procedure. Old adults made many more errors than young adults in coordinative complexity conditions in Experiment 1, but were "forced" to trade time for errors through the adaptive assessment in Experiment 2.

An important difference between this model and previous accounts of cognitive slowing is that for particular task conditions (those involving coordinative complexity) old adults may not only be slowed in every processing step. Because of working memory failures they may also require more of the same processing steps than do young adults. Thus, for coordinative complexity conditions the correspondence assumption of age-invariant processing algorithms (Cerella, 1990) is not tenable and, consequently, extant slowing models are no longer applicable. Current slowing models, specifically the one by Myerson et al. (1990), attempt to explain age differences across large complexity variations (within the nonlexical domain) by an aging mechanism on a very low, probably neural level, affecting unconditionally every processing step. In contrast, the present model locates the age-differential effect of coordinative complexity at a higher, algorithmic level. At the same time, however, the present model shares with the other cognitive slowing models their tentative status. For example, further empirical tests must await studies in which more information is available about algorithmic paths used in complex tasks and age differences therein (e.g., Carpenter, et al., 1990; Just & Carpenter, 1985).

The model proposed here specifies a relation between working memory failures and time demands. Not much is said about the mechanisms that could produce less reliable working memory functioning in old age. One interesting possibility is that old adults suffer from lack of inhibition, causing their working memory to be flooded by irrelevant information (e.g., Hasher & Zacks, 1988). Specifically, in coordinative complexity tasks this can become very important, as working memory content needs to be updated continuously. For example, in the global task condition of Experiment 2, the information about the global transformation is highly relevant at certain points during the solution

[10] For the spatial items, a somewhat different explanation seems also conceivable: Capacity limitations could have forced old adults to check the spatial transformations in a step-by-step manner (i.e., one object at a time) whereas young adults proceeded in a more integrative way. At the algorithmic level, this is a different explanation than the one proposed here. Nevertheless, it also attributes old adults' particular problems in the spatial conditions to age-related working memory limitations. The model we suggest seems to be more parsimonious, as it also accounts for the global condition from Experiment 2, where it is difficult to argue for an age-specific contrast between an integrative and a step-by-step solution process.

[11] This equation is based on the assumption that a given algorithm consists of a number of processing steps, each slowed by a constant proportion f and subject to repetitions with a probability of $1 - p$. With the additional assumption that repetitions can fail with the same probability of $1 - p$, one obtains $O = f * Y + (1 - p) * f * Y + (1 - p) * (1 - p) * f * Y \cdots$. This series can be rewritten as $O = 1/p*f*Y$. A similar logic was used by Cerella (1990) to explain proportional slowing as a function of breakage of neural links.

process, but irrelevant for the actual response. If it is the case that old adults have more problems with inhibiting information that was relevant earlier in the task (Hartman & Hasher, 1991), they should make more confusion errors than young adults by responding with the global transformation instead of the single-object transformation. This actually was the case; 34% of young adults' errors were caused by naming the global transformation as the solution, which is close to the chance level of 33.3% (note that there were always three possible wrong responses). In contrast, old adults named significantly more often—in 47% of their errors—the global transformation, $t(30) = 2.25$, $p < .05$. This finding is intriguing given that age groups were equated in accuracy by adjusting presentation times. Thus, it is unlikely that old adults named the global transformation more often than did young adults because termination of the presentation time disrupted the processing sequence at different stages for old and young adults. This observation is post hoc and alternative accounts are conceivable. The result is consistent, however, with the assumption of specific age-related working memory problems when currently relevant information has to compete with information that was relevant during earlier stages of the solution process.

In conclusion, the present research demonstrated that in complex cognition two dimensions, sequential and coordinative complexity, can be dissociated for the case of developmental differences between young and old adults. This research suggests that cognitive aging goes along with a decline in processing speed and coordination efficiency. In future research a similar dissociation may be shown to hold true for child development and individual differences in general. Finally, the separation of processing speed and coordinative activities may provide important constraints on models of working memory.

References

Arenberg, D. (1974). A longitudinal study of problem solving in adults. *Journal of Gerontology, 29,* 650–658.

Arenberg, D., & Robertson-Tchabo, E. A. (1985). Adult age differences in memory and linguistic integration revisited. *Experimental Aging Research, 11,* 187–191.

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Clarendon Press.

Baltes, P. B., & Kliegl, R. (1992). Negative age differences in cognitive plasticity of a memory skill during adulthood: Further testing-the-limits. *Developmental Psychology, 28,* 1121–1125.

Baron, A., & Matilla, W. R. (1989). Response slowing of older adults: Effects of time limit contingencies on single and dual task performances. *Psychology and Aging, 4,* 66–72.

Brinley, J. F. (1965). Cognitive sets, speed and accuracy of performance in the elderly. In A. T. Welford & J. E. Birren (Eds.), *Behavior, aging, and the nervous system* (pp. 114–149). Springfield, IL: Charles C Thomas.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of processing in the Raven Progressive Matrices Test. *Psychological Review, 97,* 404–431.

Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin, 98,* 67–83.

Cerella, J. (1990). Aging and information processing rates in the elderly. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (3rd ed., pp. 201–221). New York: Academic Press.

Cerella, J. (1991). Age effects may be global, not local: Comment on Fisk & Rogers (1991). *Journal of Experimental Psychology: General, 120,* 215–223.

Charness, N., & Campbell, J. I. D. (1988). Acquiring skill at mental calculation in adulthood: A task decomposition. *Journal of Experimental Psychology: General, 117,* 115–124.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–566.

Dunn, J. C., & Kirsner, K. (1988). Discovering functionally independent mental processes: The principle of reversed association. *Psychological Review, 95,* 91–101.

Farah, M. J., Gazzaniga, M. S., Holtzman, J. D., & Kosslyn, S. M. (1985). A left hemisphere basis for visual mental imagery? *Neuropsychologia, 23,* 115–118.

Fisk, A. D., Fisher, D. L., & Rogers, W. A. (1992). General slowing alone cannot explain age-related search effects: Reply to Cerella (1991). *Journal of Experimental Psychology: General, 121,* 73–78.

Gick, M. L., Craik, F. I. M., & Morris, R. G. (1988). Task complexity and age differences in working memory. *Memory & Cognition, 16,* 353–361.

Hale, S., Myerson, J., & Wagstaff, D. (1987). General slowing of nonverbal information processing. *Journal of Gerontology, 42,* 131–136.

Hartman, M., & Hasher, L. (1991). Aging and suppression: Memory for previously relevant information. *Psychology and Aging, 6,* 587–594.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). New York: Academic Press.

Hertzog, C. (1989). Influences of cognitive slowing on age differences in intelligence. *Developmental Psychology, 25,* 636–651.

Hertzog, C., & Rypma, B. (1991). Age differences in components of mental-rotation task performance. *Bulletin of the Psychonomic Society, 29,* 209–212.

Hunt, E. (1978). Mechanics of verbal ability. *Psychological Review, 85,* 109–130.

Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review, 92,* 137–172.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109,* 490–501.

Kemper, S. (1987). Life-span changes in syntactic complexity. *Journal of Gerontology, 42,* 323–328.

Kliegl, R., & Lindenberger, U. (1993). Modeling intrusions and correct recall in episodic memory: Adult age differences in encoding of list context. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 617–637.

Kliegl, R., & Mayr, U. (1992). Commentary. *Human Development, 35,* 343–349.

Kliegl, R., Mayr, U., & Krampe, R. T. (in press). Time-accuracy functions for determining process and person differences: An application to cognitive aging. *Cognitive Psychology.*

Kliegl, R., Smith, J., & Baltes, P. B. (1989). Testing-the-limits and the study of adult age differences in cognitive plasticity of a mnemonic skill. *Developmental Psychology, 25,* 247–256.

Krueger, L. E. (1984). A theory of perceptual matching. *Psychological Review, 85,* 278–304.

Krueger, L. E., & Allen, P. A. (1987). Same-different judgements of foveal and parafoveal letter pairs by older adults. *Perception & Psychophysics, 41,* 329–334.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity?! *Intelligence, 14,* 389–433.

Light, L. L. (1991). Memory and aging: Four hypotheses in search of data. *Annual Review of Psychology, 42,* 333–376.

Light, L. L., Zelinski, E. M., & Moore, M. M. (1982). Adult age differences in reasoning from new information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 435–447.

Lima, S. D., Hale, S., & Myerson, J. (1991). How general is general slowing? Evidence from the lexical domain. *Psychology and Aging, 6,* 416–425.

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8,* 207–220.

Lohman, D. F. (1988). Spatial abilities as traits, processes, and knowledge. In R. J. Sternberg (Ed.). *Advances in the psychology of human intelligence* (Vol. 4, pp. 181–248). Hillsdale, NJ: Erlbaum.

Madden, D. J., & Nebes, R. D. (1980). Aging and the development of automaticity in visual search. *Developmental Psychology, 16,* 377–384.

Mulholland, T. M., Pellegrino, J. W., & Glaser, R. (1980). Components of geometric analogy solution. *Cognitive Psychology, 12,* 518–528.

Myerson, J., Hale, S., Wagstaff, D., Poon, L. W., & Smith, G. A. (1990). The information loss model: A mathematical theory of age-related cognitive slowing. *Psychological Review, 97,* 475–487.

Offenbach, S. I. (1974). A developmental study of hypothesis testing and cue selection strategies. *Developmental Psychology, 10,* 484–490.

Salthouse, T. A. (1985). *A theory of cognitive aging.* Amsterdam, Netherlands: North-Holland.

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review, 10,* 101–124.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science, 2,* 179–183.

Salthouse, T. A. (1992). Shifting levels of analysis in the investigation of cognitive aging. *Human Development, 35,* 321–342.

Salthouse, T. A., Babcock, R. L., & Shaw, R. J. (1991). Effects of adult age on structural and operational capacities in working memory. *Psychology and Aging, 6,* 118–127.

Salthouse, T. A., & Mitchell, D. R. D. (1989). Structural and operational capacities in integrative spatial ability. *Psychology and Aging, 4,* 18–25.

Salthouse, T. A., & Somberg, B. C. (1982). Skilled performance: Effects of adult age and experience on elementary processes. *Journal of Experimental Psychology: General, 111,* 176–207.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: 1. Detection, search, and attention. *Psychological Review, 84,* 1–66.

Shepard, R. M., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171,* 701–703.

Snow, R. E., Kyllonen, P. C., & Marshalek, B. (1984). The topography of ability and learning correlations. In R. J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 2, pp. 47–103). Hillsdale, NJ: Erlbaum.

Sternberg, R. J. (1977). Component processes in analogical reasoning. *Psychological Review, 84,* 353–378.

Thompson, L. A., & Kliegl, R. (1991). Adult age-differential effects of plausibility on memory: The role of time constraints during encoding. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 542–555.

Wechsler, D. (1955). *Hamburg Wechsler Intelligenztest für Erwachsene (HAWIE).* Bern, Switzerland: Huber.

Welford, A. T. (1958). *Ageing and human skill.* London: Oxford University Press.

Wickelgren, W. A. (1977). Speed–accuracy tradeoff and information processing dynamics. *Acta Psychologica, 41,* 67–85.

Yee, P. L., Hunt, E., & Pellegrino, J. W. (1991). Coordinating cognitive information: Task effects and individual differences in integrating information from several sources. *Cognitive Psychology, 23,* 615–680.

Young, M. L. (1966). Problem-solving performance in two age groups. *Journal of Gerontology, 21,* 505–509.