

Ulrich Mayr

# **Age-based performance limitations in figural transformations**

The effect of task complexity  
and practice



Max-Planck-Institut  
für Bildungsforschung

Ulrich Mayr, geboren 1962 in Ingolstadt, studierte Psychologie an der Universität Konstanz und an der Freien Universität Berlin. 1988 bis 1991 Promotionsstipendiat am Max-Planck-Institut für Bildungsforschung, Berlin, von 1991 bis 1993 wissenschaftlicher Mitarbeiter am Institut, 1993 Auszeichnung mit der Otto-Hahn-Medaille der Max-Planck-Gesellschaft. Seit Oktober 1993 ist Mayr mit einem Auslandsstipendium der MPG an der University of Oregon, USA, tätig.

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AGE-BASED PERFORMANCE LIMITATIONS  
IN FIGURAL TRANSFORMATIONS:  
THE EFFECT OF TASK COMPLEXITY AND PRACTICE

ULRICH MAYR

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## Abstract

Effects of two types of task complexity on adult age differences in figural transformations were investigated in an intervention study. Task conditions varied in two dimensions of complexity: (a) the number of independent, simple transformations affecting single geometrical objects (sequential complexity) and (b) the amount of coordinative activities operationalized through a complex spatial transformation and the combination of both spatial and object transformations (coordinative complexity). Old adults ( $N = 18$ ; mean age: 74.4) and young adults ( $N = 20$ ; mean age: 23.2) were exposed to extensive instruction, training, and eight sessions of practice. Main dependent variable was response latency. Before and after practice, accuracy of performance was also assessed in highly complex testing-the-limits conditions.

Age differences in the sequential complexity conditions were predicted to be determined by a general, age-related reduction in processing speed. In coordinative complexity conditions, however, processing limitations beyond general slowing were expected to affect both the performance level and the learning rate of old adults. In addition, the highly complex testing-the-limits situations were assumed to constitute boundary conditions of old adults' cognitive plasticity.

Consistent with predictions, in all coordinative complexity conditions containing a spatial transformation, relative age effects in response latencies were twice as large as in sequential complexity conditions. However, no additional age-related effects were observed in conditions including both spatial and object-related transformations. Counter to predictions, learning rates were highly similar for both age groups in all task conditions. As expected, performance of old but not of young adults was only little above chance level in testing-the-limits conditions both before and after practice. This breakdown of old adults' performance could be attributed to problems with coordinating multiple, interrelated processing steps. Results were in line with the theoretical distinction between sequential complexity and coordinative complexity. Alternative interpretations, in particular that of an age-related deficit in terms of spatial

processing rather than a complexity-specific deficit, are discussed. Also, a tentative model is proposed which can account for the present data, and which integrates both general, age-related slowing and aspects of working memory functioning.

## Zusammenfassung

Sind die Bedingungen für kognitives Altern im Bereich der fluiden Intelligenz in einem einzelnen, unspezifischen Prozeß zu suchen, oder lassen sich verschiedene Mechanismen unterscheiden? Dies ist die zentrale Frage der vorliegenden Studie. Die Tatsache, daß die intellektuelle Leistungsfähigkeit in den fluiden oder „mechanischen“ Aspekten der Intelligenz abnimmt, ist hinreichend dokumentiert; welche Faktoren für diesen Abbau verantwortlich sind, ist jedoch weitgehend ungeklärt. In dieser Studie wird der Einfluß verschiedener Aspekte der Aufgabenkomplexität auf Altersunterschiede in einer figuralen Transformationsaufgabe untersucht. Die generelle Hypothese ist, daß zwischen *zwei Dimensionen* der Aufgabenkomplexität differenziert werden kann, die mit jeweils unterschiedlichen, altersabhängigen Mechanismen im Zusammenhang stehen. Wird die Anzahl einfacher, unabhängiger Prozeßschritte variiert (sequentielle Komplexität), dann sind Altersunterschiede von einer *relativ unspezifischen Verlangsamung mentaler Basisoperationen* determiniert. Wenn eine Aufgabe jedoch das gleichzeitige Verarbeiten und Zwischenspeichern von Information (koordinative Komplexität) erfordert, werden zusätzliche altersabhängige Verarbeitungsbegrenzungen angenommen: Alte Personen sollten besondere Schwierigkeiten mit der *Koordination kognitiver Prozesse* im Arbeitsgedächtnis haben. Es wird erwartet, daß diese beiden Komplexitätsdimensionen (sequentielle und koordinative Komplexität) Unterschiede zwischen jungen und alten Personen an den Plastizitätsgrenzen (nach intensivem Üben) und in der Lernrate moderieren. Demnach sind wichtige Merkmale des hier gewählten Untersuchungszugangs eine differenzierte Betrachtung der *Aufgabenkomplexität* sowie die Betonung der kognitiven *Plastizität*.

Das Interesse am Konstrukt Aufgabenkomplexität in der gegenwärtigen kognitiven Altersforschung liegt in der Bedeutung des sogenannten „Komplexitätseffekts“ begründet (Birren & Renner, 1977; Cerella, Poon, & Williams, 1980; Kay, 1959; Myerson et al., 1990; Salthouse, 1985). Der Komplexitätseffekt bezeichnet das vielfach dokumentierte Phänomen, daß Leistungsunterschiede zwischen Altersgruppen mit der Aufgaben-

komplexität kontinuierlich zunehmen. Viele kognitive Altersforscher interpretieren diesen Effekt im Sinne einer altersabhängigen Reduktion kognitiver Ressourcen. Ressourcen werden dabei als mentale Entitäten mit beschränkter Kapazität verstanden, die Geschwindigkeit und Qualität von Performanz determinieren und in einer komplementären Beziehung zur Aufgabenkomplexität stehen (z. B. Navon & Gopher, 1974; Norman & Bobrow, 1975; Salthouse, 1988). Je komplexer also eine kognitive Anforderung ist, desto mehr Ressourcen werden benötigt. Der Reiz der Ressourcenkonzeption liegt in dem „Versprechen“, Altersunterschiede über Aufgabenbereiche hinweg auf sparsame Weise zu erklären, das heißt mit einigen wenigen „Grundparametern“ des kognitiven Systems.

Innerhalb der kognitiven Altersforschung (und darüber hinaus) beschäftigt Ressourcentheoretiker seit langem die Frage, welche und wie viele Dimensionen der Komplexität zu unterscheiden sind, um Performanzunterschiede in Abhängigkeit von Altersgruppen (aber auch zwischen Bedingungen oder Personen gleichen Alters) zu erklären (z. B. Cerella, 1990; Detterman, 1986; Navon, 1984; Salthouse, 1985). Erkenntnisse über die Dimensionalität von Komplexität in bezug auf Altersunterschiede sollten daher über das System altersabhängiger kognitiver Ressourcen Aufschluß geben.

Wie in der Literaturübersicht der vorliegenden Arbeit dargestellt wird, geht eines der gegenwärtig vorherrschenden Modelle in der Altersforschung von der Geschwindigkeit mentaler Operationen als der zentralen altersabhängigen, kognitiven Ressource aus (Birren & Renner, 1965; Cerella, 1990; Myerson et al., 1990; Salthouse, 1985). Die Prozeßgeschwindigkeit wird als ein genereller Parameter kognitiver Systeme angesehen, der Altersunterschiede unabhängig von den beteiligten, spezifischen Prozessen determiniert. Mit anderen Worten: Das kognitive System älterer Menschen funktioniert exakt so wie das jüngerer Menschen, nur um eine gewisse Rate verlangsamt. Tatsächlich zeigen Ergebnisse von Metaanalysen, die eine große Anzahl von Studien mit altersvergleichenenden, verschiedenartigen Reaktionszeitexperimenten integrieren, daß die Altersunterschiede in den Latenzzeiten unabhängig vom Aufgabentyp beinahe vollständig aus der Latenzzeit junger Erwachsener vorhergesagt werden können (Cerella, 1985, 1990; Hale, Myerson, & Wagstaff, 1987). Bei diesen Metaanalysen wird mit sogenannten Alt-Jung-Funktionen gearbeitet. Dabei werden Reaktionszeiten alter Erwachsener aus unterschiedlichsten Aufgabenbedingungen als Funktion der Reaktionszeiten junger Erwachsener in entsprechenden Bedingungen dargestellt. Wenn, wie es die genannten Metaanalysen zeigen, die Vorhersagekraft der Reaktionszeiten älterer durch die der jüngeren Erwachsenen sehr hoch ist,

dann kann dies als Indiz für eine relativ unspezifische Verlangsamung mentaler Prozesse gewertet werden. Dieses Modell einer generellen Verlangsamung impliziert also, daß Aufgabenkomplexität ein generelles, unidimensionales Konstrukt darstellt, meßbar über die Reaktionszeit junger Erwachsener.

In der vorliegenden Arbeit soll die Gegenthese aufgestellt werden, daß mindestens zwei Dimensionen der Aufgabenkomplexität unterschieden werden können. Unter *sequentieller Komplexität* soll eine Variation in der Anzahl unabhängiger Aufgabenschritte verstanden werden, die der Reihe nach abgearbeitet werden können, ohne daß zusätzlicher Aufwand für die Koordination der einzelnen Schritte entsteht (Logan, 1978; Sternberg, 1969). In der Bearbeitungszeit für die Gesamtaufgabe sollte sich daher im wesentlichen die Bearbeitungszeit für die einzelnen Basisprozesse widerspiegeln. Es wird die These aufgestellt, daß diese Basisprozesse von der generellen Verarbeitungsgeschwindigkeit determiniert sind. Daher sollten Altersunterschiede in sequentiellen Aufgaben eine Funktion einer altersabhängigen, relativ unspezifischen Verlangsamung sein.

Als zweite Komplexitätsdimension wird die *Koordinationskomplexität* postuliert. Aufgaben, die in diesem Sinne komplex sind, erfordern zum Beispiel parallele Verarbeitung und Zwischenspeicherung von Information. Derartige Aktivitäten sind nicht nur durch die Prozeßgeschwindigkeit determiniert, sondern außerdem durch die Arbeitsspeicherkapazität (Baddeley & Hitch, 1974; Kyllonen & Christal, 1990; Mulholland, Pellegrino, & Glaser, 1980; Snow, Kyllonen, & Marshalek, 1984; Welford, 1958). Arbeitsgedächtniskapazität gilt neben der Verarbeitungsgeschwindigkeit als weitere, möglicherweise altersrelevante Ressource (Charness & Campbell, 1988; Light, 1991; Salthouse, 1990; Welford, 1958). So gibt es vielfache Hinweise darauf, daß ältere Personen im Vergleich zu jüngeren in Arbeitsgedächtnisaufgaben schlechter abschneiden (Hasher & Zacks, 1989; Light, 1991), und daß sie beim Lösen komplexerer Aufgaben relevante Information verlieren (einen umfassenden Überblick gibt Salthouse, 1990). Die Auswertung der relevanten Literatur zu allgemeinen interindividuellen Unterschieden ergibt ferner, daß in komplexeren Aufgaben die Verarbeitungsgeschwindigkeit eine eher unwesentliche Rolle spielt (z.B. Keating & MacLean, 1987). Vielmehr scheint hier die individuelle Arbeitsspeicherkapazität eine zentrale Determinante zu sein (Kyllonen & Christal, 1990). Schließlich erlauben sowohl theoretische Modelle als auch empirische Befunde den Schluß, daß die Arbeitsspeicherkapazität von zentraler Bedeutung für die übungsabhängige Lerngeschwindigkeit in komplexen Aufgaben ist (Anderson, 1987; Snow, Kyllonen, & Marshalek, 1984; Woltz, 1988). In

dieser Studie soll daher die generelle Hypothese aufgestellt werden, daß in Aufgaben mit hoher Koordinationskomplexität ältere Personen in besonderer Weise – das heißt in stärkerem Maße, als man es aufgrund der kognitiven Verlangsamungshypothese erwarten dürfte – benachteiligt sind, und dies nicht nur hinsichtlich des generellen Bearbeitungsniveaus, sondern auch in der Lerngeschwindigkeit.

Ein wesentliches Merkmal dieser Studie ist, daß der Einfluß der Komplexität auf die kognitive Plastizität, und nicht nur auf die Altersunterschiede in einer punktuellen Leistungsmessung, erfaßt wird. Kognitive Plastizität kennzeichnet das Ausmaß an intraindividueller Variabilität in der Performanz. Plastizität und ihre Grenzen können durch unterschiedlichste leistungsbeeinflussende Maßnahmen – vor allem jedoch Instruktion und Übung – ausgelotet werden (Baltes, 1987; Brown et al., 1983; Gollin, 1981; Labouvie-Vief & Gonda, 1976; Lerner, 1984; Wiedl, 1984; Willis, 1985). Ist eine Person an ihr Leistungsmaximum herangeführt, dann erlauben es zusätzliche, gezielte experimentelle Manipulationen, die Grenzen und Bedingungen der Plastizität näher zu bestimmen („Testing-the-Limits“). Aus der Perspektive der Entwicklungspsychologie der Lebensspanne gibt das Ausmaß an Plastizität, das eine Person in einer gegebenen Aufgabe zeigen kann, Aufschluß über das latente Potential hinsichtlich ihrer möglichen Entwicklungsverläufe und damit letztlich über die funktionale Kapazität ihres kognitiven Systems (Baltes, 1987; Brown et al., 1983; Vygotski, 1978). In vorangegangener Forschung wurde insbesondere die Plastizität im Gebrauch einer Gedächtnistechnik („Methode der Orte“) untersucht (Kliegl, Smith, & Baltes, 1989; Thompson & Kliegl, 1991). Gezeigt wurde dabei einerseits, daß auch ältere Personen ein beträchtliches Ausmaß an Plastizität erbringen, daß aber andererseits die Altersunterschiede an den Leistungsgrenzen an Deutlichkeit eher zunehmen. Als Bedingungen, die Altersunterschiede an den oberen Leistungsgrenzen beeinflussen, wurden zum Beispiel berufliche Expertise (Lindenberger, Kliegl, & Baltes, 1991) oder auch der Zeitdruck bei der Aufgabenbearbeitung identifiziert (Kliegl, Smith, & Baltes, 1989). Das vorliegende Forschungsvorhaben beschreitet neues Terrain in zweierlei Hinsicht: Erstens wird die Untersuchung kognitiver Plastizität auf den Bereich figuraler Transformationsaufgaben ausgedehnt. Zweitens werden Altersunterschiede, sowohl in den Leistungsgrenzen als auch in der Lernfähigkeit, mit den beiden oben eingeführten Komplexitätsdimensionen (sequentielle und koordinative Komplexität) in Beziehung gesetzt.

Um die Überlegungen zum Einfluß sequentieller und koordinativer Komplexität auf Altersunterschiede in der Leistungsfähigkeit zu über-

prüfen, wurden alte ( $N = 18$ , Altersdurchschnitt = 74,4) und junge Erwachsene ( $N = 20$ , Altersdurchschnitt = 23,2) für eine insgesamt 14 Sitzungen umfassende Untersuchung rekrutiert. Der zentrale Teil der Untersuchung bestand aus acht Sitzungen, in denen eine neuartige figurale Transformationsaufgabe geübt wurde. Vor und nach dieser Übungskomponente wurde die Transferleistung in zum Teil hochkomplexen Testing-the-Limits-Varianten der Grundaufgabe erfaßt. Das Aufgabenparadigma war mit dem Ziel entwickelt worden, die beiden theoretisch relevanten Dimensionen – sequentielle Komplexität und koordinative Komplexität – zu implementieren. Die beiden Grundkomponenten der Aufgabe sind zwei verschiedene Transformationsarten, die auf ein Feld von insgesamt acht figuralen Objekten anzuwenden sind: Objekttransformationen betreffen die Merkmale (z. B. Form, Farbe) einzelner figuraler Objekte; räumliche Transformationen betreffen die räumliche Konfiguration des gesamten Objektfeldes (z. B. Rotation, Spiegelung). Für die Versuchsperson stellt sich die Aufgabe folgendermaßen dar: Auf einem Computermonitor sind zwei Felder mit jeweils acht Objekten und eine oder mehrere symbolisch angezeigte Transformationsregeln zu sehen. Die Versuchsperson soll nun so schnell wie möglich überprüfen, ob die geforderten Veränderungen (räumliche und/oder objektbezogene Transformationen) zwischen den beiden Feldern mit den tatsächlichen Veränderungen übereinstimmen. Bei einer objektbezogenen Transformation könnte zum Beispiel die Veränderung eines bestimmten Objektes innerhalb des Feldes in der Farbe verlangt sein. Tatsächlich hat entweder die geforderte Veränderung stattgefunden – dann wäre als Antwort die „Ja“-Taste zu drücken – oder aber ein anderes Merkmal, etwa die Form, hat sich verändert. In letzterem Falle wäre die „Nein“-Taste zu drücken. Bei einer räumlichen Transformation könnte zum Beispiel eine Rotation oder eine Spiegelung des gesamten Feldes mit allen acht Objekten zu überprüfen sein.

Figurale Transformationen bieten sich im vorliegenden Kontext aus mehreren Gründen an. Zum einen eröffnen sie einen reichhaltigen Raum an Aufgabenmöglichkeiten, von der einfachsten Wahrnehmungsgeschwindigkeitsaufgabe bis hin zu komplexen Problemlöseaufgaben. Vor allem aber konnten die beiden theoretisch postulierten Komplexitätsdimensionen – sequentielle und koordinative Komplexität – *durch eine Variation in der Anzahl objektbezogener und räumlicher Transformationen realisiert werden*. Sequentielle Komplexität konnte über die Variation der Anzahl der Objekttransformationen bei Abwesenheit einer räumlichen Transformation manipuliert werden: Einzelne Objekttransformationen können nämlich abgearbeitet werden, ohne daß – weder innerhalb einzel-

ner Transformationen noch über Transformationen hinweg – großer Koordinationsaufwand entsteht. Anders verhält es sich bei den räumlichen Transformationen: Schon eine einzelne räumliche Transformation erfordert, wenn, wie im vorliegenden Fall, das Stimulusmaterial relativ komplex ist, Koordinierungsaktivitäten mit hoher Anforderung an die Arbeitsspeicherkapazität (Hertzog & Rypma, 1991; Just & Carpenter, 1985; Lohman, 1988). Zudem wurde erwartet, daß in Aufgaben, in denen sowohl räumliche als auch objektbezogene Transformationen enthalten sind, eine besonders große Koordinationskomplexität entsteht. In diesem Falle ist nämlich die eine der beiden Transformationsarten nicht ohne gleichzeitige Berücksichtigung der anderen zu lösen, so daß in besonderem Maße das Speichern von Zwischenlösungen notwendig wird (Mulholland, Pellegrino, & Glaser, 1980). Koordinationskomplexität sollte daher in allen Bedingungen mit mindestens einer räumlichen Transformation entstehen, vor allem jedoch in Bedingungen mit sowohl räumlichen als auch objektbezogenen Transformationen.

In jeder Übungssitzung wurden sechs Aufgabenbedingungen bearbeitet, die sich aus der orthogonalen Variation der beiden Transformationskomponenten ergaben. Die Anzahl der Objekttransformationen pro Aufgabe wurde dreistufig (0, 1, 2), die der räumlichen Transformationen zweistufig (0, 1) variiert. In zusätzlichen sechs Transferaufgaben für die Testing-the-Limits-Bedingungen vor und nach den acht Übungssitzungen wurden Aufgaben mit bis zu drei objektbezogenen Transformationen und bis zu zwei räumlichen Transformationen realisiert. Der Großteil dieser Transferaufgaben verlangt in besonderem Ausmaß die Koordination der einzelnen Prozeßkomponenten.

Mit diesem Untersuchungsdesign wurden vier Vorhersagen bzw. Vorhersagenbündel überprüft:

(1) Einerseits sollten beide Altersgruppen beträchtlichen Leistungszuwachs über alle Bedingungen hinweg zeigen (Vorhersage 1a). Andererseits wurde erwartet, daß auch am Ende der Übungsphase die alten Probanden deutlich unter dem Performanzniveau der jungen Probanden liegen (Vorhersage 1b). Diese Vorhersagen ergeben sich aus der Annahme, daß über die Lebensspanne hinweg ein beträchtliches Ausmaß an Plastizität bewahrt wird; gleichzeitig sollte die Plastizität jedoch deutlichen, altersabhängigen Grenzen unterworfen sein (Kliegl, Smith, & Baltes, 1989).

(2) Das zweite Vorhersagenbündel bezieht sich auf die Unterscheidung zwischen sequentieller und koordinativer Komplexität in bezug auf Altersunterschiede in der Geschwindigkeit der Aufgabenbearbeitung. Im



einzelnen wurde erwartet, daß Altersunterschiede unter sequentieller Komplexität (Variation von Objekttransformationen bei Abwesenheit einer räumlichen Transformation) eher gering sind, das heißt von einer Größenordnung, wie man sie aufgrund des Modells einer generellen Verlangsamung erwarten kann (Vorhersage 2a). Hingegen sollten in allen Bedingungen, die räumliche Transformationen enthalten, Altersunterschiede entstehen, die durch eine allgemeine Verlangsamung nicht erklärt werden können (Vorhersage 2b). Besonders groß aber sollten die Alterseffekte ausfallen, wenn sowohl objektbezogene als auch räumliche Transformationen auszuführen sind (Vorhersage 2c). Die beiden letzteren Vorhersagen begründen sich aus der Annahme, daß räumliche Transformationen, vor allem aber die Kombination von räumlichen und objektbezogenen Transformationen, große Koordinationsleistungen erfordern und daher in besonderer Weise von möglichen altersabhängigen Beschränkungen im Arbeitsgedächtnis betroffen sind. Zusätzlich wurde vorhergesagt, daß, in Bedingungen mit hoher Koordinationskomplexität, alte Probanden nicht nur im Durchschnitt verlangsamt sind, sondern darüber hinaus die individuellen Reaktionszeitverteilungen ein größeres Ausmaß an sehr langen Latenzen enthalten sollten als bei jungen Probanden (Vorhersage 2d). Ein solcher Effekt würde die Annahme stützen, daß bei alten Probanden Arbeitsgedächtnisfehler während der Aufgabebearbeitung in größerem Ausmaß als bei jungen Probanden vorkommen, die durch zusätzliche, zeitraubende Prozeßschritte kompensiert werden müssen.

(3) Die dritte Vorhersage bezieht sich auf die Lerngeschwindigkeit in den einzelnen Aufgabenbedingungen: Es wurde erwartet, daß alte Probanden in Bedingungen mit hoher Koordinationskomplexität langsamer als junge Probanden lernen; die Lerngeschwindigkeit in „sequentiellen“ Bedingungen sollte hingegen nicht altersabhängig sein.

(4) Schließlich wurde in der vierten und letzten Vorhersage die Erwartung formuliert, daß in den hochkomplexen Testing-the-Limits-Bedingungen alte im Gegensatz zu jungen Probanden einen beträchtlichen Leistungseinbruch in bezug auf die Bearbeitungsgenauigkeit erfahren würden. Ein derartiger Nachweis von Plastizitätsgrenzen wäre ein besonders deutliches Indiz für die Probleme von älteren Personen mit der Koordination unterschiedlicher, aufeinander aufbauender Prozesse im Arbeitsgedächtnis. Die Ergebnisse ergaben eine Bestätigung der Vorhersagen 1a und 1b bezüglich des generellen Lerngewinns und dessen altersabhängigen Grenzen: Alte und junge Probanden zeigten einen Lernzuwachs um etwa 50 Prozent in der generellen Geschwindigkeit der Aufga-

benbearbeitung (Vorhersage 1a). Sowohl am Anfang als auch am Ende der acht Übungssitzungen waren die älteren Erwachsenen jedoch etwa doppelt so langsam wie die jüngere Vergleichsgruppe (Vorhersage 1b).

Gemäß den zentralen Vorhersagen dieser Untersuchung, 2a, 2b und 2c, sollten Altersunterschiede unter koordinativer Komplexität größer sein als unter sequentieller Komplexität. Übereinstimmend ergab die Analyse von logarithmisch transformierten Reaktionszeiten, von Reaktionszeiten, die an einem Indikator für generelle Prozeßgeschwindigkeit relativiert waren, sowie die Analyse der Alt-Jung-Funktion (Reaktionszeiten alter Probanden als Funktion der Reaktionszeit junger Probanden), daß *Altersunterschiede unter koordinativer Komplexität größer waren als unter sequentieller Komplexität* ( $p < .01$ ; Vorhersagen 2a und 2b). Insbesondere die Analyse der Alt-Jung-Funktion zeigte, daß Altersunterschiede in allen Bedingungen, die eine räumliche Transformation enthielten, doppelt so groß waren (alte Probanden um den Faktor 2,2 langsamer als junge) wie in Bedingungen ohne räumliche Transformation (alte Probanden um den Faktor 1,6 langsamer als junge). Interessanterweise entsprach die Verlangsamung, die unter sequentieller Komplexität gefunden wurde, in etwa der, die in verschiedenen metaanalytischen Untersuchungen zur altersabhängigen Verlangsamung berichtet wurde (z. B. Cerella, Poon, & Williams, 1980; Salthouse, 1985). Dieser Befund einer *zweifachen Verlangsamung* in Bedingungen sequentieller und koordinativer Komplexität impliziert aber auch eine Widerlegung der Vorhersage 2c: Wider Erwarten zeigten alte Probanden keine zusätzlichen Leistungseinbußen bezüglich der Verarbeitungsgeschwindigkeit, wenn sowohl räumliche als auch objektbezogene Transformationen zu bearbeiten waren. Demnach erzeugte die räumliche Transformation den entscheidenden, alters- und bedingungsspezifischen Effekt. Diese Schlußfolgerung muß jedoch insofern relativiert werden, als alte Personen in Aufgaben, die sowohl räumliche als auch objektbezogene Transformationen enthielten, beträchtliche Fehlerraten zeigten, so daß Latenzzeiten alter Personen hier möglicherweise unterschätzt wurden.

Eine Analyse der verschiedenen Perzentile aus den individuellen Reaktionszeitverteilungen (10 %, 30 %, 50 %, 70 %, 90 %) ergab zudem, daß, gemäß Vorhersage 2d, unter koordinativer Komplexität die Altersunterschiede über die Perzentile hinweg größer wurden, nicht jedoch unter sequentieller Komplexität. Die Reaktionszeitverteilungen älterer Probanden enthielten demnach in diesen Bedingungen mehr relativ lange Latenzen als die junger Erwachsener. Dies kann durch die Annahme von zusätzlichen Prozeßschritten, verursacht durch Arbeitsgedächtnisfehler, erklärt werden.

Widerlegt wurde die Vorhersage 3, nach der alte Probanden unter koordinativer Komplexität langsamer lernen als unter sequentieller Komplexität. Die Analyse von individuellen Lernkurven mittels Anpassung von Potenzfunktionen (Newell & Rosenbloom, 1981) *ergab gleichartige Lernraten für beide Altersgruppen in allen Bedingungen*.

Hingegen konnte gemäß Vorhersage 4 gezeigt werden, daß alte im Gegensatz zu jungen Probanden selbst nach der Übungsphase nur eine sehr geringe Lösungsgenauigkeit in den hochkomplexen Testing-the-Limits-Bedingungen erbrachten. Bedeutsam für die Interpretation dieses Befundes war der Versuch, die empirischen Fehlerraten durch ein probabilistisches Fehlermodell vorherzusagen: Es konnte gezeigt werden, daß der Zusammenbruch der Leistung sehr wahrscheinlich durch die Koordinationsanforderungen verursacht wurde und nicht so sehr durch den „sequentiellen“ Aspekt einer multiplikativen Verknüpfung der Fehlerwahrscheinlichkeiten einzelner Aufgabenkomponenten.

Neben den Analysen, die auf bestimmte Vorhersagen zielten, wurden noch eine Reihe von Kontrollanalysen durchgeführt. Das Ziel war hier, Alternativinterpretationen auszuschließen. Insbesondere konnte gezeigt werden, daß die alters- und bedingungsspezifischen Effekte nicht durch Geschwindigkeits-/Genauigkeitsprobleme (Speed-Accuracy Tradeoff) oder Spezifika der Stichprobenzusammensetzung erklärt werden können.

In der Diskussion der dargestellten Ergebnisse wird zunächst auf mögliche Alternativerklärungen des Hauptbefundes einer besonders starken altersabhängigen Verlangsamung unter koordinativer Komplexität eingegangen. Insbesondere ist zu berücksichtigen, inwiefern dieser Befund möglicherweise nicht so sehr auf eine fundamentale Kapazitätseinschränkung älterer Erwachsener als vielmehr auf Performanzfaktoren oder bestimmte Stichprobencharakteristika zurückzuführen sein könnte. In der Diskussion wird dabei zum einen auf die Ergebnisse der oben angesprochenen Kontrollanalysen hingewiesen. Außerdem wird argumentiert, daß gerade die Erfassung der Plastizität, das heißt die Analyse von Leistungsobergrenzen, strategische oder erfahrungsabhängige Einflüsse minimieren sollte (Kliegl, Smith, & Baltes, 1989).

Eine weitere mögliche Einschränkung der Interpretierbarkeit der Befunde ergibt sich aus der Tatsache, daß koordinative Komplexität über räumliche Transformationen operationalisiert wurde. Räumliche Transformationen sind jedoch möglicherweise in einem analogen Verarbeitungsmedium angesiedelt, das von dem der diskreten, propositionalen Verarbeitung zu unterscheiden ist (z. B. Kosslyn, 1981) – möglicherweise sogar hinsichtlich der beteiligten neuroanatomischen Strukturen (Farah, 1988). Daher ließe sich einwenden, daß im vorliegenden Untersuchungs-

design Komplexität und Verarbeitungsbereich konfundiert wurden. Statt auf ein komplexitätsspezifisches Phänomen könnten die vorliegenden Ergebnisse auch auf bereichsabhängig unterschiedlich starke Alterstrends hinweisen. In der vorliegenden Studie kann diese Konfundierung nicht aufgelöst werden. In einem auf dieser Untersuchung aufbauenden Experiment, bei dem koordinative Komplexität auch durch nichträumliche Transformationen erzeugt wurde, ließ sich jedoch das zentrale Ergebnis dieser Studie replizieren (Mayr & Kliegl, im Druck). Der besonders große Alterseffekt unter koordinativer Komplexität kann somit aller Wahrscheinlichkeit nach nicht auf eine bereichsspezifische Erklärung reduziert werden.

Im weiteren Verlauf der Diskussion wird das vorliegende Ergebnis auf die Befundlage zur kognitiven Verlangsamung bezogen. Zwei Aspekte sind dabei interessant: Erstens gehen die Modelle zur allgemeinen Verlangsamung, gestützt auf empirische, metaanalytische Befunde, von einer einzigen, generellen Komplexitätsdimension aus. Hingegen lassen sich die Daten dieses Experimentes am besten durch die zwei Dimensionen, sequentielle und koordinative Komplexität, erklären. Zweitens wird, aufbauend auf metaanalytischen Ergebnissen im Rahmen von aktuellen Modellen kognitiver Verlangsamung, argumentiert, daß eine kurvenlineare Beziehung zwischen Reaktionszeiten alter und junger Erwachsener existiert: Der proportionale Altersunterschied sollte mit zunehmender Komplexität größer werden (Cerella, 1990; Myerson et al., 1990). Hingegen weisen die vorliegenden Ergebnisse auf zwei *proportionale* Verlangsamungsfunktionen hin, wenn die theoretisch motivierte Unterscheidung zwischen sequentieller und koordinativer Komplexität vorgenommen wird.

Wie läßt sich dieser Befund erklären? In der vorliegenden Arbeit wird ein Modell vorgeschlagen, das auf folgenden Annahmen basiert: Zum einen wird eine relativ generelle Verlangsamung kognitiver Prozesse um einen konstanten Faktor angenommen, die alleine die Altersunterschiede unter „sequentieller Komplexität“ determiniert. Zum anderen wird eine altersabhängige Einschränkung der Arbeitsspeicherkapazität postuliert. Diese bewirkt, daß in Aufgaben mit hohem Koordinierungsaufwand lösungsrelevante Information verlorengeht. Die Folge ist, daß Prozeßschritte (wiederum verlangsamt um den oben genannten „generellen Faktor“) bei alten Erwachsenen mit größerer Wahrscheinlichkeit wiederholt werden müssen als bei jungen Erwachsenen. Eine Formalisierung dieses einfachen Modells zeigt, daß es prinzipiell in der Lage ist, den vorliegenden Befund von zwei proportionalen Verlangsamungseffekten zu erklären. Allerdings bedarf es zukünftiger Forschung, um dieses oder ein

ähnliches Modell zu verifizieren. Insbesondere wäre es wünschenswert, mehr Detailinformation als in dieser Studie über die Verarbeitungswege alter und junger Probanden in komplexen Aufgaben zu gewinnen.

Mit der theoretisch postulierten und empirisch weitgehend bestätigten Unterscheidung zwischen sequentieller und koordinativer Komplexität fügt die vorliegende Arbeit einen wichtigen, differenzierenden Aspekt zum Bild kognitiven Alterns hinzu. Altersabbau in verschiedenen intellektuellen Leistungen läßt sich demnach nicht ohne weiteres auf einen einzigen, letztlich physiologisch zu begründenden, Parameter reduzieren. Vielmehr dürfen die algorithmischen, also kognitiven, Aspekte der Aufgabenbearbeitung nicht aus dem Blickfeld geraten. In zukünftiger Forschung muß sich zeigen, inwiefern die postulierte Unterscheidung zwischen sequentieller und koordinativer Komplexität durch kognitive Prozeßanalysen gestützt werden kann, und ob sie auf andere Aufgabenbereiche generalisierbar ist.

# 1. Introduction

## **Cognitive Plasticity Across the Life-Span**

Why is it that intellectual performance in a large variety of functions declines as people grow older? Are these developmental changes caused by one general aging mechanism or are multiple processes involved? These are longstanding questions in psychometric and cognitive research on the aging of mind; they also motivate the present study. A particular approach to the understanding of aging mechanisms is chosen in this research: the investigation of developmental plasticity and its conditions. The notion of plasticity designates the possible range of intraindividual change in the functional level due to supportive or impeding environmental circumstances (Baltes, 1987; Brown, 1982; Denney, 1979; Gollin, 1981; Kliegl & Baltes, 1987; Lerner, 1984; Wiedl, 1984). Within a life-span approach to intellectual development this concept represents the appraisal that old-age cognitive functioning is not the product of a uniform, one-directional process. Rather, multidirectionality of developmental trajectories in different abilities (e.g., Botwinick, 1977; Cattell, 1971; Horn, 1982) and modifiability of performance (e.g., Baltes & Lindenberger, 1988; Labouvie-Vief, 1985; Schaie & Willis, 1986) are emphasized. Consequently, life-span psychologists perceive baseline performance as only one of many possible developmental outcomes. Their ultimate interest, however, lies in the developmental reserve capacity, that is the latent potential for different developmental trajectories (Baltes, 1987). Assessment of the range of intellectual plasticity provides information on an individual's true capacity and thus opens the way for detailed analyses of age-related processes. An important component of this approach is the emphasis on "testing-the-limits" situations in which boundary conditions of functioning are explored through theory-driven experimental variations (Kliegl & Baltes, 1987; Kliegl, Smith, & Baltes, 1989).

The main theoretical feature of this framework is twofold: On the one hand, lifelong potential for developmental growth is assumed (Baltes, 1987; Denney, 1984; Labouvie-Vief, 1985; Perlmutter, 1988; Willis, 1985).

On the other hand, the aging cognitive system is believed to exhibit severe limits of plasticity: The space of possible cognitive states accessible by old adults is assumed to be smaller than that of young adults (e. g., Kliegl & Baltes, 1987; Kliegl, Smith, & Baltes, 1989). It is suggested that at the heart of older adults' limited developmental capacity lies a decline in "mechanical" (Baltes, Dittmann-Kohli, & Dixon, 1984) or "fluid" (Cattell, 1971) capacities of the aging brain. The dual character of the above propositions can be illustrated by the pattern of results obtained in studies exposing old and young adults to extensive training in a mnemonic skill (Baltes & Kliegl, in press; Kliegl & Baltes, 1987; Kliegl, Smith, & Baltes, 1989). In general, there was a dramatic enhancement of performance, so that after training both age groups qualified as "mnemonic experts." At the same time, young adults improved more than old adults leading to an almost complete separation of the two age groups.

A prime interest within this perspective on developmental plasticity is on identifying determinants of old and young adults' range of functioning. With respect to the sample case of a mnemonic skill age effects were shown to be a function of both task variables, such as encoding time (Kliegl, Smith, & Baltes, 1989) or relatedness of to-be-remembered word pairs (Thompson & Kliegl, 1991), and subject variables, such as professional expertise (Lindenberger, Kliegl, & Baltes, 1991) or psychometric abilities (Kliegl, Smith, & Baltes, 1990). The present study extends prior research in two ways. First, age-differential cognitive plasticity is studied in a novel task domain, namely, figural transformations. Second, this study constitutes a further attempt to explore the conditions of plasticity. Specifically, performance limits as a function of different aspects of complexity will be investigated.

### **Conditions of Plasticity and its Limits: The Effect of Task Complexity and Practice**

How do age differences in the range of functioning depend on conditions of the task? In the current study the investigation of this question will be guided by the thesis that, whenever large amounts of cognitive resources have to be mobilized, old adults' *functional limits and learning* will be severely constrained. Cognitive resources denote a limited capacity entity which determines quality and rate of processing (e. g., Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, 1980). The notion of an age-related decline in resources as a precursor of adult age differences is certainly not new (e. g., Birren, 1964; Craik & Byrd, 1982; Crossman &

Szafran, 1956; Salthouse, 1988a; Welford, 1958). The crucial, unresolved question, however, is *which* and *how many* resources have to be distinguished to explain age differences across various task conditions.

The investigation of task complexity is one way of approaching this issue. Task complexity is regarded as a prime variable determining expenditure of cognitive resources: The more complex a task, the more resources need to be allocated (e. g., Navon & Gopher, 1979; Snow, Kyllonen, & Marshalek, 1984). Thus, knowledge about the dimensionality of task complexity with respect to age differences should be indicative about the system of resources involved in adult intellectual development.

The main theoretical assumption of the present research is that two aspects of task complexity can be distinguished, one of them more critical for age-related plasticity than the other. The first dimension of complexity is labeled *sequential complexity* and can be described as a variation in the number of *independent* processing steps. The term "independent" refers to the fact that one step can be processed after the other in a strictly serial way (Logan, 1979; Sternberg, 1969). Tasks differing in the number of such potentially independent processing steps should yield information about basic processing speed (e. g., Salthouse, 1985), but should not reflect any other potential age-differential resources. The second aspect, denoted as *coordinative complexity*, can be implemented through task components which require keeping-track of prior solutions or parallel storage and processing of information. Conditions high in coordinative complexity are assumed to demand a maximum of age-sensitive "fluid" or "mechanical" resources, such as working memory capacity (e. g., Baddely & Hitch, 1974; Broadbent, 1958; Daneman & Carpenter, 1980). Older adults should therefore exhibit dramatic performance decrements in such conditions. Moreover, the degree to which learning processes require cognitive resources can also be regarded as a function of coordinative complexity (e. g., Anderson, 1987; Kyllonen & Christal, 1990; Woltz, 1988). Thus, aside from large general age differences in tasks of high coordinative complexity, a joint effect of practice and task complexity is proposed: Old adults are expected to learn at a slower rate than young adults when coordinative activities are required.

### **The Figural Transformation Task: A New Paradigm for Studying Age-Differential Plasticity**

To investigate how the unfolding of task complexity determines age-differential cognitive plasticity, a novel experimental paradigm was devel-

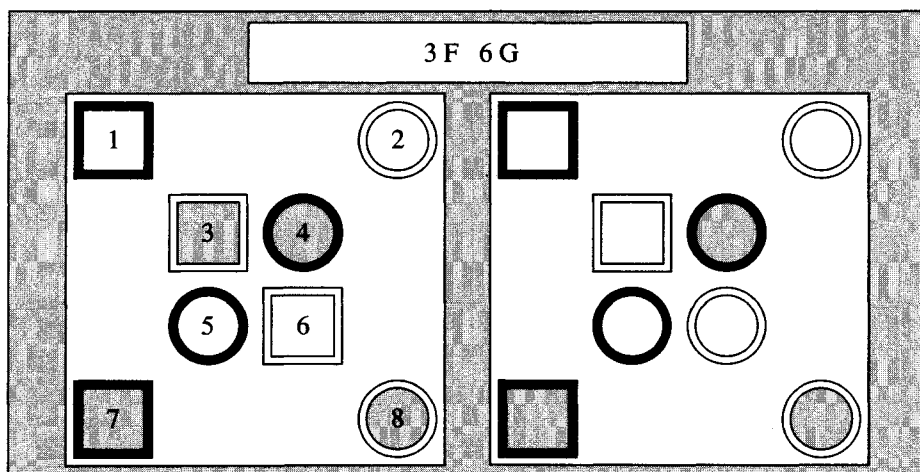


oped: the Figural Transformation Task. The central feature of this paradigm is that, within one task format, a variety of conditions differing in sequential and coordinative complexity can be implemented by varying the number of two basic task components. The general domain of processing are transformations with figural material (Mulholland, Pellegrino, & Glaser, 1980; Sternberg, 1977). Speed and accuracy of solving items differing in type and number of transformations are the dependent variables.

To equip the reader with a clear understanding of the two dimensions of complexity and their implementation in the current paradigm, two typical items, one low, the other high in terms of coordinative complexity are presented already at this point. Consider the two arrays in Figure 1.

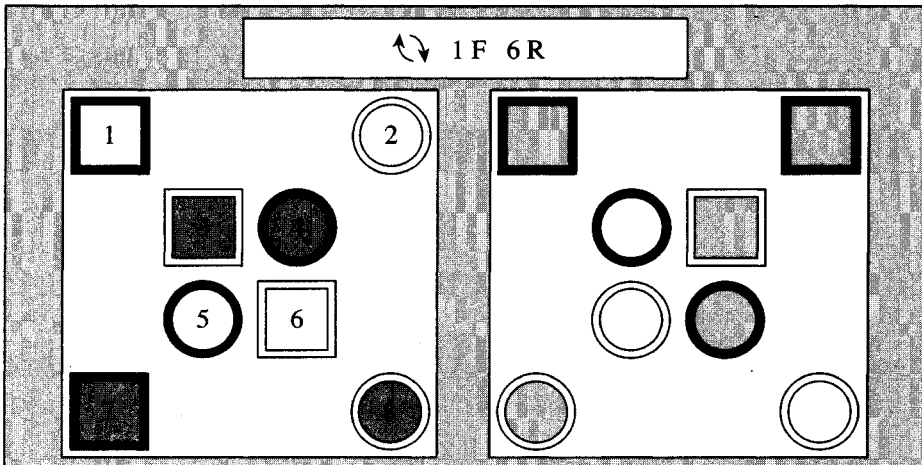
The participant's task is to check whether both of the following transformations between the two arrays are true: (a) Object 3 should change its color between the two arrays and (b) Object 6 should change its shape. (An instructed participant would know the required transformation rules from the symbols in the upper box.) Each one of the single transformations requires very little coordination activities and to solve the second transformation it is not necessary to have the solution to the first transformation in mind so that both transformations can be worked through in a sequence and independently of each other. Thus, although this task

Figure 1  
Sample Item from the Condition with Two Object-Related Transformations



Note. Both transformations are applied correctly so that the participant would have to respond with "yes." For further explanation see text.

Figure 2  
Sample Item from the Condition with One Spatial  
and Two Object-Related Transformations



*Note.* This is an example where one transformation (6 R) is applied incorrectly so that the correct response would be "no." For further explanation see text.

would be regarded as being at least of moderate complexity, little coordinative activity is necessary to find the correct answer. A respective condition with lower sequential complexity would involve only one object transformation or even only a physical match between the two arrays.

Now consider Figure 2. Aside from two object transformations an additional one has to be checked: The whole array should be rotated 90 degrees clockwise. A great deal of coordinative activity is necessary in this item. First, checking the rotation itself consists of several steps, and products of earlier steps have to be kept in mind. Second, the three transformations cannot be executed independently of each other: When checking the rotation, the two possible changes of single objects must be taken into account. Vice versa, potential changes of single objects can only be checked when the spatial rearrangement due to the rotation is kept in mind. Thus, just as sequential complexity can be increased and decreased through the number of object transformations in the absence of a spatial transformation, different levels of coordinative complexity are produced (a) by spatial transformations per se and (b) especially by the combination of both spatial and object transformations.

Taken together, by manipulating the number of the two types of transformations per item, a large continuum of task complexity can be

established which encompasses conditions varying systematically in sequential and coordinative complexity. On the one end of this continuum, conditions are realized which represent simple information processing tasks that would be regarded as perceptual speed measures from a psychometric perspective. On the other end lie highly complex testing-the-limits conditions, which come close to what would be labeled figural reasoning in psychometric terminology.

In the present study, young and old adults are exposed to extensive practice in responding both quickly and accurately in various conditions differing systematically in the two aspects of task complexity. The main predictions are that for conditions high in coordinative complexity old adults will exhibit (1) particularly large processing deficits in terms of slow performance despite extensive practice and (2) a smaller learning rate than young adults. Additionally, testing-the-limits conditions of high complexity are expected to constitute boundary conditions of old adults' but not of young adults' cognitive plasticity.

Hypotheses referring to condition-specific age differences have to compete against a strong baseline model: So-called cognitive slowing models are currently very dominant in cognitive aging research. The basic assumption in these models is that age differences are determined solely by an age-related decrease in "basic" and "general" processing speed. These models predict uniform age differences across a large spectrum of task conditions (e. g., Cerella, 1990; Myerson et al., 1990; Salthouse, 1985). Special care will be taken to scrutinize the question of "true" conditionspecific limitations in plasticity versus unspecific effects of old adults' reduced processing speed. Thus, the present study provides information not only about conditions of plasticity, but also contributes to a currently virulent topic in the field of cognitive aging by subjecting basic assumptions of general slowing models to a critical test.

## 2. Review of the Literature

The review of the relevant literature starts with placing the present study into the larger context of a life-span perspective on intellectual aging (*Intellectual Development from a Life-Span Perspective*). In the second section (*Task Complexity and the General Resource Account of Cognitive Aging*), the role of task complexity and cognitive resources in the aging of intellectual functions will be portrayed. Emphasis will be placed on processing speed and working memory as potentially important, age-relevant resources. The role of task complexity from the perspective of interindividual differences research will be briefly reviewed in the third section (*Task Complexity and Interindividual Differences*). How age differences in tasks differing in complexity are affected through learning and practice is the topic of the final section (*Aging, Learning, and Complexity*). Taking a cognitive perspective on skill acquisition, the existing literature on aging and skill acquisition will be examined with regard to potential sources of age effects in learnability.

### **Intellectual Development from a Life-Span Perspective**

There is little debate in contemporary research on cognitive aging over the question that a decline in mental functioning is a salient feature in adult intellectual development (e.g., Botwinick, 1977; Hollingworth, 1927; Horn, 1982; Kausler, 1991; Salthouse, 1985; Sanford, 1902). Three facets of the phenomenon of adult intellectual decline are important in the current context: First, decrements in intellectual functioning can be found in both cross-sectional and longitudinal research. Thus, despite the existence of considerable cohort differences (Schaie, 1983), large portions of age-related changes with high likelihood represent true developmental trajectories (Hertzog & Schaie, 1988; Schaie, 1989). Second, age-related decline as represented in normative age trends is of considerable size. Horn, Donaldson, and Engstrom (1981), for example, state that there is a reduction in fluid intelligence of three to seven IQ points per decade

between the ages of 20 and 60. And Salthouse (1982), based on an extensive review of the literature, concludes that 65-year-olds, in general, exhibit about 60 percent of young adults' level of performance. Finally, age-related decline is a relatively general phenomenon. This last aspect is highlighted in a recent textbook by Kausler (1991) in which normative age differences are portrayed in tasks representing such diverse domains as perception, attention, various memory processes, problem solving, and different aspects of intelligence.

The latter observations do not form a closed body of knowledge. As shown in the next section, they have to be integrated into a broader and more differentiated picture of adult cognitive development. Also, these statements are mostly descriptive and therefore constitute a starting point for research endeavors which, like the current one, attempt to reveal explanatory factors in adult cognition.

### *Variability Between Individuals and Functions*

The above portrait of the aging mind is a representation of normative age changes. Important aspects have been added to this general picture by the life-span perspective on adult development (e. g., Baltes, 1987; Labouvie-Vief, 1985; Perlmutter, 1988; Schaie, 1990). This approach emphasizes the inter- and intraindividual variability in both levels of performance and developmental trajectories. For example, there are many individuals who exhibit a great deal of stability across the life course and, at least when focusing on single-session assessments of intellectual functioning, many old adults can be found who operate on the level of young adults (Schaie, 1990).

Also, the acknowledgement of the fact that intelligent behavior is a multidimensional construct has led from a simple decline model to a more differentiated picture in which various dimensions are connected with different age trends. Extending a prior distinction between fluid and crystallized intelligence (Cattell, 1971; Horn, 1982), Baltes, Dittmann-Kohli, and Dixon (1984) proposed the mechanics and the pragmatics of intelligence as two general processes relevant for intellectual development across the life-span. The pragmatics of intelligence are regarded as context-related intelligent behavior based on accumulated knowledge and experience. Stability and even growth across the life-span can be found in this domain (Cornelius & Caspi, 1987; Hayslip & Sterns, 1979; Schaie, 1990; Smith & Baltes, 1991).

Decline in intellectual functioning (at least up to the age of 75) is assumed to be restricted to the mechanics of intelligence. With this concept reference is made to the content-free basic cognitive components which largely reflect biological "hardware" (e.g., Cattell, 1971; Charness, 1981; Kliegl, Smith, & Baltes, 1989). As the mechanics of intelligence underlie a great variety of intellectual functions, age-related decline can be found, for example, in the domain of episodic memory (e.g., Craik & Rabinowitz, 1984), in tasks involving rapid execution of simple operations (perceptual speed; e.g., Schaie, 1989), or in tasks involving complex problem solving (e.g., Arenberg, 1982). One of the crucial questions of contemporary cognitive aging research and also of the present study is whether decrements within the mechanics of intelligence represent a uniform change produced by one common factor or whether they are more specific to particular task conditions (e.g., Salthouse, 1985).

### *Latent Potential and Testing-the-Limits*

Particularly important for the present research is the emphasis of lifespan psychologists on the latent potential for developmental change in functioning. For example, exposing old adults to cognitive interventions can trigger considerable improvements even in fluid/mechanical tasks, thus indicating sustained plasticity of the aging cognitive system (e.g., Baltes & Lindenberger, 1988; Baltes & Willis, 1982; Labouvie-Vief & Gonda, 1976). Given the malleability of both young and old adults' performance, the upper range of functioning an individual can achieve is perceived as the ultimate indicator of his/her true capacity or competence (Baltes, 1987; Campione et al., 1985; Guthke, 1982; Kliegl et al., 1989; Vygotsky, 1978; Wiedl, 1984). Whereas baseline assessments are clouded by performance and possible cohort-specific knowledge factors, estimates of developmental reserve capacity promise insights about organismic limitations of cognitive systems.

Focusing on latent potential rather than on baseline performance calls for innovations in the design of age-comparative research. One methodology proposed to obtain estimates of developmental reserve capacity is the testing-the-limits paradigm (Kliegl & Baltes, 1987; Kliegl, Smith, & Baltes, 1989). Its first component consists of well-planned cognitive interventions, such as instruction or practice, which ideally bring participants to their performance asymptote and beyond the levels of performance attainable by uninstructed persons. This laboratory estimate of the maximum performance represents an approximation of what is pos-

sible under optimal developmental circumstances and thus is an indicator of true capacity irrespective of "capacity-extraneous" performance factors. The second component consists of theory-guided experimental variations that challenge the skill under observation. The goal is to identify boundary conditions of plasticity (Kliegl & Baltes, 1987). For example, breakdown of accurate performance due to well-planned experimental variations informs about the nature of constraints on old and young adults' processing (Lindenberger, Kliegel, & Baltes, 1991).

This general framework will be adopted in the present research to identify age-differential processing limitations due to particular task conditions. An important feature of the current study is that age differences will be regarded as true age-related limitations only when they are stable despite extensive experience with the task conditions under consideration.

### **Task Complexity and the General Resource Account of Cognitive Aging**

Throughout this research, two related concepts are of crucial importance: cognitive resources and task complexity. Cognitive *resources* have been defined as "... any internal input essential for processing (e.g., locations in storage, communication channels) that is available in quantities that are limited at any point in time" (Navon, 1984, p. 217). Also, cognitive resources are assumed to be fairly general (e.g., Norman & Bobrow, 1975) and to differ between individuals or age groups (e.g., Craik & Rabinowitz, 1984; Salthouse, 1988a). As will be shown in the following sections, an age-related decline in cognitive resources is assumed to be one of the prime causal factors in cognitive aging.

Task *complexity* is regarded as the main theoretical variable determining requirements for cognitive resources (Navon, 1984). Thus, resources and complexity have a complementary relationship. In fact, some researchers deploy the terms "resource requirements" and "complexity" in a synonymous way (e.g., Salthouse, 1988a). Various task variations have been suggested as manipulations of task complexity, such as the number of repetitive processing steps (Kantowitz & Knight, 1976), the number of different mental operations in general (Salthouse, 1985), the requirements for parallel processes (Navon, 1984), the degree to which complex algorithms have to be assembled (Snow, Kyllonen, & Marshalek, 1984), or the degree of uncertainty (Jensen, 1987).

Which and how many different resources are necessary to account for performance across various complexity manipulations, individuals, and age groups? Although not always stated explicitly, the question of the dimensionality of cognitive resources probably motivated research in diverse fields, such as cognitive psychology (e.g., Norman & Bobrow, 1975; Wickens, 1980), research on interindividual differences (e.g., Carroll, 1981; Detterman, 1986; Gardener, 1983; Jensen, 1985; Kosslyn et al., 1984; Sternberg, 1990), and research on developmental changes (Case, 1974; Cerella, 1990; Kail, 1991; Morris, Gick, & Craik, 1988; Fisk & Rogers, 1991; Salthouse, 1988a). In the following sections, currently dominant views of the resource account of cognitive aging will be presented. This review will begin with a short historical sketch of the work leading to the current significance of the resource concept in research on adult developmental changes in cognition.

### *The Complexity Effect*

The broad distinction between crystallized/pragmatic and fluid/mechanical aspects of intelligence was one step beyond mere description of developmental changes. From this perspective, intellectual development was characterized as a joint process of accumulation of knowledge in crystallized/pragmatic abilities on the one hand, and decline in fluid/mechanical domains due to organismic changes, on the other. With respect to the latter domains, however, this theoretical approach did not specify precise mechanisms. Further attempts to identify such mechanisms of aging can be portrayed as a succession of two eras, differing with respect to the generality of the specified processes.

Influenced by the information processing paradigm, researchers in the past assumed that decline in intellectual functioning was a function of deficits in specific processing steps. Such deficits were typically inferred from age  $\times$  condition interactions: If larger age differences were obtained in the presence of a theoretically age-sensitive processing component, it was assumed to be particularly affected by aging. Processing components identified this way were, for example, the ability of utilizing redundant information (Rabbitt, 1982), elaborative rehearsal (Kausler & Puckett, 1979), retrieval (Craik & Masani, 1969), ability to ignore irrelevant information (Hoyer, Rebok, & Sved, 1979), or reduced abstract thinking ability (Bromley, 1963), to name only a few (see Salthouse [1985] for an extensive discussion of this issue).



This approach to determine aging mechanisms on the basis of observations in restricted task domains was criticized as not doing justice to the generality of the cognitive aging phenomenon (Birren & Renner, 1977; Cerella, Poon, & Williams, 1980; Salthouse, 1985). The main argument was based on the observation that almost any task variation leading to performance decrements in young adults did the same in old adults, only to a larger degree. In recent research, this phenomenon was labeled as the complexity effect (Botwinick, 1977; Cerella, Poon, & Williams, 1980; Salthouse, 1985), but it has been observed long before by researchers like Birren (1965), Kay (1959), or Welford (1958). According to Salthouse (1985) and Myerson et al. (1990), complexity in this context can be perceived as a hypothetical dimension representing the number of “atomic” steps underlying each processing component, irrespective of type and domain.

What does the complexity effect tell us about the phenomenon of intellectual aging? Most researchers interpret this effect as indicating a decline in a cognitive resource which (a) has to be very basic and general to account for age differences in a large variety of tasks and (b) which is required to a larger degree in complex (many cognitive operations) than in simple tasks (few cognitive operations). The most important resource considered in this context is processing speed (e. g., Birren, 1964; Cerella, 1990; Myerson et al., 1990; Salthouse, 1985). The reasoning behind the different variants of the processing speed models is crucial to the present study. Therefore, an extensive, critical review of these models will follow in the next two sections. Then, additional conceptualizations of potentially age-specific resources will be considered.

### *Speed as an Age-Related Processing Resource*

The most persuasive demonstration of the complexity effect was obtained with a particular sort of metaanalysis. Using a technique first proposed by Brinley (1965) and reintroduced into the literature by Salthouse (1978), old adults’ latencies from a variety of speeded tasks were plotted against young adults’ latencies. In these old-young functions young adults’ latencies serve as a task-independent indicator of task complexity and interest centers on the characteristics of the emerging function. The typical finding obtained in such meta-analyses can be seen in Figure 3: Latencies of old adults can be represented as a function of latencies of young adults with high precision (usually more than 90% variance explained) without need for taking any task-specific information into regard (e. g., Cerella,

Poon, & Williams, 1980; Cerella, 1985; Hale, Myerson, & Wagstaff, 1987). The relation reported in the first accounts of this kind (Cerella, Poon, & Williams, 1980; Cerella, 1985; Salthouse, 1985) indicated that old adults' latencies could be predicted from young adults' latencies using a linear function with a slope of about 1.6<sup>1</sup> and an intercept that was near zero (mostly somewhat negative). The slope can be regarded as a general slowing factor, that is, the proportion to which old adults are slowed compared to young adults. Thus, across task conditions old adults were slowed by a factor of about 1.6 compared to young adults.

At first sight, the fact that task complexity is defined in an absolutely atheoretical and circular manner—namely, through the latency of the young adults—could be regarded as a problem of this approach. Yet, what the meta-analyses seem to indicate is that a theoretical explication of the complexity dimension, even though it is one of the crucial—and unresolved—issues of cognitive psychology (e.g., Kantowitz & Knight, 1976; Navon, 1984), is simply unnecessary for the question of age differences. Theoretically, this finding was interpreted according to the general resource account introduced in the preceding section. Young adults' latency ( $L_Y$ ) was assumed to be a composite of a number of basic processing steps ( $S$ ):

$$(1) \quad L_Y = S_1 + S_2 + \dots + S_n.$$

Latencies of old adults were proposed to be a composite of the same number of processing steps, only that age-related loss in processing speed was assumed to affect all mental steps by a constant factor larger than one (b):

$$(2) \quad L_O = b * S_1 + b * S_2 + \dots + b * S_n = b * (S_1 + S_2 + \dots + S_n).$$

Combining equations 1 and 2 yields:

$$(3) \quad L_O = b * L_Y.$$

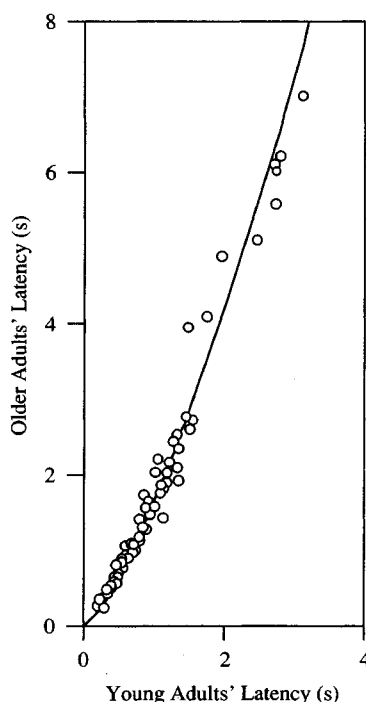
Thus, with increasing task complexity (i.e., number of mental operations), age differences in absolute latencies become larger, the ratios between old and young adults, however, remain invariant and are determined by the slowing factor  $b$ . The basic slowing was, for example, hypothesized to represent the accumulating breakdown of neural links with increasing age (Cerella, 1990).

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<sup>1</sup>The mean of the slopes across several studies reported by Salthouse (1985) was 1.65, the slopes of two meta-analyses reported by Cerella were 1.46 (Cerella, 1985), and about 1.65 (Cerella, 1987; after Cerella [1990, Figure 3c]).

The proportional slowing model was, subsequently, challenged by variants of the basic models which claimed that a non-linear function, in particular a power function yielded a better representation of the data. As shown especially in one meta-analysis (Hale, Myerson, & Wagstaff, 1987), linear models seemed to underestimate age differences for large latencies (see Figure 3). Based on the power function representation, attempts were also made to construct explanatory, mathematical models. For example, Myerson et al. (1990) proposed that older adults' cognitive system could be characterized as losing somewhat more information with each processing step on the neural level than that of young adults. Compensating for this accumulating loss then produces the nonlinear slowing. In contrast, Cerella (1990) argues for an "organizational overhead" which increases as a function of the number of mental operations for old adults but not for young adults. The theoretical functions of both

Figure 3  
Illustration of an Old-Young Function  
Comprising Data Points from 70 Task Conditions



*Note.* Data are fitted by a power function (after Myerson et al., 1990).

models are extremely similar. Therefore, with the available data sets, there is no way of distinguishing between them. Nevertheless, the two approaches are important, because they represent attempts to subsume age differences in tasks with large complexity (so far, up to 17 seconds for old adults) under one single "aging" parameter.

One additional important aspect of the slowing account has to be mentioned. Both in the models by Myerson et al. (1990) and Cerella (1990), the claim is made that age-differential slowing is not only orthogonal to type of task and complexity, but also to the practice or learning dimension. For example, Myerson et al. (1990) report data from a small age-comparative intervention study by Salthouse (1978) using the Digit Symbol Substitution. When representing the data points from all measurement occasions within one old-young plot, they "slide" down the complexity function across the course of practice. The same phenomenon was demonstrated recently by Cerella (1991) in his reanalysis of learning data reported by Fisk and Rogers (1991). Thus, what these authors suggest is that at any point of the practice function, age differences are solely governed by the age differences in basic processing speed. Essentially, this means that learning processes which are in effect during practice are not assumed to be subject to age-related decline. This important aspect will be taken up in a later section.

In conclusion, general slowing models make strong claims about the nature of age differences with respect to almost any potential task variations that cognitive psychologists can think of (complexity, type of processing, practice, levels of accuracy). For example, from this perspective, the difference between various conditions of a memory-scanning task have the same significance for age effects as the differences between a memory-scanning condition and a condition from a mental rotation task. Any further differentiation of the complexity dimension is regarded as unnecessary for the explanation of age differences. Thus, in its extreme form this general approach comes down to a "one-parameter model" of cognitive aging. Yet, despite its parsimonious elegance, this approach can be criticized in several ways.

### *Critique of the General Slowing Account*

The general slowing account is based on data which are impressive in terms of quantity, but, at the same time, are limited. First, within the meta-analytic studies, little information is available about tasks of moderate and high complexity. Across the four data sets reported in the

"Handbook of the Psychology of Aging" by Cerella (1990), 95 percent of the data points are derived from task conditions in which young adults needed less than 1.5 seconds and still 87 percent from conditions where young adults demanded less than one second. Thus, any inference about the form of the slowing function for more complex tasks has to be considered with care. Of course, this is especially true when it comes to tasks which are so complex that accuracy and not response latency are the more meaningful dependent variable. Current slowing models provide no explanation for the fact that in some tasks older adults seem to be unable to reach accuracies comparable to the young adults, even when enough time is available (e.g., Kliegl, Smith, & Baltes, 1989).

Second, and even more importantly, a closer look at the data reveals that there is a confound between complexity and type of task. In the only meta-analysis in which a considerable amount of complex tasks were included, namely, the Hale, Myerson, and Wagstaff (1987) data base, there is only little overlap between low complexity reaction time or memory-scanning tasks, on the one hand, and mental rotation tasks, on the other. Some researchers assume that mental rotation demands rather complex executive processes (Just & Carpenter, 1985; Lohman, 1988). Such a confound between complexity and processing domain is critical both for the issue of the generality of the slowing function and for the question what form the slowing function takes. For example, it is possible that the power function revealed in the Hale, Myerson, and Wagstaff (1987) is produced by a mixture of two different linear functions—a shallow one for the simple, and a steeper one for the mental rotation conditions. A similar argument was put forward by Cerella (1985) with respect to the form of the slowing function near zero by proposing an overlay of a perceptual-motor and a steeper, cognitive slowing function. In order to scrutinize the question of potential condition-specific age differences, tasks have to be developed in which various aspects of complexity can be manipulated in overlapping regions of the measurement space.

Third, to interpret the parameters derived from the old-young functions as reflections of a pure, "hardware"-based age-related slowing, one has to accept the preassumption that both age groups were processing the task in exactly the same way (i.e., with equivalent number of mental operations). This may be plausible for simple tasks, but it can be questioned for any of the more complex tasks, because all data-points used for the meta-analyses stem from one-session experiments, with minimal instruction and practice. Again, this aspect is especially critical with regard to the question of linear versus nonlinear slowing: Deviations from a

linear slowing model could easily be explained by assuming that at least a subgroup of older adults tends to apply less efficient strategies when tasks become more complex. In any case, it is worth noting, that the only study in which latencies were derived from a complex task (mental squaring) and in which both old and young adults were exposed to extensive practice, the slowing function was linear (Charness & Campbell, 1988).

Each of these three points of critique refer particularly to the more complex tasks. Therefore, one can take the finding of a linear slowing function with a slope of about 1.6 derived from simple tasks seriously. It can be regarded as a baseline model against which any task-specific aging phenomenon has to be tested (e. g., Salthouse, 1988b). However, it seems unwarranted to make strong claims about age differences in tasks which demand more than a small number of simple operations. Thus, given the current empirical basis, the generality of the slowing model is limited. The situation calls for studies in which latencies are assessed from tasks (a) differing widely in complexity, (b) in which processing domain and complexity are unconfounded, and (c) in which great care is taken that old and young adults perform tasks in similar ways by providing instruction and practice.

### *Working Memory Capacity as an Age-Related Resource*

An alternative, prominent candidate for an age-sensitive general resource is working memory capacity (e. g., Craik & Rabinowitz, 1984; Salthouse, 1990; Welford, 1958). Working memory is generally perceived as a module with limited capacity. It is regarded as the "workbench" in which both the processing and storage functions required for most tasks take place (Baddeley & Hitch, 1974; Broadbent, 1971; Craik & Rabinowitz, 1984; Daneman & Carpenter, 1980). The "classic" working memory model is the one proposed by Baddeley (1986) who distinguishes a processing component, the central executive, from two storage components, the rehearsal buffer for verbal information and the visuo-spatial "scratch-pad" for spatial information. For the present purpose, however, a commitment to this particular model or one of the other existing conceptualizations is not necessary (e. g., Anderson, 1983; Carlson, Sullivan & Schneider, 1989; Schneider & Deteiler, 1988). Relevant here is the fact that different conceptualizations agree that working memory capacity constrains the degree to which information can be stored and processed simultaneously (Baddeley & Hitch, 1974; Broadbent, 1971; Craik & Rabinowitz, 1984; Daneman & Carpenter, 1980). A related concept is

that of a limited capacity for executive, coordinative, and goal management processes (e.g., Carpenter, Just, & Shell, 1990; Snow, Kyllonen, & Marshalek, 1984).<sup>2</sup>

Nearly any task of at least moderate complexity—not only those explicitly assessing working memory capacity—requires some parallel retainment and processing of information or keeping track of a sequence of solution steps. Therefore, a reduction in working memory capacity could, in principle, account for age differences in a large scope of cognitive functions, such as reasoning (Horn, 1975; Welford, 1958), language production and comprehension (Cohen, 1979; Kemper, 1987), mental calculation (Campbell & Charness, 1990), or mental rotation (Hertzog & Rypma, 1991). In fact, as summarized in a comprehensive review by Salthouse (1990), there are numerous studies indicating that during processing at a complex task, older adults lose more task-relevant information than young adults (e.g., Arenberg, 1974, 1988; Arenberg & Robertson-Tschabo, 1985; Light, Zelinski, & Moore, 1982; Young, 1966). An example of old adults' reduced ability for retaining and processing information at the same time comes from a study conducted by Wright (1981). He used a procedure introduced by Baddely and Hitch (1974) in which a reasoning and a digit span task had to be performed concurrently. Old adults could retain only two digits without decrements in the reasoning task, whereas young adults' reasoning performance was only affected when more than three digits had to be recalled. Findings obtained by Salthouse and his colleagues (Salthouse & Mitchell, 1989; Salthouse et al., 1989) also suggested that not the mere quantity of information to be retained is of age-differential importance, but rather the number of operations that must be performed while preserving products of earlier processes. Similar conclusions, namely, that the active processing aspects of working memory rather than the storage component are affected by age were drawn by Craik and his colleagues (e.g., Gick, Craik, & Morris, 1988; Morris, Gick, & Craik, 1988).

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<sup>2</sup>In addition to processing speed and working memory, there is also a third potential age-related resource, namely, attentional capacity (e.g., Hasher & Zacks, 1979; Light, 1991). However, the notion of attentional capacity builds heavily on the distinction between active and passive processing which does not seem warranted in the light of recent evidence (e.g., Naveh-Benjamin, 1987). Also, in many ways, predictions made by the attentional capacity model are almost identical to those made by the working memory model. Therefore, this review will be selective in highlighting working memory as a possible age-related resource in addition to processing speed.

### *Speed, Working Memory, and Age Differences in Complex Tasks*

There is only little experimental research which provides information on the functional relations between working memory, processing speed, and performance in more complex tasks. Very likely, the reason for this is that speed and working memory measures usually yield dependent variables in different measurement spaces—latencies and accuracies—which are difficult to map onto each other. Currently, only correlational evidence is available from studies in which an attempt was made to account for age differences in complex psychometric tasks by controlling for speed, working memory, or both.

Salthouse (1985), for example, reports 43 task conditions from nine different studies and three task domains for which second-order correlations between age and task performance controlling for speed were available. Averaging across all task conditions, the speed-related proportion of the age-performance variance was about 75 percent. In many conditions, however, particularly some of the more complex ones, only very small amounts of the age-related variability could be accounted for by speed. Salthouse (1985) concludes from these findings that the results are mixed with respect to the cognitive slowing account. A comparable reduction of age-related performance variance after controlling for speed was also obtained by Horn, Donaldson, and Engstrom (1981). Clear support for the speed model came from a recent study conducted by Hertzog (1989) using multiple indicators for both speed and several more complex abilities. Here, for most domains, only between 10 and 20 percent of the age-related variance in performance was not explained by speed.

There are some data sets in which working memory measures were used as a predictor for age differences in complex tasks, such as memory for discourse (Hartley, 1986; Light & Anderson, 1985) or bridge-bidding (Charness, 1979). In all of these studies, attenuation of age differences was minimal after accounting for age differences in working memory. In two studies by Salthouse and his colleagues (Salthouse, 1988a; Salthouse, Kausler, & Saults, 1988), both speed and working memory measures were deployed. In the Salthouse (1988a) study, speed was the best predictor of age differences, and working memory, indicated by digit span and spatial memory, accounted for no additional age-related variance. In the Salthouse, Kausler, and Saults (1988) study, the overall age-related performance variability was smaller than the performance variance unique to age for both speed and working memory measures. However, clear



evidence in line with the working memory hypothesis was reported in a study by Tun, Wingfield, and Stine (1991): Age differences in concurrent choice reaction time (while learning a text for later recall) were eliminated when old and young were equated for working memory performance. In a multiple-indicator study conducted by Stankov (1988), speed measures accounted for about 75 percent of the age-related variability in fluid intelligence; working memory (here labeled short-term acquisition and retrieval) explained a little more than 50 percent. Finally, in a recent large-scale study by Salthouse (1991), three independent samples and two measures each of speed, working memory, and complex functioning (e. g., Raven, Analogies, Paper Folding) were used. The general finding was that (a) speed accounted for large amounts of the age-related variability in the complex functions, and (b) working memory did account for additional age-related variability beyond speed, but (c) large proportions of the age-related variance in working memory performance could be explained by speed. An additional aspect of this study was that working memory explained more age-related variance when for the complex task the proportion of correct items relative to the attempted items instead of the total number of correct items was used as dependent variable. This measure can be regarded as a post-hoc "simulation" of a power condition.

All in all, the findings from correlational studies using speed and working memory measures as predictors for age differences are mixed. If anything, evidence in favor of the cognitive slowing model is stronger than for the working memory model. The moderate failure of working memory measures to account for age differences in complex tasks stands in a peculiar contrast to both the repeated findings of older adults' high probability of losing relevant information during task performance (e. g., Arenberg & Robertson-Tschabo, 1985) and the "logical clearness of the theoretical position" (Tun, Wingfield, & Stine, 1991, p. 8). One reason for this might be, that in past research, measures of working memory were often unreliable and showed small convergent validity (e. g., Dobbs & Rule, 1989; Light & Anderson, 1985). In contrast, perceptual speed measures are usually very reliable. The difficulty of implementing reliable measures of working memory has raised doubts as to whether it is a unitary construct at all or whether there are multiple instantiations depending on the processing context or content (e. g., Carlson, Sullivan, & Schneider, 1989; Daneman, 1987; Hasher & Zacks, 1988; Navon, 1984). Recent research, however, has shown that it is possible to identify reliable measures which share considerable portions of variance (Carpenter, Just, & Shell, 1990; Kyllonen & Christal, 1990). Especially, the use of multiple indicators and structural equation modeling (Kyllonen & Christal, 1990)

could lead to a more precise representation of individual differences in working memory functioning.

When comparing the contribution of speed and working memory to age differences in complex tasks, it is also important to mention that there are no studies using experimentally derived measures of processing speed, such as memory search rate (Sternberg, 1969) or the difference score between a semantic and a physical match condition (Posner & Mitchell, 1967). Instead, psychometric measures are deployed, such as the Digit Symbol Substitution or Number Comparison. At least some of these tasks are of moderate complexity and require parallel processing, keeping track of prior steps, and memory activities. Thus, it is questionable whether they reflect true processing speed or a mixture of speed and some working memory components.

A similar problem is connected with the criterion measures of complex performance: In most studies reviewed above—including the one by Hertzog (1989) which yielded the largest support for the speed model—complex psychometric tasks were used under time-limited conditions (see also Hertzog & Schaie, 1988). Thus, these studies investigated whether speed measures are predictive of the ability to perform complex processes quickly rather than the ability to perform them in principle. Findings from Lohman (1989) indicate that measures of speed and maximum possible performance from the same task can represent quite different aspects of interindividual variability. In line with this, the study by Salthouse (1991) showed that the contribution of working memory was actually larger when the dependent variable used was more sensitive to accurate performance than to speeded performance. Also, from a testing-the-limits perspective, age differences in the principle ability to perform highly complex tasks should be especially severe (Kliegl, Smith, & Baltes, 1989; Schaie, 1990). Thus, the theoretically important question as to whether speed is successful in accounting for the limitations with respect to accurate functioning remains unsettled.

Finally, the principal limitation of all the research reviewed above is its correlational nature. Thus, it is not possible to distinguish between speed as a critical processing resource or speed measures as reliable indicators for some underlying mechanisms affecting cognitive performance in various conditions. There are some studies attempting to identify the functional relations between working memory and age differences in complex tasks (e.g., Light, Zelinski, & Moore, 1982). However, little research is available looking at the functional link between processing speed and complex task performance in an experimental setting. Of course, the main problem is that the critical variables, such as processing speed cannot be

manipulated. In this context, age simulation could be an interesting research strategy (Baltes, Reese, & Nesselroade, 1977; Goulet, 1972). The effects of age on complex functioning could be simulated through an experimental variation affecting variables which are considered important for complex performance, such as speed of processing in basic task components (e. g., through training of old adults or degradation of input stimuli for young adults). The critical question then would be how age differences in complex conditions constructed from the basic components are affected by this procedure.

Another approach would be to analyze age differences in task conditions that differ systematically in the requirements for each of the two resources relevant here—processing speed and working memory. A similar pattern of age effects across both task variations would indicate that a theoretical differentiation of resources is not necessary. Particularly large age effects in conditions with high working memory requirements, however, would suggest that working memory is an important age-related resource. Research that provides at least some information with respect to this issue will be presented in the following section.

### *Working Memory Functioning in Response Time Tasks*

To answer the question whether working memory constitutes an age-related resource besides processing speed, it would be important to compare age differences in complex tasks that require working memory activities and tasks that assess processing speed only. It is a plausible assumption that in complex tasks small working memory capacity should lead to problems with coordinating processing steps, and that the need to repeat processes or to recover lost information should require additional time (e. g., Bethell-Fox, Lohman, & Snow, 1984; Just & Carpenter, 1985).

Studies explicitly devoted to the investigation of age effects in working memory typically use accuracy as dependent variable, whereas studies focusing on speed usually use latencies. Also, the integration of latencies and accuracies in the context of cognitive aging is not very advanced (Cerella, 1985; see, however: Hertzog, Vernon, & Rypma, 1993; Salthouse & Somberg, 1982a). There are several studies, though, that deployed latency measures in tasks that involve a considerable amount of coordinative and memory management processes usually attributed to working memory. For example, in a study by Charness and Campbell (1988), young and old adults were trained across six sessions to perform a complex algorithm for squaring numbers, a task which involves a large

portion of memory management. A ratio between old and young adults of about 2.4<sup>3</sup> (derived from Charness & Campbell, 1988; p. 120, Figure 3) can be found for the mean latencies across four complexity levels of squaring problems.<sup>4</sup> In contrast, the mean ratio of the latencies for the single task components (e.g., simple addition and multiplication) was about 1.5 (derived from Charness & Campbell, 1988; p. 125, Figure 7).

Clark and Gardener (1990) recently conducted a study in which individual and age differences in verbal analogy performance were modeled using a task decomposition technique introduced by Sternberg (1977). With this method, the duration of single problem-solving components can be estimated. Only small age differences were obtained for the latency estimates of the simple processing components (encoding/inference, comparison), but very large relative differences were found for the more complex components (justification, response) theoretically involving reiteration through prior solution steps and metacognitive processes (Sternberg, 1984).

Of interest in this context are also studies using a response-speed measure within a secondary task paradigm because coordination of two tasks can be assumed to require working memory activities. Consistent with this expectation, in several studies response latencies of old adults have been shown to increase in an overproportional way when simple responses are to be performed in the presence of a concurrent task (Madden, 1986, 1987; Salthouse & Sauls, 1987; Tun, Wingfield, & Stine, 1991).

Finally, one type of tasks in which control and memory processes are assumed to play a major role are mental rotation tasks using complex stimuli (e.g., Hertzog & Rypma, 1991; Just & Carpenter, 1985; Lohman, 1988). According to this view, spatial transformations of complex stimuli often cannot be executed in one step but require a sequence of transformations, retainment of intermediate products, and rechecking.<sup>5</sup> Just and Carpenter (1985), for example, proposed that individuals who exhibit low performance in rotating three-dimensional figures (a) rotate at a slower

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<sup>3</sup>The ratio can be regarded as a proxy of the slowing factor; it represents the slope of the proportional slowing function assuming a zero intercept.

<sup>4</sup>For reasons of comparability with the other studies reviewed here, reference is made only to the data from the first session.

<sup>5</sup>The claim that internal spatial transformations are performed in a stepwise manner does not imply a commitment to one of the two positions assuming either analog, imagined transformations (e.g., Kosslyn, 1981; Shepard & Metzler, 1971) or discrete, propositional processes (Pylyshyn, 1973). A complex stimulus can be transformed in a stepwise manner, while the single steps are still—at least in part—analog processes (Bethell-Fox & Shepard, 1988).

rate and (b) have "... more difficulty in keeping track of intermediate products, resulting in reinitializations of various processes" (p. 162). In line with this, Hertzog and Rypma (1991) have recently shown that old adults exhibit slower rotation rates than young adults, but at the same time also require considerably more post-rotational processes which the authors attributed to their degraded working memory representation. As mentioned above, all of the more complex tasks in the meta-analysis by Hale, Myerson, and Wagstaff (1987) are mental rotation tasks. Moreover, data points from these tasks are largely responsible for the nonlinear, upward deviation in the direction of increased age differences. Taken together, all studies which assessed age differences in speed of rotating complex stimuli (Berg, Hertzog, & Hunt, 1982; Gaylor & Marsh, 1975; Sharps & Gollin, 1987), an old-young ratio of more than 2.0 can be found. This clearly is more than the slowing factor of about 1.6 found in meta-analyses of simple response time tasks and thus is consistent with the assumption of a particularly large age difference for mental rotation tasks.

The findings reported above suggest that tasks involving working memory activities do produce large age differences in terms of response speed. For the time being, however, the question has to remain open whether a discontinuity between age effects in simple and more complex tasks actually exists. Instead of a model assuming two distinct sources of age-specific limitations also a model proposing a continuous but nonlinear increase of age effects with complexity could hold (Cerella, 1990; Myerson et al., 1990). To resolve this issue, it would be necessary to conduct studies in which latency is used as dependent variable and, at the same time, working memory load is manipulated systematically.

Finally, an additional prediction can be made with respect to age effects in speeded tasks that involve working memory components. If it is true that the reduced working memory capacity of old adults can lead to a breakdown of performance with the need for repeating processing steps, then this should not only produce larger mean response times. In addition, the distribution of latencies should be particularly skewed to the direction of very long latencies for old adults but not for young adults. This prediction follows from the assumptions that (a) loss of information and breakdown of performance is a probabilistic phenomenon that occurs only in a certain proportion of items, and (b) this proportion is larger for old adults than for young adults. Thus, individual latency distributions of old adults should contain a large number of items with very long processing times reflecting time-consuming recursions and recovery pro-

cesses. In contrast, when distributions are similar across age groups, a more low-level aging process affecting all items in a uniform way, such as a general reduction of processing speed, would be indicated.

Recently, it was argued that distributional characteristics of response times represent important information to be considered in cognitive research (e.g., Heathcote, Popiel, & Mewhort, 1991; Townsend, 1990). In the context of cognitive aging, the investigation of latency distributions is only just beginning (Allen, 1990; Myerson et al., 1990). In the current study, distributional characteristics will be used besides mean latencies as an additional source of information to evaluate the hypothesis that working memory functioning can affect response times in speeded tasks.

### *Conclusion*

Past research does not allow to discriminate between the two conceptualizations of resources, processing speed and working memory, with respect to their importance for age differences in complex tasks. In general, speed measures account for a large portion of age-related variability. It is unclear, however, whether (a) speed actually is a resource in a functional sense, and (b) whether additional age-related resources, such as working memory, contribute to age differences at least in certain conditions. In line with a working memory hypothesis of cognitive aging, age differences seem to be particularly large in tasks requiring parallel retainment and processing of information. So far there is, however, almost no research explicitly aimed at this question. Finally, it is proposed that analyzing latency distributions can provide additional information relevant to identifying processes that lead to age-related decrements in speeded tasks.

The issue of basic sources of age-related changes in intellectual abilities touches upon a more general question: What determines interindividual differences in complex cognitive functioning? It is possible that relations that hold for individual differences can be applied to the special case of age differences. Thus, at this point it is useful to look at some of the research dealing with interindividual differences in cognitive functioning among age-homogeneous groups.

## Task Complexity and Interindividual Differences

### *Reductionist Approaches*

The central aspect of the resource accounts of cognitive aging is the reductionist effort to attribute age-related differences in a variety of cognitive tasks to basic parameters of the cognitive system. In the research on (non-age-specific) interindividual differences in intellectual functioning, similar attempts have been made. There was—and in part still is—a particularly strong effort to explain efficiency in complex, psychometric intelligence tasks in terms of the speed of executing simple cognitive tasks or task components. Three different approaches of this kind can be distinguished: (a) the attempt to relate performance in intelligence tests to performance in choice reaction time tasks (e.g., Jensen, 1987), (b) the cognitive correlates paradigm (e.g., Hunt, 1978), and (c) the cognitive components paradigm (e.g., Sternberg, 1977).

### *Intelligence-Reaction-Time Relationships*

The central feature of the first approach is the assumption that speed of performing basic decisions (choice reaction time) is indicative of a general cognitive efficiency (often, identified with “g”) which, in turn, should determine the level of performance in complex psychometric tasks, as for example, Raven’s matrices (e.g., Carlson, Jensen, & Widaman, 1983; Jensen, 1982; Jensen & Munro, 1979; Vernon, 1983). Studies conducted within this framework usually report correlations between psychometric tasks and one or more parameters derived from reaction time tasks.

The theoretically most relevant parameter is the slope of reaction times as a function of the number of choices. The slope is assumed to represent the rate of information gain (Hick’s paradigm; Hick, 1952). Unfortunately, correlations between ability measures and the reaction time slope are usually rather low. Jensen (1987) reports a mean of .16 across more than 30 studies. Also, the other, theoretically less meaningful, parameters rarely account for more than 10 percent of the ability variance (for a critical review, see Keating & McLean, 1987). Thus, these results are not a very strong support for the hypothesis that speed of performing simple decisions contributes in an important way to complex cognitive functioning.

### *Cognitive Correlates*

The cognitive correlates approach constitutes a somewhat more differentiated attempt to identify sources of interindividual ability variance. Not one general resource is proposed, but several component skills. Also

here, mostly correlative techniques were used. The predictors of psychometric ability are derived from experimental paradigms that are designed to measure specific processing skills which are theoretically relevant with respect to the criterion task (e.g., Carroll, 1988; Hunt, 1978; Hunt, Lunneburg, & Lewis, 1975). For example, a task representing speed of lexical access (lexical decision) would be regarded as a critical component for verbal comprehension (Hunt, Davidson, & Lansman, 1981), whereas mental rotation speed (Shepard & Metzler, 1971) would be expected to play an important role for spatial ability tasks (Keating, List, & Merriman, 1985). Usually, correlations obtained this way are small to moderate, indicating that some, but not all of the ability variance can be accounted for by simple cognitive measures. Problematic is the fact that often not the theoretically relevant parameters (e.g., rotation speed), but, for example, overall response speed show higher correlations (e.g., Lansman et al., 1982). Also, little attention has been devoted to questions of convergent-discriminant validity. Keating, List, and Merriman (1985), who did approach this problem using cognitive measures and ability tests from both the spatial and the verbal domain, obtained rather disappointing results: Not only were overall correlations between abilities and specific skills low, they also did not show the expected pattern of high within- and low between-domain correlations.

### *Cognitive Components*

Finally, the third attempt to trace complex abilities to basic processes employs precuing and mathematical modeling techniques to identify task components critical for interindividual differences. Sternberg (1977, 1983; Sternberg & Gardener, 1983) has been the main proponent of this approach. His attempt to identify components of inductive reasoning, especially analogical problem solving, was elegant and produced important insights into processes of problem solving. Yet, it is questionable whether Sternberg actually succeeded in identifying invariant components of inductive reasoning which carry substantive interindividual variance. To name only a few problems: In general, Sternberg constructed simple reasoning problems so that purely additive models could be fitted. This means that the overall latency was solely determined by the composite of the latencies for the components. Nevertheless, the degree of fit depended strongly on the complexity of the different sets of problems: The more complex the problems, the worse the model fit indicating additional processing not captured by the specified basic components (Keating, 1984). Another point of critique was that across different studies different components were specified, so that the processing mod-



els constructed were rather task-specific (e. g., Neisser, 1983). Also, correlations between task components and ability measures were often not very meaningful. For example, the encoding and the response component showed higher correlations than the components representing activities specific for solving analogies (Keating, 1984; Sternberg, 1990). It is possible that some of these problems are a result of the fact that Sternberg attempted to fit strictly linear models without leaving the possibility for interactions between processing components. Such interactions could represent memory management and coordinative activities which have been shown to be critical for more complex tasks (e. g., Carpenter, Just, & Shell, 1990; Charness & Campbell, 1988; Mullholland, Pellegrino, & Glaser, 1980). Sternberg (1990) acknowledged most of the above problems. Specifically, in reaction to the critiques regarding the use of purely additive processing models, he proposed so-called metacomponents responsible for executive and monitoring activities.

These three approaches, although diverse, yield as a common message that the whole is more than the sum of its parts: Complex cognitive performance as measured in psychometric intelligence tasks resists reduction to a set of basic "building-blocks" of cognition or a single general parameter of the cognitive system. In line with this conclusion, Kyllonen and Christal (1990) recently evaluated the cognitive correlates and the cognitive components approach as a "modest failure" (see also Keating, 1984; Keating & McLean, 1987; Salthouse, 1985; Sternberg, 1990).

### *Characteristics of Complex Processing*

Present research on interindividual differences in intellectual functioning is taking new directions. Both psychometric and cognitively oriented efforts increasingly consider complexity as an ability-relevant dimension in its own right. Two recent examples of such attempts, a psychometric and a cognitive approach to complexity, are reviewed briefly in the following sections.

#### *Psychometric Approach to Complexity*

Based on earlier work by Guttman (1965), Snow, Kyllonen, & Marshalek (1984; Marshalek, Lohman, & Snow, 1983) used nonmetric scaling techniques to reanalyze intercorrelation matrices of psychometric tasks. The major finding was the so-called "radex map" of abilities: Tasks, grouped together with respect to domains, are located around a center representing maximum complexity. Usually, complex reasoning tasks of different

domains (e.g., Raven, Letter Series) define the center; the less complex a task, the more it is located in the outer regions of the radex. For example, typical psychometric speed measures (e.g., Digit Symbol Substitution) have maximum distance from the center. The authors suggested that the complexity dimension could represent requirements on "... executive assembly and control processes that organize and monitor the operation of response components assembled into a performance program for the task" (Snow, Kyllonen, & Marshalek, 1984, p. 94). These activities come close to what usually is regarded as a property of working memory. Convincing support for the latter proposition was recently reported by Kyllonen and Christal (1990). The data of four independent large-scale studies ( $N > 600$ ) using multiple indicators for reasoning, working memory, perceptual speed, and knowledge were fitted by a factor structure in which the working memory factor had a very high correlation (i.e., in all four studies, more than .80) with the reasoning factor. In contrast, the relationship between perceptual speed and reasoning was only about .30. Thus, for reasoning tasks, which typically represent the center of the complexity radex, working memory and not so much speed of simple mental operations appeared to be critical.

#### *Cognitive Approach to Complexity*

The cognitive approach to complexity is characterized by the attempt to fit processing models to existing complex tasks (e.g., Bethell-Fox, Lohman, & Snow, 1984; Carpenter, Just, & Shell, 1990; Mulholland, Pellegrino, & Glaser, 1980) rather than—as, for example, in parts of the work by Sternberg—to construct tasks to fit simplistic models (Neisser, 1983). For example, in a study by Mulholland, Pellegrino, and Glaser (1980), this strategy led to a processing model of analogical problem solving that includes working memory activities in the form of interactions between task components. Similarly, in a careful study Carpenter, Just, and Shell (1990) used verbal protocols and registration of eye-movements to link interindividual differences in the Raven's matrices to the ability for parallel management of various goals. The authors succeeded in the construction of computer simulations of "fair" and "best" problem solvers by varying the number of subgoals that could be handled in working memory.

#### *Conclusion*

There is little evidence indicating that performance in complex tasks is a direct function of performance in simple tasks: Correlations between

simple measures of response latencies and complex psychometric tasks are low, and purely additive processing models do not account for individual differences in a satisfying way. Rather, recent research points to the importance of coordinative processes usually attributed to working memory.

What can be learned from this excursion into the field of interindividual differences with respect to age-related changes in complex cognitive performance? Of course, one has to be careful not to make precipitate analogies between individual and age differences. It is still to be shown that relationships holding for individual differences can be generalized to age differences in cognitive functioning. What the above research, however, suggests is that there is a discontinuity between performance of simple tasks or task components and complex cognitive processing. For example, high-quality performance in complex tasks seems to be possible despite low speed of processing and vice versa. Therefore, it is at least a plausible proposition that speed of processing is not the only relevant explanatory variable in the context of age-related decline in cognitive functioning. Recent research on individual differences highlights the importance of working memory functioning for complex task performance.

A second aspect has to be mentioned: What in interindividual differences research is perceived as a variation of complexity, namely, manipulation of task demands in terms of coordinative and assembly processes, is severely underrepresented in research on age differences in speeded tasks. In the latter context, any task manipulation that leads to an increase in response times is regarded as a variation of complexity; as a consequence, mostly simple task conditions were used involving only little coordinative demands. In the present research, it will be argued that a more differentiated picture about the role of task complexity in cognitive aging can be achieved when both the “simple” and the “coordinative” aspects of complexity are taken into consideration.

### **Aging, Learning, and Complexity**

So far, the question of age differences and how they are determined by task complexity was only considered with respect to status assessments of cognitive performance. From a perspective that emphasizes latent competence, the main interest, however, focuses on the possible range of functioning. As already indicated in earlier sections, inferences about true limitations in latent competence, that is, developmental reserve capacity,

should ideally be based on age effects which are stable despite cognitive intervention. Therefore, it is of particular interest to find out (a) whether learning and skill acquisition efficiency is subject to age-related decline (e.g., Salthouse & Somberg, 1982b) and (b) whether age differences in learning are modulated by task complexity.

Learning can be regarded as a core feature of cognitive systems (Anderson, 1983; Hilgard & Bower, 1975; Kausler, 1991; Sternberg, 1990). From a developmental perspective, learnability determines the "zone of proximal development" (Vygotsky, 1978). Consequently, the question of differences in learning and skill acquisition between individuals (e.g., Ackerman, 1987; Cronbach & Snow, 1977; Ferarra, Brown, & Campione, 1986; Fleischman, 1972; Thorndike, 1908; Woltz, 1988) and also between adult age groups (e.g., Kausler, 1991; Ruch, 1933; Salthouse & Somberg, 1982b; Snoddy, 1926; Thorndike et al., 1928; Woodruff-Pak & Thompson, 1988) has stimulated research endeavors across the century.

With respect to the question of age differences in learning efficiency, a rather clear picture has emerged from past research for either "low-level" abilities or for verbal learning, that is, the domain of episodic memory. For example, old adults respond to classical conditioning (e.g., Woodruff-Pak & Thompson, 1988) or exhibit improvements in motor learning (Wright & Payne, 1985), yet to a markedly smaller degree than young adults. Similarly, it is almost a truism that old adults show deficits in virtually all verbal learning tasks (e.g., Craik & Rabinowitz, 1984; Kausler, 1991).

The domain of the current study, however, encompasses typical cognitive tasks in which emphasis is placed not so much on the acquisition of simple environmental contingencies or a large amount of facts, but rather on the continuous refinement and routinization of a set of mental rules or operators (Anderson, 1987; Kyllonen & Woltz, 1988). In this context, the issue of age-related changes in skill acquisition is currently being heavily debated (Cerella, 1991; Fisk & Rogers, 1991; Fisk, McGee, & Giambra, 1989; Myerson et al., 1990). On the one hand, proponents of the general slowing account claim that age differences in cognitive tasks across various levels of learning or practice are determined by age differences in processing speed in a highly similar way (see *Speed as an Age-Related Processing Resource*). This implies that rate and amount of skill acquisition are not affected by age (Cerella, 1990; Myerson et al., 1990). On the other hand, some researchers propose specific age-related learning deficits (e.g., Fisk & Rogers, 1991). Also, from a perspective claiming that latent potential is reduced as a function of age, less learnability would be expected for old than for young adults (Kliegl, Smith, & Baltes, 1989). As

will be shown in a review of the relevant literature, supporting evidence can be found for each of the two opposing views. But first, some considerations about potential sources of individual and age differences in the acquisition of cognitive skills will be presented based on a cognitive perspective on skill acquisition.

### *Mechanisms of Skill Acquisition*

On a descriptive level, there is consensus among different theories of skill acquisition regarding the effects of practice on performance. Whereas initial processing is described to be slow, error-prone, and flexible, performance after a large amount of practice in consistent environments is generally fast, resource insensitive, and difficult to alter (Anderson, 1983; Fitts & Posner, 1967; Schneider, 1985; Schneider & Shiffrin, 1977). Also, for a great variety of tasks, the skill acquisition curve appears to follow a power function, that is, learning proceeds in a negatively accelerated way (Logan, 1988; Newell & Rosenbloom, 1981; Shrager, Hogg, & Huberman, 1988).

Theories differ with respect to the proposed mechanisms leading to the observed change of performance with practice. The most comprehensive theory to date, incorporating ideas from earlier or more specific accounts (e. g., Fitts, 1964; Newell & Rosenbloom, 1981; Thorndike, 1908), is the learning module of Anderson's ACT\* model (1983). Anderson assumes that at the beginning of training, performance is determined by easily accessible and flexible, declarative knowledge structures. Quantity and quality of this task-relevant knowledge base is assumed to be constrained by working memory capacity (Anderson, 1987). During execution, the declarative operators are "compiled" into productions. A production can be thought of as an if-then rule which fires automatically as soon as the working memory content fits the condition clause. The main advantage of proceduralizing declarative knowledge is that processing becomes faster and that working memory is freed from otherwise resource-demanding activities. Once an operator is proceduralized, it can be affected by a second important learning mechanism: Single productions can be collapsed into larger ones by the process of composition. On the one hand, this process leads to an increase in speed and reduces the amount of information to be handled in working memory. On the other hand, the size of collapsed productions is proposed to be constrained by the relevant information which can be held in working memory simultaneously (Anderson, 1983; Woltz, 1988). Both learning mechanisms,

proceduralization and composition, occur automatically once the relevant knowledge is provided from working memory and lead to less resource-sensitive processing. However, the quantity and quality of the representation of task-relevant knowledge in working memory determines (a) the degree to which task-appropriate productions can be developed and (b) the size of composed productions. Thus, learning itself can be assumed to be resource-sensitive in certain conditions, namely, when the working memory load imposed by the task is high.

The problem of differential learnability is not within the explicit scope of Anderson's model. Nevertheless, it identifies working memory capacity as an important modulator of skill acquisition efficiency and, consequently, as a potential source of interindividual or age differences. Working memory constraints on learning should, however, become apparent only in tasks with high demands on coordination of processes and handling of task-related knowledge.

### *Individual Differences in Learning and Skill Acquisition*

The notion of working memory capacity has only very recently been introduced to the research on interindividual differences in learning and skill acquisition. Earlier studies which attempted to establish an empirical relationship between learning and general cognitive abilities (which can be assumed to reflect at least in part working memory processes), were not very successful (e.g., Fleishman & Hempel, 1955; Woodrow, 1938). From the working memory perspective, this failure is not too surprising because, mostly very simple learning tasks with small demands on cognitive resources have been used. Also, interpretability of results can be questioned because of severe methodological problems, such as the issue of baseline performance and the scaling of the learning score (for reviews, see Ackerman, 1987; Cronbach & Snow, 1977). More recently, Snow, Kyllonen, and Marshalek (1984) reported reanalyses of two earlier studies by Allison (1960) and Stake (1961) both of which deployed learning tasks differing in complexity and diverse psychometric measures as predictors of learning gains. The general finding from the two studies was that the relation between learning gains and psychometric intelligence was small to non-existent when learning was assessed in simple perceptual or motor tasks. However, this relation increased dramatically with the complexity of the learning task. Consistent with the notion of working memory as a constraining factor of skill acquisition, Snow, Kyllonen, and Marshalek (1984) attributed the latter effect to the shared component of

executive and assembly processes involved in both complex psychometric abilities and learning of complex skills. Of particular importance is also a recent study by Woltz (1988) which explicitly investigated the role of both working memory load and working memory capacity on the rate of skill acquisition. Using a complex response time task in which participants had to consider multiple if-then rules, the author showed that skill acquisition proceeded faster in a condition with low working memory demands than in a condition with high working memory demands. Also, learning rate depended on two aspects of working memory: (a) the ability to retain and process information simultaneously and (b) a newly introduced construct, namely, activation capacity.<sup>6</sup> An interaction between working memory demands of the task and working memory capacity as an individual differences factor was found for performance accuracy but not for latencies. The latter result might be due to the fact that even in the conditions with low-working memory demands, quite a large amount of task-relevant information had to be handled. In any case, this research supports the proposition that working memory efficiency is a constraining factor on skill acquisition not only at the beginning of practice but throughout.

To sum up, research on interindividual differences in learning is consistent with theories of skill acquisition in identifying working memory as a resource that constrains the rate of learning. In general, results support the notion of a relationship between psychometric abilities or working memory capacity, on the one hand, and learning rate, on the other. This relation, however, only exists when the skill under observation actually is sufficiently complex, thus requiring the assembly of multiple component processes (Snow, Kyllonen, & Marshalek, 1984). Based on this observation and on the assumption that working memory capacity declines with age, one can expect less learning for old adults than for young adults for complex skills. In the following two sections, age-differential learning experiments will be reviewed—first portraying research using simple tasks, then studies in which more complex skills were practiced. The guiding questions will be (a) whether the rate of learning differs between age groups and (b) whether—according to the working memory perspective on skill acquisition—age differences in learning increase as a function of task complexity.

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<sup>6</sup>Activation capacity was conceptualized as the efficiency of the spread of activation in semantic memory. It had a small effect on the learning rate but its importance increased in later stages of learning. In a subsequent study, this effect could not be replicated (Kyllonen & Woltz, 1989). Therefore, the question whether activation capacity actually represents a new and important construct in interindividual differences and learning research has still to be settled.

## *Age-Comparative Intervention Studies*

### *Simple Tasks*

The distinction between simple and complex tasks is somewhat arbitrary. In the current context, however, it seems warranted to use the amount of working memory load as a criterion. Thus, only those studies are reviewed in this section that (a) use tasks in which little task-relevant knowledge has to be processed and (b) require little coordination and assembly of subprocesses. As will be seen below, such a categorization cannot always be made in a clear way. In general, however, based on the working memory account of individual differences in skill acquisition, only small age differences in the rate of learning are to be expected here.

A variety of simple tasks were used to assess learning and amount of improvement across the life-span. One primary motivation of this research was to clarify the question whether age effects are reversible and thus mostly a function of experiential factors, or whether they are stable despite interventions and thus probably more determined by biological and physiological aspects (Murrell, 1965; Salthouse & Somberg, 1982b).

For example, Murrell (1970) exposed two young women and a 57-year-old woman to 12,000 trials in a simple reaction time task. The old participant eventually reached the same level of performance as the two young adults. The findings of other age-differential intervention studies using more subjects and less training were not as dramatic. Jordan and Rabbitt (1977), who also used a reaction time task reported somewhat more improvement for old adults than for young adults, but no elimination of age differences. In a study by Hertzog, Williams, and Walsh (1976), old and young adults exhibited equal rates of improvement, but stable age differences throughout practice in a tachistoscopic perception task.

One of the most widely used measures in research on intellectual aging is the Digit Symbol Substitution (Wechsler, 1964). This task involves the placement of symbols under a series of numbers according to a coding key. It is a measure in which effects of aging usually are very pronounced (e.g., Birren & Morrison, 1961; Salthouse, 1985). Grant, Storandt, and Botwinick (1978) trained adults in twenty 30-second trials with the same coding key across trials. Old and young adults exhibited similar improvement, although there was a very small but significant magnification of age differences through learning. In a study deploying a more extensive five-day training program with varying coding keys, Beres and Baron (1981) revealed similar practice gains for old and young adults. However, the authors stated that: "If anything, training had the opposite effect of



tending to increase differences.” (Beres & Baron, 1981, p. 598) In a short one-session training program in which subjects had to indicate whether given pairings were correct (thus reducing the motor component), Salthouse (1978) found a similar practice gain for young and old adults. Finally, in a five-session training study by Wu, Xu, Sun, and Kliegl (1990), old and young adults exhibited fairly similar training gains.

Most age-comparative training studies were probably conducted in the domain of visual and memory search. The search paradigm is of special interest to researchers in the field of cognitive aging, because it provides an ideal experimental setting for investigating the automatization of cognitive processes (Schneider, 1985; Schneider & Shiffrin, 1977). Typically, in these tasks participants have to compare short-term memory content or a visual array with a target item. In so-called hybrid search tasks, both the search and the target set vary systematically in size. Automatization should take place when stimuli and responses are consistently mapped (i.e., no overlap between target and nontarget stimuli throughout practice). In inconsistent mapping conditions (i.e., overlap between targets and nontargets), only small improvement is to be expected. The main dependent variable is the response time slope of as a function of the comparison set size. The size of the slope reflects the rate of search, whereas the intercept captures the more peripheral processes (Sternberg, 1969). When the search is automatic, the slope should be zero, which means that the search rate is not affected by the size of the comparison set.

Several studies have addressed the question whether both young and old adults profit in consistent search conditions in the same way. For example, Madden and Nebes (1980) report a study in which old and young adults were exposed to nine days of practice on a consistent hybrid visual and memory-search task. Gains in comparison slopes were comparable for both young and old adults. The authors concluded that age groups did not differ in the rate at which automaticity was developed. The picture looks a little different when calculating young and old adults' proportional gains for the search rates.<sup>7</sup> Whereas young adults showed an

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<sup>7</sup>Assuming that learning leads to a reduction of processing steps (Anderson, 1983; Newell & Rosenbloom, 1981) and that old adults perform each processing step proportionally slower than young adults equal learning would lead to larger absolute learning effects for old adults than for young adults (Myerson et al., 1990). Proportional gains compensate for this effect and therefore, very likely, lead to a better representation of age-differential improvement than raw latencies (Cerella, 1990). Most age-differential intervention studies, however, rely solely on raw latencies as dependent variable. In this review, proportional gains are reported whenever possible. As they had to be calculated from the reported group means, no statistical tests could be conducted.

improvement of 60 percent for positive, and 74 percent for negative items, percentages for old adults were 40 and 36 percent, respectively. In contrast, old adults exhibited more relative improvement than young adults for the intercept. A similar pattern of results was observed in a study conducted by Madden (1983), which, again, exposed old and young adults to a hybrid search task. When considering absolute latencies, both age groups improve their search behavior in about the same manner as suggested by a nonsignificant age-by-session interaction. But again, percentage gains of search rates were larger for young adults than for old adults (75% vs. 33%). Both age groups exhibited nearly equal gains for the intercepts.

Plude and Hoyer (1981) investigated training gains in a hybrid memory and visual search task in both consistent and inconsistent mapping conditions over six sessions. They found that baseline age differences were preserved in the inconsistent mapping condition, whereas age differences in the consistent mapping condition were relatively small. Old adults reached an asymptotic level of performance in the same session as young adults, thus learning seemed to be similar for both age groups. However, no information about latencies across the practice procedure was provided, so that further evaluation of the results in terms of proportional gains is not possible. Also a study by Plude et al. (1983) which, again, used consistent and inconsistent mapping conditions of a hybrid search task, revealed similar learning for old and young adults in the consistent mapping condition. Older adults, however, needed somewhat more practice than young adults to reach the asymptote. Again, no descriptive practice-related information was provided, so that proportional gains could not be computed.

In one of the most extensive, age-comparative studies, Salthouse and Somberg (1982b) provided 52 sessions (5,000 trials) of practice on a consistent mapping memory search task using complex figural stimuli. They found larger gains for old adults compared to young adults in both absolute and relative terms and both in the intercept and the slope parameter. Comparison slopes were similar for both old adults and young adults at the end of practice indicating equivalent search rates. This finding of a reduction of age differences through training does not necessarily mean that old adults actually learned more than young adults. As suggested by the authors, it probably indicates that both old and young were able to routinize processing to such a degree that age-sensitive resources were no longer necessary for task solution. Salthouse and Somberg (1982b, p. 202), who also conducted additional simple training tasks in the same experiment concluded: "... the acquisition and retention

of simple perceptual and cognitive skills over long periods is not impaired with increasing age.”

In none of the studies were young or old adults actually moved to the state of automatized processing, at least when one adopts the zero slope criterion introduced by Schneider and Schiffman (1977; see Logan, 1978, 1979 for further discussion regarding this criterion). In a study by Fisk, McGee, and Giambra (1988), old and young adults were trained for 14 sessions in a semantic category search task. Whereas young adults reached the level of automatic processing (zero slope) at the 7th session, old adults continued to exhibit large slope values throughout the whole training procedure. Thus, young adults exhibited a 100 percent improvement whereas old adults' gain was only about 50 percent. Fisk, McGee, and Giambra (1988, p. 331) concluded that "... early (...) practice effects found with old adults may not be predictive of later development of automatic processing." The semantic category search task used in this study was more complex than the search tasks generally used in age-comparative research. Therefore, the status of this result with respect to the rest of the literature is not clear.

Recently, Fisk and Rogers (1991) reported a series of three experiments which integrated most aspects manipulated in prior research. They exposed participants to a full factorial combination of one to three item sets both for target and search sets, so that pure visual, pure memory, and hybrid search conditions were realized. Experiment 1 consisted of six practice sessions in consistent letter search, Experiment 2 of twelve sessions in consistent, category search and Experiment 3 of six sessions in varied category search. Analyzing raw latencies with analysis of variance of raw latencies, the authors reported as the main result that young adults were able to reduce their search rate in the consistent visual and hybrid search conditions to a much larger degree than old adults. No age-differential effects were, however, found for the pure memory search. As Experiment 2 closely resembled the Fisk, McGee, and Giambra (1988) study reviewed above, it is interesting to note that the strong age-differential effect found in the earlier study (with a zero slope for young adults and a substantial slope for old adults at the end of practice) was much smaller in this study (in particular young adults did not reach automatic performance).

In a reply to the Fisk and Rogers (1991) study, Cerella (1991) questioned the finding of an age-specific learning deficit from the perspective of general slowing models of aging. His main point of critique being that analysis of raw latencies does not do justice to the general complexity effect (see *The Complexity Effect* and Footnote 7), he convincingly

showed that almost *all* data points throughout practice can be accounted for by one general slowing function. Thus, contrary to the authors' interpretation, this impressive data set probably contains little evidence for condition-specific age differences in learning. Rather, age effects seemed to be governed by general slowing at the beginning and at the end of practice irrespective of visual or memory-search set sizes. In the same reply, Cerella also extends his analysis to other age-differential training studies using visual search. Here he tries to make the point that age differences in response times at the end of practice are determined by exactly those slowing functions usually found in single-session experiments. In fact, with a mean slowing factor of 1.81 across age-differential search studies, quite similar values emerge compared to a factor of 1.68 he reports from other age-differential studies. The variability of slowing factors across studies using the search paradigm was, however, very large (between .98 and 2.63). Also, Cerella did not distinguish the intercept from the slope of the memory or visual search function, but used overall response latencies instead. Only the slopes are the actual interesting parameter in this context, and age-differential effects in the search function could easily be clouded by looking at overall response times only.

In summary, three important aspects emerged from this review of age-comparative intervention studies using simple tasks: (a) In most cases, practice did not lead to an elimination of age differences. This result indicates age-related limitations of plasticity which are not modifiable by experiential factors. (b) In general, age-differential learning effects are scarce and small. The dominant pattern of results is that old and young adults improve in a rather similar way in simple tasks. This is in line with the assumption that in tasks with small working memory demands, mechanisms of learning are not affected by age. Rather, it seems that in these tasks age differences are determined across practice by a general cognitive slowing effect as suggested by Cerella (1990, 1991) and Myerson et al. (1990). (c) With respect to search tasks, the pattern of results was more complicated. When looking at the overall latencies or at the intercepts of the search-set functions, learning was similar for old and young adults. This is also in line with the conclusion of recent reviews of age-comparative studies on visual search presented by Cerella (1990, 1991). Findings were, however, more inconsistent with respect to the slope of the comparison-set function. At least in some of the studies and depending on the measure one regards as more relevant (i.e., absolute or proportional gains) learning gains are similar for both age groups or old adults exhibit less improvement than young adults. Negative age effects in proportional gains could be observed especially in the hybrid search task.

According to Plude and Hoyer (1981), the hybrid search constitutes a double-task condition and thus involves more coordinative processes than other search tasks. In line with this, Rogers and Fisk (1990) recently stated that the hybrid search involves a component of coordinating the switch between memory set and display items which possibly affects older adults' learning in a negative way. Finally, there were indications that old adults, compared to young adults, have problems in reaching the final state of automaticity in a category search task (Fisk, McGee, & Giambra, 1988). However, given that several factors are varied across studies, final conclusions are difficult to draw. If anything, old adults' rate of improvement appears to be constrained in those tasks that involve some degree of coordinative processes.

### *Complex Tasks*

The search for age-related training effects in basic tasks is important for understanding processing limitations across the life-span. However, the findings obtained from simple tasks are not necessarily applicable to more complex skills. This is especially true as the relation between basic cognitive tasks and tasks with more complex problem solving or reasoning demands seems to be low (Keating & McLean, 1987). Complicating matters further, only a few age-comparative studies in which more complex intellectual skills were trained have been carried out (Charness & Campbell, 1988). An early exception is a study by Thorndike et al. (1928) in which young and old adults (between 35 and 57 years of age) learned the artificial language Esperanto. Older adults exhibited about 28 percent less learning than young adults at least in some measures. It has to be noted, however, that acquisition of a new language probably contains at least as much episodic learning as procedural learning components.

In a more recent study, Berg, Hertzog, and Hunt (1982) exposed adults of four age groups to a four-session practice procedure in a moderately complex mental rotation task. As argued in an earlier section, spatial transformations, most likely, require working memory and coordinative activities. Latencies for the most complex conditions were about two seconds for young and between three and five seconds for the oldest group. Although there was no significant age  $\times$  session interaction with respect to the speed of mental rotation (i.e., rotation slopes), proportional gains were larger for young adults than for old adults (males: 54% vs. 14%; females: 51% vs. 27%).

Charness and Campbell (1988) conducted a study in which young, middle-aged, and old adults practiced a complex algorithm for squaring two numbers. The baseline solution time for the most complex problem

was about 40 seconds for old adults and 20 seconds for young adults. Across six sessions of practice this time was reduced by about 50 percent for both age groups indicating equal (proportional) learning. There were some indications that old adults had greater difficulty in establishing a smooth control routine linking subprocesses than the middle-aged adults. However, the general finding was that "... learning proceeded essentially in the same way for the three age groups" (Charness & Campbell, 1988, p. 127)—a conclusion which is clearly inconsistent with the working memory perspective on individual differences in skill acquisition. It is important to consider though that, although the task was rather complex, subjects essentially had to learn to combine overlearned component processes (e. g., mental calculation) into a smooth algorithm. Perhaps old adults would be more at a disadvantage in a complex skill in which less preexisting knowledge about component processes is available.

In a study by Kliegl, Smith, and Baltes (1989), old and young adults received extensive training in a mnemonic skill (method of loci). To enhance recall performance participants had to generate interactive images combining certain locations with words. Although old adults could achieve a remarkable level of performance, posttraining age differences were larger compared both to pretest performance and age differences normally reported in the literature (distributions of the age groups showed almost no overlap). Using the same paradigm, Thompson and Kliegl (1991) assessed the encoding times required by young and old adults for meeting a criterion of 50 percent correct recall in a six-session adaptive criterion-referenced training and testing procedure. Using raw encoding times, no significant age  $\times$  session interaction evolved. But in terms of proportional gains between the first and the sixth session, young adults exhibited more relative improvement (67% vs. 32%; extracted from Figure 2, p. 547). The latter findings are consistent with the proposition that plasticity declines with age and that age effects are most pronounced at the limits of plasticity (Baltes, 1987; Kliegl, Smith, & Baltes, 1989).

### *Conclusion*

What conclusions can be drawn from the above review with respect to old and young adults' cognitive plasticity as a function of task complexity? Considering the research on simple information-processing tasks with a low working memory load—and disregarding the inconsistencies with respect to the comparison slope in search tasks—there seems to be evidence for similar learning curves across age groups and a preservation

of age differences. At the same time, there are indications that in more complex tasks—including hybrid search tasks—old adults' range of plasticity is reduced. Compared to the young adults, old adults exhibited less proportional improvement, at least in some of the studies. This is what one would expect based on the proposition of age-related working memory constraints on skill acquisition. However, findings from different studies using complex tasks were not fully consistent and, in part, depended on the selection of the learning measure (absolute vs. proportional improvement) so that definite conclusions are not warranted.

Considering the research reviewed above, it is somewhat puzzling that aging exerts a relatively strong effect on almost all fluid/mechanical cognitive functions, but that age differences in procedural learning are either nonexistent or small and difficult to detect. What could be the reasons for this paradoxon? Why is it, for example, that old adults show a marked decline in terms of episodic learning (e. g., Kausler, 1991), but not in procedural learning tasks? One additional, often overlooked, aspect has to be considered here: There is an important difference between procedural learning and episodic learning situations with respect to the role of time constraints during acquisition. In episodic learning tasks, material (e. g., word lists) is usually presented for a fixed amount of time (either per list or word). The amount of available study time has proven to be highly critical for performance (e. g., Kliegl, Smith, & Baltes, 1989; Rabinowitz, 1989). For example, by providing old adults with more exposure time than young adults, age groups can be equated in terms of performance level (Thompson & Kliegl, 1991). This, of course, fits to the notion of a reduction in processing speed: To perform the necessary amount of learning activities (e. g., elaborations), old adults need more time than young adults because each process is slowed by a certain proportion. Now, consider the way procedural learning tasks are conducted. Participants are exposed to a certain number of items, and they work on each item until they come up with the answer. Because old adults usually perform slower they work longer on each item than young adults. Thus, the situation in procedural learning has the character of a self-paced learning situation in which time is *not a limiting factor*. It is interesting to speculate what would happen if a procedural learning situation was modeled after an episodic learning procedure: Both age groups would have a fixed amount of time to work on as many items as they could finish per session. Of course, old adults would accomplish less items because they require more time for each. In this case, one would not be surprised to find slower learning for old adults than for young adults across sessions.

The goal of this discussion was to show that relative to the typical time-constrained assessment of cognitive abilities (of which episodic learning is only one example) procedural learning situations constitute a very conservative test of age differences: The effect of age-related slowing, most likely one important determinant of age-differential decline in many cognitive functions, is probably eliminated because of the particular nature of the acquisition situation. If this reasoning is correct age-differences in procedural learning can be obtained only in tasks in which learning activities are constrained not only by speed of processing but also by other limitations such as working memory.

To summarize, the thesis that in tasks in which learning involves coordinative and assembly processes old adults will exhibit less learning than young adults deserves further investigation. The working memory account of skill acquisition has received some support from research on individual differences in learning. In the context of cognitive aging the picture is mixed. In part this is probably due to the fact that the particular acquisition situation used in procedural learning yields a very conservative test of age differences in rate of skill acquisition. What is needed are studies in which conditions encompassing a wide range of task complexity are submitted to training and practice. The realization of such a design is one of the goals of the present study.



### 3. The Current Research

The quest for mechanisms in adult intellectual development calls for the precise assessment of relationships between task characteristics and age differences in cognitive functioning (Kausler, 1991; Kliegl, Smith, & Baltes, 1989; Salthouse, 1985). Task complexity in this context has emerged as a core construct. In particular, the fact that age effects are usually a function of complexity has reached almost the status of a general law within cognitive aging research. This so-called complexity effect has been attributed to the age-related decline of a very general cognitive resource, such as processing speed (e.g., Cerella, Poon, & Williams, 1980; Myerson et al., 1990; Salthouse, 1985).

There are, however, important unsettled questions with respect to the role of task complexity in adult intellectual functioning. Little is known, for example, about the way complexity influences age differences in *cognitive plasticity*, which many researchers regard as the optimal indicator of a cognitive system's capacity (e.g., Baltes, 1987; Schaie & Willis, 1986). Another issue is the *dimensionality* of task complexity: Is there actually one unspecific factor or can various aspects of complexity be differentiated? This question is especially important. An answer to it would provide valuable insights into the system of age-related resources underlying cognitive aging. In the next section, the main theoretical thesis of this research regarding the effects of task complexity on adult cognition is introduced. Subsequently, the rationale for implementing these ideas within a task environment will be provided. In the final section, the specific predictions will be introduced.

#### Two Aspects of Task Complexity

The role of task complexity as a general modulator of differences between individuals and age groups in cognitive processing and learning has been portrayed from various perspectives in the above literature review. One general conclusion from this review is that the appraisal of task complex-

ity differs markedly between currently dominant models in cognitive aging, on the one hand, and individual differences and skill acquisition research, on the other. Two different conceptualizations of complexity are used—one very broad, the other more specific. From the perspective of the general slowing models, task complexity is a *single unspecific dimension*, defined only through the latencies of young adults (e.g., Cerella, 1990; Myerson et al., 1990). Any task variation leading to longer latencies is perceived as an increase in task complexity, no matter whether it is produced by a variation in the number of repetitive mental operations or an increase in coordinative activity.

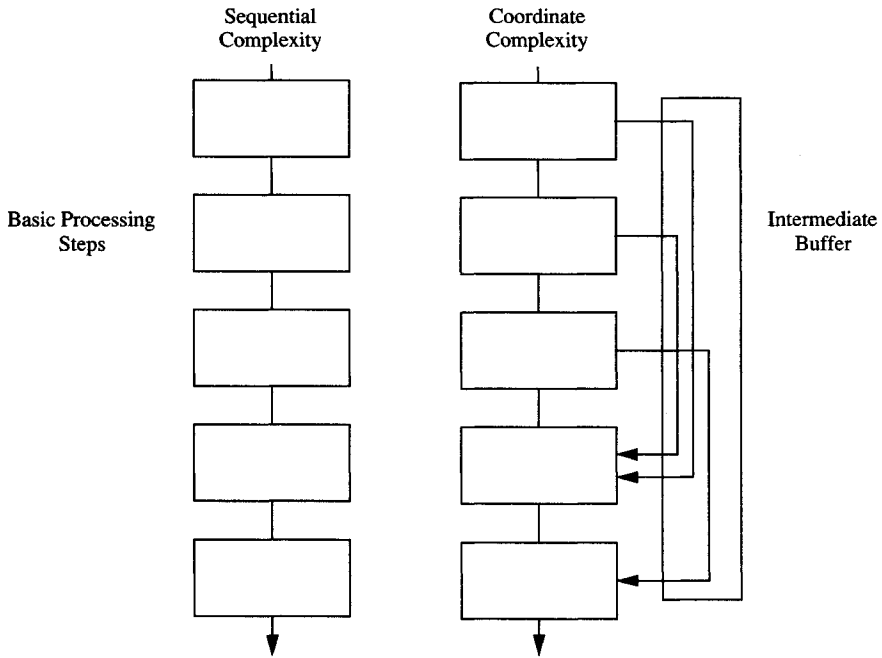
Only the latter aspect, the requirements for *coordinative activities*, would be accepted as a true variation in terms of task complexity in the context of research on individual differences in intellectual functioning (e.g., Carpenter, Just, & Shell, 1990; Snow, Kyllonen, & Marshalek, 1984). From this perspective, particularly the requirements for working memory activities are tied to the complexity dimension. Also, based on current models of skill acquisition, individual and age differences in learning efficiency can be expected in tasks with high demands on working memory (e.g., Anderson, 1983; Woltz, 1989).

Cognitive aging research can profit from a conceptualization of task complexity that takes the demands on working memory activities into account. Specifically, a more differentiated picture about age differences in cognitive plasticity should emerge if a distinction is made between a first aspect of complexity denoting the *number of independent mental operations* and a second aspect denoting the *amount of coordinative activities*. Pronounced age differences, that is, age differences larger than would be predicted by a general slowing model, are expected only for tasks high in coordinative complexity, not for tasks with a large number of independent processing steps. The two dimensions of complexity and their role in cognitive aging will be introduced in the next two sections.

### *Sequential Complexity*

Sequential complexity can be described as a variation in the number of independent processing steps that can be executed in a strictly sequential manner. Thus, demands in terms of parallel processing and storage of information, or coordination across processing steps should be low in sequential complexity conditions. An idealized flowchart of a sequential complexity condition is provided in the left panel of Figure 4.

**Figure 4**  
**Idealized Flowcharts of a Sequential Complexity**  
**and a Coordinative Complexity Condition**



*Note.* In the sequential complexity condition, basic processing steps are combined which do not require interchange of information. In the coordinative complexity condition processing steps are inter-related: The outcome of particular steps depends on the outcome of other steps in the sequence.

Typical examples of this manipulation are the increase of the search set in a visual scanning task (e.g., Madden & Nebes, 1980) or the difference between a physical and a semantic match task (Posner & Mitchell, 1967). Latencies in these conditions may be assumed to be an additive composite of their independent basic components (Sternberg, 1969). Consequently, they can be regarded as a pure measure of the speed of basic processing steps and thus of age-related decline in information processing speed. Based on the research on cognitive slowing a slowing factor of about 1.6 can be expected for sequential complexity conditions (e.g., Cerella, Poon, & Williams, 1980; Cerella, 1985, 1990; Salthouse, 1985). In the current context, two additional assumptions are made: (a) Such a slowing factor can be found in conditions of sequential complexity only and (b) in contrast to models assuming nonlinear slowing (e.g., Myerson et al.,

1990) the slowing factor should be invariant across variations of this complexity dimension. So far, there are almost no age-differential studies in the literature in which large latencies (more than 1.5 s) are obtained through the manipulation of sequential complexity. If the present conceptualization is correct, a variation in terms of sequential complexity should lead to a slowing factor of about 1.6, no matter how many independent processing steps have to be combined.

### *Coordinate Complexity*

Coordinative processes designate a broad category of mental activities that regulate flow of information and interaction between different processing steps. This concept captures both processing and storage aspects within working memory functioning (Baddely, 1986) and it is related to the notion of assembly processes as proposed by Snow, Kyllonen, and Marshalek (1984). Coordinative activities are limited by a central capacity with respect to the amount of processing and/or the storage of information (Broadbent, 1958; Craik & Byrd, 1982; Daneman & Carpenter, 1980; Kyllonen & Chrystal, 1990). An idealized flowchart of a coordinative complexity condition is depicted in the right panel of Figure 4. As one can see, flow of information is not strictly sequential. Rather, information is processed while at the same time outcomes of prior steps are retained for later use. The figure shows one particular implementation of high coordinative complexity. Another example would be the monitoring of a complex sequence of processing steps where different tracks of processing have to be taken depending on the outcome of earlier steps.

From a theoretical perspective, assuming that aging correlates with a decline in working memory capacity (e.g., Craik & Rabinowitz, 1984; Salthouse, 1990), large age effects are to be expected for high coordinative complexity tasks. In such tasks, coordination requirements usually produce larger error rates for old adults than for young adults. These are indicative of age-differential loss in relevant information (e.g., Arenberg & Robertson-Tschabo, 1985; Light, Zelinski, & Moore, 1982). In tasks with an emphasis on high accuracy and moderate coordinative complexity, age differences in response speed should also emerge which are larger than those predicted by a general slowing model. This expectation is based on the assumption that old adults can compensate loss of information due to working memory by additional processing steps, which lead to longer response times. Thus, in contrast to sequential complexity tasks,

age differences in response times should not only represent general slowing but also old adults' difficulties with coordinating cognitive processes.

Two qualifications concerning the status of the two complexity dimensions proposed here are necessary at this point: First, it was mainly for didactical reasons that coordinative complexity was introduced as a uniform dimension. Given the present knowledge, it will be an empirical question whether a constant slowing factor emerges or whether slowing increases as a function of different levels within the coordinative complexity dimension. As will be seen in the next sections, in the present study the explicit expectation will be formulated that the magnitude of age-related processing limitations in coordinative complexity conditions will be a function of the specific implementation of this task dimension.

Second, although both dimensions theoretically capture distinct aspects of cognitive processing, they are empirically probably not fully orthogonal. Whereas it should be possible to vary sequential complexity without creating coordinative complexity, every task manipulation leading to more coordinative processing will to some degree also increase the pure number of processing steps (i.e., sequential complexity). Thus, it should be close to impossible to construct a condition which is high in terms of coordinative complexity but contains no sequential complexity. Nevertheless, in the present design, an attempt will be made to contrast conditions of relatively high sequential and no coordinative complexity with conditions of relatively high coordinative but low sequential complexity.

### **Studying Age Differences as a Function of Task Complexity: Conclusions with Respect to the Choice of the Task**

Given the two aspects of task complexity, what is an appropriate task domain to implement them? In this section (a) the choice of the task domain and (b) the rationale of manipulating sequential and coordinative complexity within the task are outlined.

#### *Figural Transformations*

As a general domain of processing, figural transformations were selected. Figural transformations refer to changes in basic features of stimulus objects (e.g., shape, size, color) or their spatial arrangement (e.g., rotation, reflection). Both types of transformations are important compo-

nents in most psychometric figural reasoning tasks (e.g., Cattell, 1971), but also in tasks used in experimental studies (e.g., Lohman, 1988; Sternberg, 1977). Much research has been conducted to identify processing algorithms and sources of individual differences in transformations of figural stimuli (e.g., Carpenter, Just, & Shell, 1990; Lohman, 1988; Mulholland, Pellegrino, & Glaser, 1980; Shepard & Metzler, 1971; Sternberg, 1977). Figural transformations qualify as a domain in which a small set of operators can open up a rich task space allowing for large variations of task complexity including the two dimensions introduced above.

The general format of the Figural Transformation Task constructed for the present purpose was the following (refer also to Figures 1 and 2): Participants were presented with (a) two arrays of eight figural objects each differing in terms of features of single objects or the spatial arrangement of the whole array and (b) symbolically presented transformation rules. Participants had to respond as quickly and accurately as possible whether the actual changes between the two arrays corresponded to those indicated by the symbolically suggested transformation rules.

### *Implementation of Sequential Complexity*

The main criterion for the construction of conditions varying in terms of sequential complexity is that the number of processing steps can be increased while, at the same time, the amount of information to be managed in working memory remains low. A rationale for such a manipulation used in the present study can be borrowed from the work on figural analogies by Mulholland, Pellegrino, and Glaser (1980) and Sternberg (e.g., 1977; Sternberg & Gardener, 1983). Mulholland, Pellegrino, and Glaser (1980), for example, showed that strictly serial processing models hold (indicating little working memory load) when different transformations referred to different geometrical objects within one item. In this case, transformations can be worked through one at a time, without consideration of information related to prior task components.

In the present study, this method of manipulating the amount of sequential complexity was realized by varying the number of transformations between the two arrays that referred to single objects (see Figure 1). These transformations are simple per se; they essentially require the participant (a) to find two easily identifiable objects within the two arrays of eight objects and (b) to check whether the change between the objects (either in size, color, or margin) matches the one suggested. Two or more

such components can be combined without introducing the need for passing on information or keeping information in memory for later use.

### *Implementation of Coordinative Complexity*

In order to manipulate the amount of coordinative activities two related methods were used in the present study. Both were assumed to create high demands in terms of parallel storage and processing of information.

As a first source of coordinative complexity, spatial transformations of the whole array of eight objects are proposed. Thus, here participants have to check transformations affecting the spatial arrangement of all eight objects. The array could be rotated, reflected on the vertical axis or on the horizontal axis. As stated above, spatial transformations of complex stimuli can be regarded as a process with high demands on coordinative activities. Lohman (1988), for example, writes that "... complex spatial tests are primarily measures of G or Gf" (p. 232). In line with that, Just and Carpenter (1985) demonstrated that a complex sequence of processing steps is necessary to mentally rotate the three-dimensional Shepard and Metzler figures. There has been some research on features of the stimulus material that determine the complexity of spatial transformations. Critical aspects are that the stimulus consists of a number of independent elements (Bethell-Fox & Shepard, 1988) and that it contains no salient "landmarks" which allow shortcuts by transforming small parts instead of the entire stimulus (Hochberg & Gellman, 1977). The material used in the present study fulfills these criteria: It contains eight different objects which are arranged in a completely symmetric way so that the overall gestalt contains no salient features (see Figures 1 and 2).

As a second way of achieving high demands on coordinative activities, task conditions were constructed in which—in a more explicit way than through the spatial transformation—highly interrelated processes need to be executed. Thus, information has to be passed on between single steps creating high working memory load. Results reported by Mulholland, Pellegrino, and Glaser (1980) indicate that such a condition can be implemented by applying more than one transformation to the same figural element. The outcome of prior transformations then has to be stored in working memory in order to apply subsequent ones in a correct way. In the current study, this principle is realized by applying both spatial transformations regarding the whole array of eight objects and transformations of single objects to the same stimulus array. As can

be seen in Figure 2, correct execution of one of these two categories of transformations is based on information from the other. For example, the suggested object transformations can be verified only when the way the arrangement of objects should have changed due to the spatial transformation is present in working memory. Note, that in the absence of a spatial transformation the variation of the number of object transformations is used to manipulate sequential complexity. In the presence of a spatial transformation, however, the same task variation should increase coordinative demands.

## Design

The variation of the number of object and spatial transformations described above was combined to the task design shown in Figure 5. Six task conditions (labeled as practice task) were realized by varying the object transformations between zero and two and by varying the spatial transformation between zero and one. Low to moderate sequential complexity is realized through the variation of the number of object transformations

Figure 5  
Design of Task Factors

		Object Transformations			
		0	1	2	3
Spatial Transformations	0				
	1		Practice		
	2		Transfer		

*Note.* Sequential complexity is manipulated through the variation of the number of object transformations in the absence of a spatial transformation; coordinative complexity is assumed to be high (a) in all spatial transformation conditions and (b) especially in all spatial-plus-object transformation conditions.



in the absence of a spatial transformation.<sup>8</sup> Within practice conditions, high coordinative complexity is realized by the spatial transformation. Coordinative complexity was expected to be high (a) in conditions with a single spatial transformation and (b) especially in the two conditions containing a combination of both object and spatial transformations.

Two groups of old and young adults were exposed to extensive training, practice, and testing in these six basic task conditions. Before and after practice, additional transfer conditions were presented. Here, complexity was systematically increased to highly complex conditions containing up to two spatial and three object transformations (see Figure 5). These transfer conditions represent testing-the-limits conditions which challenge the skill under observation and thus should provide additional information about old and young adults' range of plasticity.

## Predictions

### *Plasticity and Limits of Plasticity: General Effects*

The first two predictions were based on current knowledge about developmental capacity across the life-span indicating both lifelong potential for change and fundamental limits of cognitive plasticity (Baltes, 1987; Kliegl, Smith, & Baltes, 1989). They refer to the general pattern of performance gains independent of task conditions.

*Prediction 1a:* Both age groups exhibit large general performance gains as a function of practice indicating considerable reserve capacity across the life course.

*Prediction 1b:* At the same time, old adults are not able to reach young adults' level of performance indicating limits of plasticity that cannot be eliminated by accumulation of task-related experience.

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<sup>8</sup>This is not a very large variation of sequential complexity. However, (a) time constraints due to the fact that extensive practice was provided in each condition excluded the presentation of additional conditions; and (b) the condition with two object transformations is still more complex than most tasks typically used to assess processing speed in the context of cognitive aging. Nevertheless, it has to be taken into consideration that the generality of findings will be restricted to the complexity variations realized here.

### *Age Differences in Cognitive Plasticity as a Function of Task Complexity*

It was a main goal of the current study to go beyond the above general propositions by identifying characteristics of the task environment which modify the degree of age-related plasticity. In other words, position is taken against the strong form of a general resource model predicting a highly similar age-related decrease in response speed across a wide range of task domains and amount of task-related experience (Cerella, 1990; Myerson et al., 1990; Salthouse, 1985). Instead, it is proposed that, beyond a general slowing of any given cognitive operation, decrements in working memory capacity lead to additional age-related deficiencies in certain task conditions. In particular, it was expected that age differences in response speed will be affected to a larger degree by variations in coordinative complexity than by variations in sequential complexity. In line with the general focus on cognitive plasticity and its limits, the following set of predictions refers mainly to individuals' upper range of functioning at the end of practice.

*Prediction 2a:* Age differences are small and in line with cognitive slowing in conditions varying solely in terms of sequential complexity (i.e., variation of the number of object transformations in the absence of a spatial transformation).

*Prediction 2b:* Age differences are larger and not accountable for by cognitive slowing in coordinative complexity conditions containing a spatial transformation.

*Prediction 2c:* Age effects across practice will be even more severe in those conditions in which coordinative complexity is further increased through the combination of both object and spatial transformations.

*Prediction 2d:* The latency distributions of old adults, but not those of young adults are particularly skewed towards long response times in coordinative complexity conditions indicating time-consuming recursions and recovery processes due to working memory failure.

The rationale for this set of predictions is that basic speed of processing should be the main source of age differences across conditions differing in sequential complexity. However, in tasks demanding coordinative activities, working memory capacity is assumed to become increasingly important. Therefore, in addition to cognitive slowing, age differences in working memory are expected to lead to a further increase of age effects.

Evaluation of these predictions requires to distinguish condition-specific age effects from a general age  $\times$  complexity effect. This will be done by employing data transformations that account for the proportional effect of cognitive slowing (e.g., Cerella, 1990) and by simulating age-equivalent processing speed through practice.

### *Age-Differential Learning*

In addition to the interest in what old and young adults can achieve in various task conditions, an additional focus is on age differences in learning rate as a function of task complexity.

*Prediction 3:* In coordinative complexity conditions, but not in sequential complexity conditions, rate of learning (as reflected in response latencies) is lower for old adults than for young adults.

This prediction was based on the assumptions that (a) old adults' working memory capacity is reduced and (b) working memory constraints on learning become important when tasks involve a large amount of information to be retained and processed simultaneously.

### *Testing-the-Limits*

The focus of the final prediction is on the exploration of boundary conditions of old and young adults' ability to perform the Figural Transformation Task. In the transfer conditions which are assessed before and after practice, conditions of high coordinative complexity were constructed from the two basic task components (spatial and object transformations). A breakdown of performance in these conditions would provide additional support for the notion of working memory as a constraining resource for age differences in plasticity.

*Prediction 4:* In the highly complex conditions, old adults, but not young adults will exhibit considerable decrements in terms of accuracy even after practice, which can be attributed to the requirements in coordinating multiple processing components.

In testing this prediction, special emphasis will be placed on the distinction between two sources of low accuracies in complex conditions: (a) the accumulation of errors in respective task components, and (b) errors as a function of large demands on coordination of task components.

## 4. Method

### Participants

Twenty old adults and 20 young university students participated in this study. There were 15 women in each age group. Young participants responded to announcements posted at the campus of the Free University Berlin. Most old participants ( $N = 15$ ) were recruited from a pool of volunteer subjects who took part in an earlier study which involved psychometric intelligence and personality testing (see Appendix B). Not all participants—as initially planned—could be recruited in this manner. Therefore, five additional old adults were included who were referred by participants of earlier studies.

Attempts were made to select participants who, in principle, were able to perform the difficult task conditions presented in this study. Mental transformations in two-dimensional space were considered as potentially critical for task performance. Therefore, participants were screened with respect to Card Rotation, a measure of spatial ability (after Form A; Ekstrom et al., 1976). In this task, participants had to check whether figures can be rotated into a reference figure or whether an additional reflection is necessary. In the sample of 20 old and 20 young adults only those participants were included who scored above a certain criterion. As the criterion the 25th percentile of the Card Rotation scores from an independent volunteer sample of an earlier study (Kliegl, Smith, & Baltes, 1989) was computed separately for old and young adults. From all participants initially recruited, one young and two old adults had to be excluded from the study because they scored below the criterion. Also, one old adult was unable to participate due to poor eye sight.

Despite these attempts to preselect the sample, two old women, who performed much worse than all other old participants throughout the experiment had to be excluded from data analysis. One of the women was the oldest participant (87 years) and had considerable motoric problems. The other woman scored three to four times worse than the lower range of the rest of the old participants in certain conditions. It was not clear

Table 1  
Means (*SD*) for Age, Health, Education, Vocabulary,  
Digit Symbol Substitution (DS), Card Rotation (CR), and Analogies  
for Young (*N* = 20) and Old (*N* = 18) Adults

	Age	Health	Education	Vocabulary	DS	CR	Analogy
Young	23.2 (2.0)	3.8 (.9)	13.0 (.3)	32.0 (3.7)	63.2 (6.1)	84.8 (20.9)	18.4 (6.2)
Old	74.4 (5.2)	3.9 (.7)	10.7 (2.1)	28.7 (4.6)	47.0 (8.7)	54.4 (18.2)	32.5 (5.7)

*Note.* Subjective health was assessed on a five-point scale in which five denoted excellent health. Education was assessed in years of schooling. Maximum score for Vocabulary was 40, for Digit Symbol Substitution 90, for Card Rotation 140, and for Analogies 46.

whether pathological causes played a role here or whether inefficient strategies were used. Exclusion of these participants reduced the predicted effects, but did not change the overall pattern of results. Characteristics of the final sample of 18 old and 20 young participants are presented in Table 1.

Participants in both age groups reported to be in good health compared to people of their age ( $t[36] = .02$ ;  $p > .5$ ). Old adults reported less years of formal education than young adults ( $t[36] = 4.8$ ;  $p < .01$ ). Also, on a short form of the HAWIE Vocabulary<sup>9</sup> subtest (after Wechsler, 1964), old adults scored lower than young adults ( $t[36] = 2.4$ ;  $p < .05$ ).<sup>10</sup> The negative age effects for the latter two variables indicate that the educational background of the old adults was not fully comparable to that of the young adults. However, the mean education of the respective cohort in Berlin (70 to 80 year olds) was still considerably lower than that of the sample used in this study (9.5 years compared to 10.7 years).<sup>11</sup> Also, the score in the Vocabulary test for the old participants was much higher than that of a sample representative for the 70 to 80 year old adults in

<sup>9</sup>This shortened form was constructed by taking every other item from the original 40 items so that it contained a total of 20 items. Its reliability and validity have been checked in a separate study (Lindenberger, Mayr, & Kliegl, 1993).

<sup>10</sup>An attempt had been made to parallel old and young adults with respect to the Vocabulary score. For the full sample of 20 young and 20 old adults, there had been no significant difference between the two groups. However, the two women who were excluded because of low performance in the experimental tasks belonged to the highest scoring old adults in the Vocabulary task. Thus, the removal of these participants from the sample led to a considerable reduction of old adults' mean Vocabulary score.

<sup>11</sup>Based on statistical records of the Berlin population (personal communication: Dr. Michael Wagner; November 11th. 1991).

Berlin (28.7 compared to 16.8).<sup>12</sup> Thus, the old participants in this study were clearly above average with respect to educational background. Nevertheless, in the results section, the degree to which the educational difference between age groups accounts for the observed age effects in cognitive functioning will be tested by considering the vocabulary score as a covariate. Age differences comparable to those typically reported for healthy subjects were obtained for the Digit Symbol Substitution ( $t[36] = 6.7$ ;  $p < .01$ ). Old adults scored significantly lower than young adults also on the Card Rotation ( $t[36] = 4.8$ ;  $p < .01$ ) and on a test of figural reasoning, namely, geometrical analogies (after Heller, Gaedicke, & Weinländer, 1975;  $t[36] = 5.2$ ;  $p < .01$ ).

All participants had normal or corrected-to-normal vision. Each participant was paid 20 Deutsche Mark per session. As the whole experiment lasted 14 to 16 sessions, the total payments to the participants ranged from 280 to 320 Deutsche Mark.

## **Apparatus**

Macintosh II computers were used for stimulus presentation and response collection. Stimuli were presented on a Macintosh II color monitor (16-color mode) with white background. All responses were entered on the normal Macintosh keyboard using the right-arrow key for the "yes" and the left-arrow key for the "no" response. Timing was in "tick" accuracy (1 tick = 16.63 ms).

## **Tasks and Stimuli**

### *General*

The Figural Transformation Task required participants to verify the correspondence between transformation rules and transformations of figural objects. In each item, participants were presented (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. In case of complete agree-

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<sup>12</sup>The "representative" Vocabulary score was computed using the respective age group from the Berlin Aging Study (e.g., Lindenberger, Mayr, & Kliegl, 1993).

ment between suggested and actual transformations, participants had to press the “yes”-key, otherwise the “no”-key. Transformations either referred to features of single objects (object transformations) within the array or to the spatial arrangement of the entire array (spatial transformations). Figures 6 and 7 show a sample item from each task condition used during this experiment. For example, in Figure 6c the symbolic rule is “2R” where R stands for a change in the object’s frame (Rahmen) and 2 denotes the object to be transformed. Also, the object has a white frame in the first and a black frame in the second array. Thus, this particular transformation is correct. A spatial transformation is provided in Figure 6b: Here, the right array should be rotated with respect to the left array. Again, this is a correct item: The suggested rule and the actually performed transformation match. As shown in the other examples, more complex items can be constructed by combining the two basic components, the object and the spatial transformation. (An explication of the full task design will be provided below.)

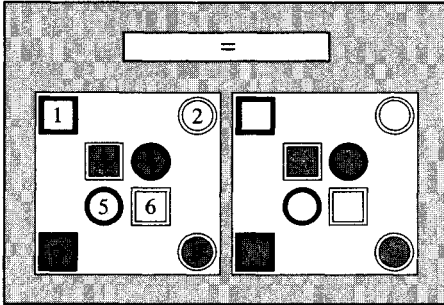
In case of more than one symbolic rule per item, the answer “yes” was correct only when each of the rules displayed corresponded to an actual figural transformation. The probability that all applications of indicated rules were correct within one item was  $p = .5$ . If the response to an item was incorrect or if the available response time was exceeded, a short error tone sounded. Between items there was an interval of one second during which the frames of the two arrays remained on the screen.

### *Stimuli*

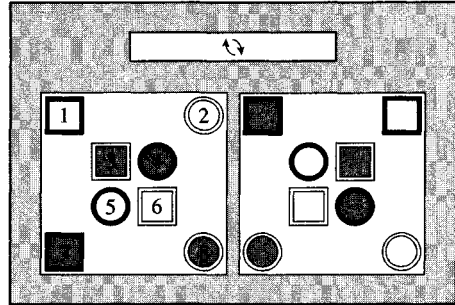
The two square arrays had a side length of 8 cm, the objects of 1.5 cm. The potential locations of the objects within the array were defined by a  $4 \times 4$  matrix. As can be seen in Figure 6, the eight objects were localized on the two diagonals of the matrix. The symbolic transformation rules were presented in a small rectangle above the two object arrays. Objects could vary on three binary value dimensions: form (square or circle), color of the object’s frame (red or black), and color of the filling (blue or yellow). Given these three dimensions, there were eight possible attribute constellations, so that eight different objects could be constructed. An invariant constellation of attributes was used throughout for the left array.

Figure 6  
Sample Items from each of the Six Practice Conditions

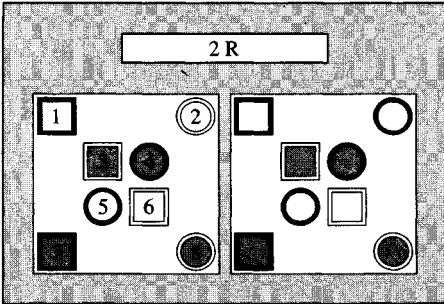
6a) 0-Spatial/0-Object (Correct)



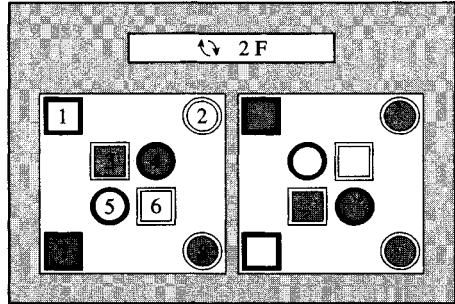
6b) 1-Spatial/0-Object (Correct)



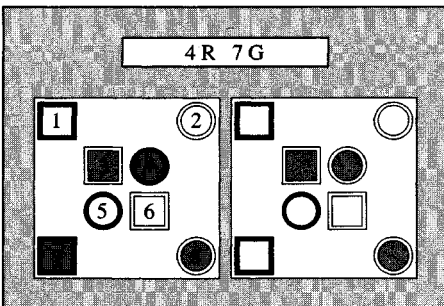
6c) 0-Spatial/1-Object (Correct)



6d) 1-Spatial/1-Object (Incorrect)



6e) 0-Spatial/2-Object (Incorrect)



6f) 1-Spatial/2-Object (Correct)

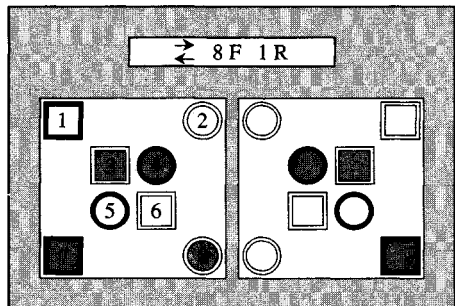
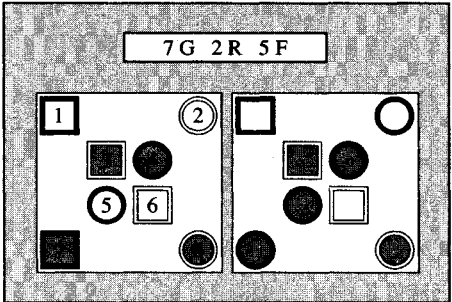


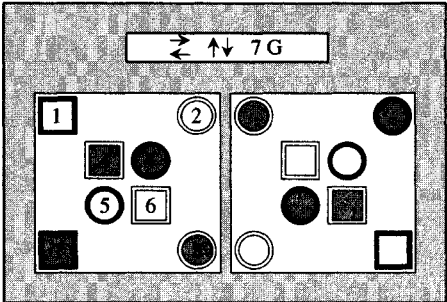


Figure 7  
 Sample Items from each of the Six Transfer (Testing-the-Limits) Conditions

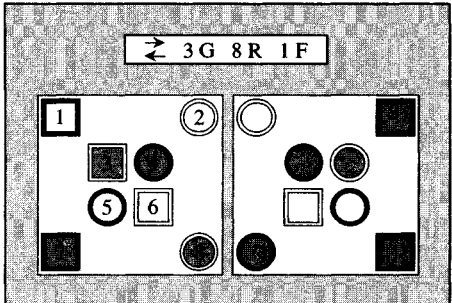
7a) 0-Spatial/3-Object (Correct)



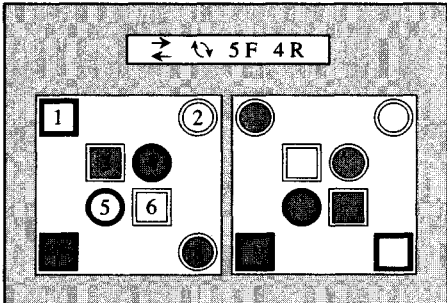
7b) 2-Spatial/1-Object (Correct)



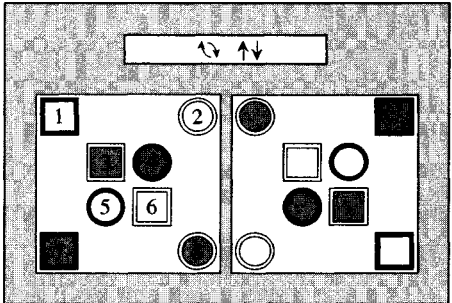
7c) 1-Spatial/3-Object (Correct)



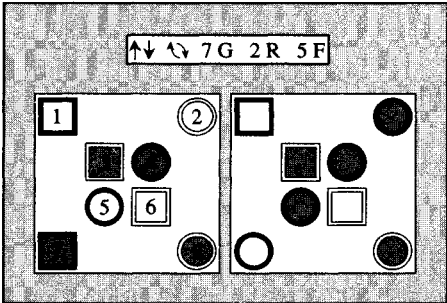
7d) 2-Spatial/2-Object (Correct)



7e) 2-Spatial/0-Object (Incorrect)



7f) 2-Spatial/3-Object (Correct)



## *Transformations*

Each of the two categories of transformations, referring either to single objects or the spatial arrangement of the entire array, was represented by three different transformations. In addition, a condition containing an identity transformation was used.

### *Spatial Transformations*

Spatial transformations referred to the stimulus array as a whole. Three transformations of this kind could occur: The array could be rotated (i. e., each object was moved 90 degrees clockwise, see Figure 6b), reflected on the horizontal axis (see Figure 7e), or reflected on the vertical axis (see Figures 6f). Spatial transformations were indicated by graphical symbols (arrows pointing to the directions of the particular spatial transformation). In task conditions containing a spatial transformation, each of the three possible transformations was presented equally often across items.

In distractor items (i. e., incorrect applications of indicated transformations), the indicated transformation either was not performed at all or was replaced by one of the other two spatial transformations. Each of these three possibilities could occur with equal probability. Due to the symmetric arrangement of the objects in terms of two diagonals the overall gestalt of the configuration remained invariant throughout all spatial transformations. Thus, spatial transformations could not be solved by attending to features of the overall arrangement.

### *Object Transformations*

The second set of transformations referred to attribute changes of individual objects. Each object could change in form (see Figure 6e), the color of the object's frame (see Figure 6c), and color of the object's inside (see Figure 6d). Object transformations were designated by the first letter of the relevant dimension ("G" for "Gestalt," "R" for "Rahmen," "F" for "Farbe") and by an additional number between one and eight indicating the object the transformation referred to. Also, the eight objects in the left array were numbered from one to eight. Thus the object to be transformed could be easily identified. The corresponding objects in the right array had no numbers so that participants had to determine corresponding objects between the two arrays through their locations. When no spatial transformation was present, an object in the right array was at the same (relative) location as in the left array (e. g., Figures 6c and 6e). When an item contained a spatial transformation, an object in the right array

could be identified by performing the respective spatial transformation relative to its position in the left array (e. g., Figure 6d). Distractors for suggested object transformations were with equal probability either one of the other two object transformations (affecting the same object as indicated) or no transformation at all. Each of the three possible object transformations occurred equally often across items within a particular task condition.

### *Identity Transformation*

When task conditions contained an identity transformation, the two arrays should be similar in terms of all possible dimensions (see Figure 6a). This transformation was symbolized by an “=” sign. Distractors were with equal probability one of the three spatial transformations. Note, that this particular condition is equivalent with a physical match between the two arrays (Posner & Mitchell, 1967).

### *Multiple Transformations Items*

In items with more than one transformation, spatial transformations (if present) always preceded object transformations. Neither particular transformations nor objects were referred to more than once per item. In conditions with more than one object transformation, objects transformations referred to were always from the same diagonal within the stimulus array. In no-items incorrect transformations were distributed equally across positions of the symbolically presented rules.

Items for all conditions were generated on-line by a random process respecting the constraints on type of transformations, number of transformations, distribution of dimensional values across objects, probability of correct items, and types of distractors. The constraints were implemented in such a way that the material was balanced with respect to all relevant aspects. Sequences of items across participants were kept invariant by specifying identical seed parameters for the randomization process.

## *Manipulation of Sequential and Coordinative Complexity*

### *Practice Task*

The number of spatial transformations (Spatial factor) and the number of object transformations (Object factor) were varied in order to manipulate both sequential and coordinative complexity. Task conditions varied orthogonally between (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 (Spatial–Object): 0–0, 0–1, 0–2, 1–0, 1–1, 1–2. Figure 6 shows a sample item from each of these six conditions. Sequential complexity was expected to increase from zero to two object transformations in the absence of a spatial transformation, whereas coordinative complexity was assumed to be low in these three conditions. Within the sequential-complexity conditions the one containing the identity transformation (0-spatial/0-object) was planned 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 especially in items containing both object and spatial transformations.

During the experiment the main emphasis, with respect to training, practice, and testing, was placed on these six conditions. In the following sections they will be referred to as the “practice task” conditions.

#### *Testing-the-Limits Transfer Conditions*

For the transfer conditions, the design of the practice task was extended by constructing conditions containing up to two spatial transformations and up to three object transformations. This led to six new conditions (Spatial–Object): 0–3, 1–3, 2–3, 2–0, 2–1, 2–2, 2–3. A sample item from each these conditions is presented in Figure 7. Together with the practice task these conditions could be described within one design by the two orthogonal factors Spatial (0, 1, 2) and Object (0, 1, 2, 3). Most of the transfer conditions, especially those containing two spatial transformations, were instantiations of high coordinative complexity. Only the condition with three object transformations and no spatial transformation is high in sequential complexity but low in coordinative complexity.

#### *Baseline Response Time Task*

As an indicator of general processing speed, the Figural Transformation Task was modified into a very 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 form, color of the inside, and color of the object’s frame. In incorrect items (non-identity), objects differed from each other in one of these attributes. The probability of incorrect items was  $p = .5$ . This task was designed to be low in both sequential and coordinative complexity. It was included in the experiment as an indicator of processing speed.

## Procedure

An overview of the assessment and the practice procedure is provided in Table 2. Participants were trained and tested in groups of one to four (except for Day 3 in which participants were tutored individually). The whole experiment was distributed across 14 to 16 days (one to three days per week), each session lasting 45 to 90 minutes.

### *Day 1*

Participants were informed about the general aspects of the study and signed an informed consent form. The Card Rotation, Vocabulary, Digit Symbol Substitution, and the Analogy tests were administered. The participants were then introduced to the Figural Transformation Task by means of an instruction booklet which explained the transformations and showed sample items (see Appendix C). Participants worked through the booklet under the guidance of a tutor.

### *Day 2*

At the beginning of this session, a second instruction booklet was presented containing further sample items. The instructions were de-

Table 2  
Sequence and Content of Sessions

Day 1	Psychometric assessment Introduction to practice task (part 1)
Day 2	Introduction to practice task (part 2) Baseline assessment of practice task Baseline response time task Learning-to-criterion of practice task (could be extended for two more sessions)
Day 3	Prepractice assessment of practice tasks Baseline response time task High-complexity transfer conditions
Day 4	Transfer tasks (not relevant here)
Day 5 to 12 (Session 1 to 8)	Practice in each of the conditions of the practice tasks Baseline response time task
Day 13	Postpractice assessment of practice task Baseline response time task High-complexity transfer conditions
Day 14	Transfer tasks (same as Day 4) High-complexity transfer conditions with liberal time constraints

signed to provide a principle understanding of the task. Before proceeding, a simple test of symbol-transformation associations was conducted in order to select participants who lacked the knowledge necessary for solving the task. All participants, however, passed this criterion.

*Baseline assessment.* The goal of the baseline assessment in the practice task conditions was to obtain an estimate of what old and young adults could achieve in the Figural Transformation Task with the minimum amount of prior knowledge provided by the initial instruction. Participants first worked through a training block of 24 items containing only one transformation (either object or spatial transformations). This was repeated if a criterion of 80 percent correct items per block was not reached. Then, performance was assessed with 24 items for each of the six complexity conditions in six 24-item blocks (total: 144 items). Maximum presentation time per item was 30 seconds. After each block, participants could take a short break. In contrast to later practice sessions, items were presented in a mixed mode, that is, items from all six conditions were distributed evenly across blocks. The reason for this was that in pilot testing with blocked presentation a strong learning effect across blocks was found which masked the effect of task conditions. This could be counteracted by using mixed blocks. Presenting items in a mixed-block mode, however, has the disadvantage that measurement of latencies becomes noisier: Response latency, in this case, not only represents the time required to process the relevant task components, but also the time to switch between items from different conditions. As this aspect was of no interest in the current research, the focus in this and the following mixed-block assessments centered on accuracy of performance, rather than on response latencies. After the baseline assessment, the response time task was presented in two blocks with 24 items each.

*Learning-to-criterion.* In the second part of this session, a tutor-guided learning-to-criterion phase began. The goal was to bring each participant to a level of functioning at which he/she was able to perform all six practice conditions of the Figural Transformation Task in principle. Starting with the easiest condition (i. e., 0-spatial/0-object), blocks of 12 items each were presented until, in two out of three blocks in a row, not more than one incorrect yes-response and one incorrect no-response were made. This procedure was repeated for each of the other five conditions of the practice task in ascending order of complexity. Items were presented with a very liberal time constraint of 60 seconds. Participants were instructed to respond only when they were sure that they knew the correct answer. When an incorrect response was entered, the display remained on the screen and the tutor explained the correct solution. Instructions given

Table 3  
Mean (*SD*) Learning-to-Criterion Blocks for Old and Young Adults  
in all Task Conditions of the Practice Task

	Conditions (Spatial-Object)					
	0-0	0-1	0-2	1-0	1-1	1-2
Young	2.1 (0.3)	2.0 (.0)	2.1 (0.2)	2.1 (0.3)	2.2 (0.4)	2.8 (1.0)
Old	2.4 (1.2)	3.3 (1.8)	2.7 (1.1)	4.4 (2.5)	6.3 (3.7)	6.5 (7.4)

by the tutor, which were provided only after an incorrect response, did not include hints to potential strategies. However, care was taken that some particular important aspects about the task were conveyed to each participant as for example knowledge about possible distractors. When the criterion for the six complexity levels was not met during the first session, the instruction phase could be extended to a maximum of two more sessions. Table 3 provides information about the number of blocks young and old adults needed for each of the six task conditions to reach the criterion. Old adults needed significantly more blocks than young adults in all conditions except for the 0-spatial/0-object condition (all  $ts[36] > 2.4$ ;  $p < .05$ ). Age differences were especially pronounced in conditions containing spatial transformations where old adults received up to three times more blocks than young adults until they reached the criterion.

#### *Days 3 and 13: Prepractice and Postpractice Assessment*

In the first part of this session, the mixed-block baseline assessment of the six practice task conditions and the response time assessment from Day 2 were repeated. In addition, six blocks of the six testing-the-limits transfer conditions were administered. Again, blocks were mixed with respect to conditions; a fixed time limit of 30 seconds per item was used. As in the baseline assessment, the main focus here was on accuracy.

#### *Day 4*

Transfer tasks were administered, which will not be analyzed in the context of this thesis. Specifically, task performance was assessed in conditions in which the stimulus material was changed in order to test hypotheses with respect to age-differential learning in the Figural Transformation Task.

### *Day 5 to 12 (Practice Sessions 1 to 8)*

*General.* Practice was conducted in eight sessions using a criterion-referenced adaptive procedure (see below). In each session, participants worked on six blocks of 12 items at each of the six complexity levels of the practice task. Thus, 72 items were presented in each complexity condition per session (i.e., total: 432 items). Summing across practice sessions, participants were exposed to 576 items per condition (i.e., total: 3,456 items). Conditions were presented in the following sequence (spatial-object): 0-0, 0-1, 1-0, 1-1, 0-2, 1-2. This particular 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. Items remained on the screen after a wrong response so that participants could check the nature of the error. Participants were free to take a break between blocks. The number of sessions per week ranged from a minimum of one to a maximum of three. At the end of each session, two blocks (24 items each) of the baseline response time task were administered.

*Adaptive practice/testing procedure.* Presentation of items during practice and testing occurred under the regime of an adaptive practice/testing procedure which was implemented independently for each of the six practice task conditions. The 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 a criterion of not more than one incorrect yes-item and one incorrect no-item was met, the presentation time was reduced in the following block. If the accuracy remained below the criterion, the presentation time was increased. Increase and reduction of presentation times occurred on a fixed scale with discrete steps (i.e., 10% downwards and 11.1% upwards, using 60 seconds as a starting point). Going downwards, the particular presentation time of the fixed scale was picked that was just above the slowest correct yes-item of the preceding block. If this was identical to the presentation time of the preceding block, reduction by one step occurred anyway. This way, the adaptive process could compensate even for a dramatic speed-up between two blocks and therefore adjust to each subject's performance precisely. In the first block of the first session, a very liberal presentation time of 60 seconds was used. In the following sessions, for the first block of each complexity level the presentation time from the last corresponding condition of the last session plus one second was used as a starting point. 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.

The adaptive assessment was used because it was regarded as superior over more traditional assessment and practice methods in two aspects. First, the adaptive process imposed a constant but individually calibrated time pressure. This was expected to create a strong motivation to work at performance limits. Using an adaptive procedure, Baron and Matilla (1989) recently demonstrated that time pressure had performance-enhancing influence especially for 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; pp. 66-72). Thus, measuring response times under time limits can be regarded as a conservative method for assessing age-differential speed of performance. One could argue that the relatively strong time pressure interferes with the learning process. However, as items remained on the screen after incorrect responses, participants had the chance to recheck their strategies in a situation with no time pressure. Secondly, it was hoped that adjusting the presentation time with respect to the number of correct responses gives the experimenter more control over the speed-accuracy trade-off which is often a problem in age-differential research (e.g., Salthouse & Somberg, 1982a). As an attempt was made to equate participants with respect to accuracy, latencies should have comparable validity in different age groups.

#### *Day 14*

The first part of this session was identical to the one on Day 4. In addition, in the second part, two blocks of 24 items each, sampled from the testing-the-limits transfer conditions were presented with a liberal time limit of 120 seconds. Items were selected with the aim of representing the moderate and very complex testing-the-limits conditions: Twelve items each were taken from the 2-Spatial/0-Object and the 2-Spatial/3-Object conditions. This assessment was included to control for the possibility that error rates in the high-complexity transfer conditions during Day 13 were caused by the time limit of 30 seconds per item. Thus, the principle ability to solve the complex items was assessed in these conditions.

## Data Analysis

In order to evaluate the main predictions of this research on condition-specific age differences, data were analyzed with an Age (2)  $\times$  Session (2)  $\times$  Object (3)  $\times$  Spatial (2) ANOVA with repeated measures on the last three factors. The Session factor referred to Sessions 1 to 8 from the practice procedure (for certain analyses also to the Prepractice and Postpractice Assessment). Orthogonal contrasts were specified for the Object factor: In a first contrast, conditions with no object transformations were tested against conditions with one and two object transformations. The second contrast tested the one-object against the two-object transformation conditions. The theoretical rationale for these contrasts was to distinguish two possible sources of age-differential processing limitations in coordinative-complexity conditions (i.e., in items containing at least one spatial transformation): (a) The condition with a single spatial transformation versus the two spatial-plus-object transformation conditions and (b) the variation in the number of object transformations from one to two in the presence of a spatial transformation. Using contrasts for the Object factor also had the advantage that all possible effects could be tested using single degree of freedom F-tests. In a complex within-subjects design like the present one, this is one way of circumventing problems related to violations against the assumption of a homogeneous variance-covariance matrix (Hertzog & Rovine, 1985). For some predictions, variations of the basic model of analysis were used.

Primary dependent variables for the main predictions were raw latencies and transformations of them. For the most analyses latency scores based on correct answers from Sessions 1 and 8 (i.e., the first and the last practice sessions) were used. In addition, error scores from the practice sessions, the Prepractice, and the Postpractice Assessment (including the high complexity conditions) were analyzed to validate and extend the results obtained with response latencies. For the ANOVAs a 5 percent error probability was adopted for rejecting the null hypothesis. For post-hoc t-tests, an  $\alpha$ -level of 1 percent was used.

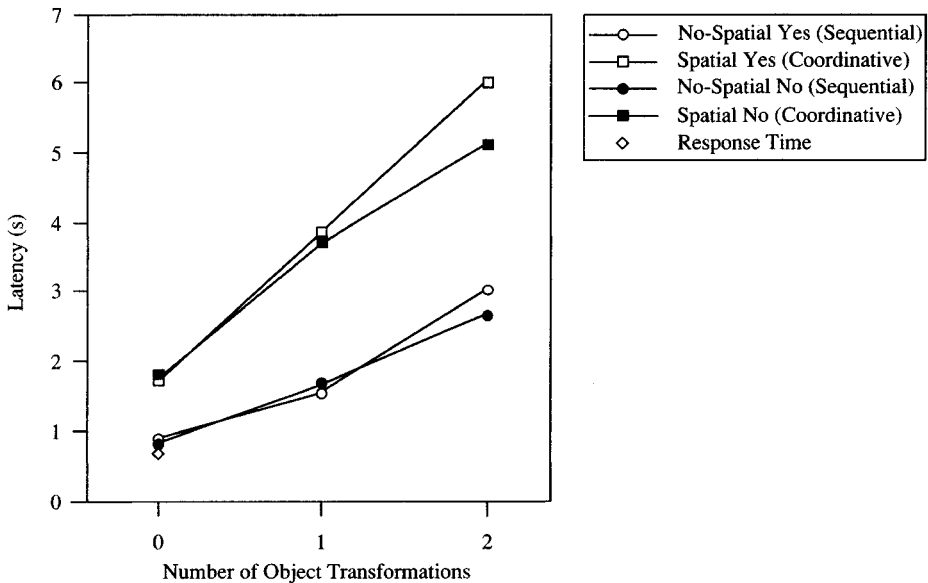
## General Characteristics of the Figural Transformation Task

The Figural Transformation Task is a novel paradigm and therefore it has to be evaluated with respect to the specific requirements of this research. In order to keep the results section focussed on the substantive age-differential issues, information about general characteristics of the para-

digm will be presented already at this point. The Figural Transformation Task was developed (a) to assess cognitive plasticity and its limits in conditions encompassing a large complexity spectrum and (b) to realize a variation in both sequential and coordinative complexity through the orthogonal manipulation of the number of spatial and object transformations. Response latencies for correct yes- and no-items in all conditions collapsed across age groups and Sessions 1 and 8 are presented in Figure 8. In addition, latencies from the external response time task are included.

Inspection of the figure reveals a considerable variation of latencies encompassing a range of about 1 to 6 seconds. Significant effects were obtained for both the Object factor and the Spatial factor (Object—first contrast:  $F[1,36] = 332.1$ ;  $p < .01$ ; second contrast:  $F[1,36] = 272.53$ ;  $p < .01$ ; Spatial:  $F[1,36] = 164.1$ ;  $p < .01$ ). Within the sequential-complexity conditions (no-spatial) latencies for the 0-spatial/2-object condition are about twice as large as for the 0-spatial/1-object condition. This indicates, as expected, a largely additive effect of the number of object transformations. A deviation from the additive pattern was found for the 0-object/0-spatial condition which was designed as a baseline situation with minimal processing requirements. Especially old adults in

Figure 8  
Response Latencies for Yes- and No-Items in all Six Task Conditions and the External Response Time Task Collapsed Across Age Groups and Sessions 1 and 8



Session 1 exhibited surprisingly long response times in this condition, thus disqualifying it as a true baseline condition.<sup>13</sup>

An important goal was to realize coordinative complexity not only in terms of spatial transformations *per se* but also through the combination of spatial and object transformations. These conditions should be more complex than would be expected on the basis of an additive combination of the contributing task components. The respective interaction is indicated in Figure 8 by the fact that the latency slopes as a function of the number of object transformations is steeper in the spatial conditions than in the no-spatial conditions. The associated interaction terms were highly significant (first contrast:  $F[1,36] = 107.8$ ;  $p < .01$ ; second contrast:  $F[1,36] = 14.8$ ;  $p < .01$ ). Thus, as expected, the two task factors were not additive: Combination of spatial and object transformations required additional time which can be interpreted as the “cost” of coordinating the two interrelated transformations.

Another aspect to be noted is that, as can be seen in Figure 8, no-items yielded shorter latencies for the two-object conditions than yes-items (both in no-spatial and in spatial conditions) which can be interpreted in terms of a self-terminating mode of processing (Sternberg, 1977). That is, processing stopped as soon as a non-correspondence between an indicated and an actually performed transformation was encountered. The inclusion of the Yes-No factor changed very little in the general pattern of age-differential results. Also, no age-differential predictions were formulated with respect to this task variation. Therefore, this factor was omitted in the subsequent analyses (mean response latencies for yes- and no-items are presented in Appendix A).

Two additional aspects should be mentioned: (a) In general, the task provided highly reliable measures of response time. Cronbach's  $\alpha$  within

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<sup>13</sup>There were several indications in this study that the no-spatial/no-object condition behaved strangely. Old adults' performance in this condition was relatively unreliable, showed no stability across practice sessions, and was unusually slow (i. e., old adults' latencies were about three times larger than those of young adults). This was surprising, as it was constructed as the condition in the design with minimal processing requirements. It essentially demanded a physical match, a type of task which is usually considered to impose very little cognitive demands. Irrespective of the causes for this phenomenon (a possible reason will be proposed in a later section) it indicates that the no-spatial/no-object condition was not the appropriate design-inherent baseline condition for both age groups which it was planned to be. This has important consequences for the analyses of age  $\times$  condition interactions. Specifically, the Age  $\times$  Spatial effect might be underestimated, whereas the Age  $\times$  Object  $\times$  Spatial effect would probably be overestimated. Therefore forthcoming analyses will be cross-checked by replacing the no-spatial/no-object condition with the external response time task. The external response time task was a simple physical match task based on the material used in the Figural Transformation Task and therefore can be regarded as a meaningful alternative baseline condition (see Figure 8). Unless reported otherwise, this alternative analysis produced no change in the general pattern of effects.

age groups were between .90 and .98 for all conditions except for old adults in the 0-spatial/0-object condition of Session 1 ( $\alpha = .78$ ; see Footnote 13). Stabilities between response latencies of Sessions 1 and 8 were between  $r = .58$  and  $r = .74$  (all reliabilities, stabilities, and inter-correlations are presented in Appendix A). Again, the 0-spatial/0-object condition for old adults was the exception: Performance of old adults in this condition showed no stability at all ( $r = -.02$ ; see Footnote 13). (b) A main reason for conducting practice was to arrive at estimates for asymptotic levels of performance (range of plasticity). Although asymptotic levels of performance can hardly be reached within eight sessions, no major changes in performance were expected at the end of practice. Comparisons of the mean latencies between Session 7 and Session 8 for each task condition showed that this actually was the case. Only for the old adults in the 0-spatial/2-object-transformations condition there was a significant improvement (137 ms;  $t[17] = 2.6$ ;  $p > .05$ ). For all other conditions, improvements between the two sessions were less than 50 ms (old: all  $ts[17] < 1.7$ ;  $p > .1$ ; young: all  $ts[18] < 1.8$ ;  $p > .08$ ). Thus, participants were not far from asymptotic performance at the end of practice.

In summary, the experimental paradigm qualified in producing reliable measures of response latencies across a large variation of complexity. More importantly, it was possible to implement at least two different types of complexity variations. The first type can be described as a variation in similar processing steps (variation in the number of object transformations in absence of a spatial transformation). The second type is a consequence of combining different task components leading to additional costs in terms of coordinative processes. This particular variation in complexity is represented by an interaction between both task factors.

## 5. Results

### Outline of the Results Section

Following the structure of the predictions, presentation of results is organized into four sections:

*Plasticity and limits of plasticity: General effects.* An overview of old and young adults' performance aggregated across task conditions will be provided for all stages of the test, training and practice procedure. In this section, the emphasis is placed on the general training and practice gains in both age groups and the age differences in performance limits irrespective of task characteristics (Predictions 1a and 1b).

*Limits of plasticity as a function of sequential and coordinative complexity.* This section contains results which refer to the main age-differential predictions. Multiple analyses focusing on modulating effects of the Number-of-Object Transformations factor (Object factor) and the No-Spatial/Spatial factor (Spatial factor) on age differences in response latencies (Predictions 2a, 2b, 2c) and latency distributions will be presented (Prediction 2d). Thus, the focus here is on what old and young adults can achieve in task conditions differing in terms of sequential and coordinative complexity given extensive practice. In addition, a series of control analyses will be conducted to rule out potential threats to the validity of the main findings.

*Age-differential learning.* In this section a closer look will be taken at the rate of learning displayed by old and young adults during the eight practice sessions (Prediction 3).

*Testing-the-limits.* In the final section, accuracy scores in the simple to highly complex testing-the-limits conditions will serve as an indicator for age-related limits of cognitive plasticity (Prediction 4).

## Plasticity and Limits of Plasticity: General Effects (Predictions 1a, 1b)

In Predictions 1a and 1b, the expectation of both substantial cognitive plasticity for the two age groups and clear limits of performance gains for old adults was formulated. A complete overview of means and standard deviations for response latencies (based on correct responses) and error percentages collapsed across all complexity conditions is presented for each measurement occasion in Figure 9. A clear picture emerged: Overall, there were considerable learning gains, especially with respect to response latencies. At the same time, large age differences remained for both latencies and errors across all measurement points.

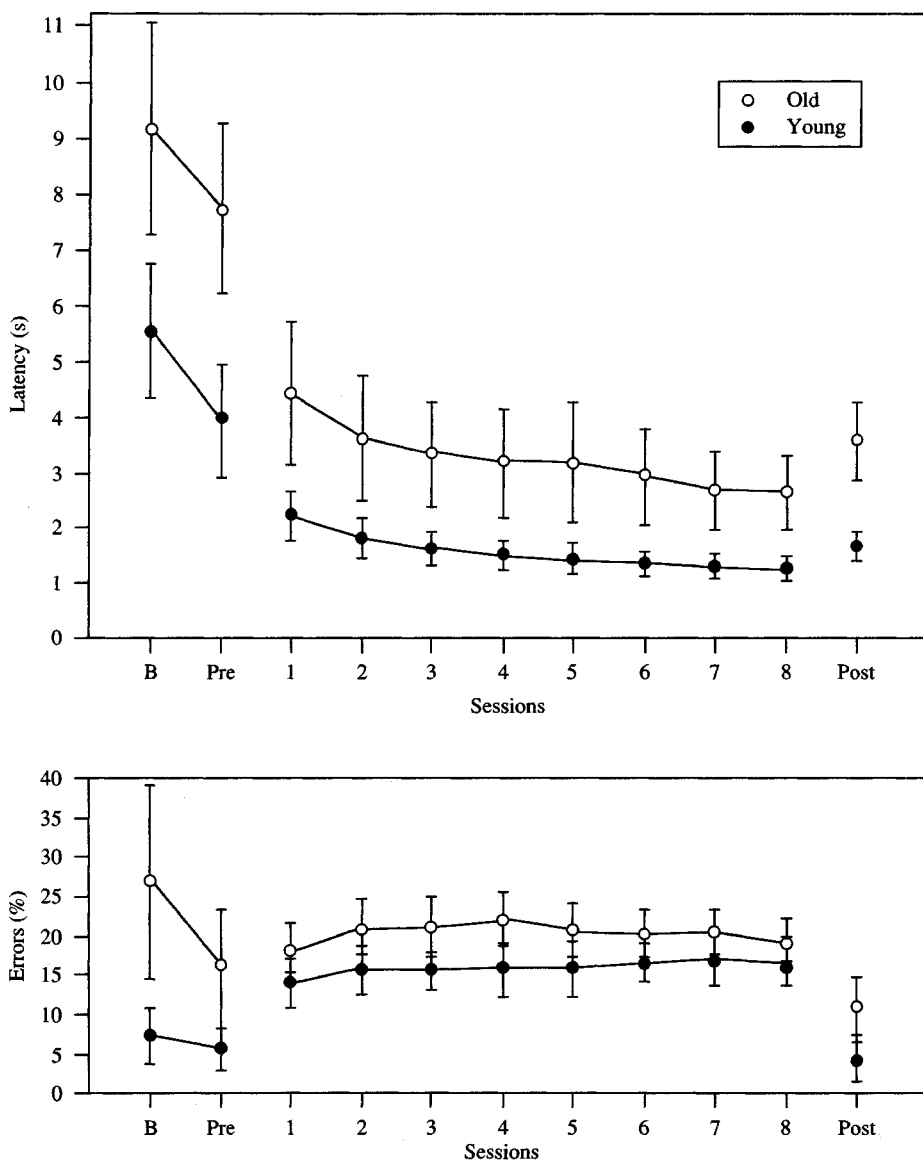
These observations were confirmed by the statistical analyses of the Prepractice and Postpractice Assessments, on the one hand, and Sessions 1 and 8 from the practice procedure, on the other. Regarding Prepractice and Postpractice Assessments all effects concerning Age and Session were significant both for latencies<sup>14</sup> (Age:  $F[1,36] = 116.4$ ;  $p < .01$ ; Session:  $F[1,36] = 328.5$ ;  $p < .01$ ; Age  $\times$  Session:  $F[1,36] = 29.9$ ;  $p < .01$ ) and for errors (Age:  $F[1,36] = 40.4$ ;  $p < .01$ ; Session:  $F[1,36] = 15.4$ ;  $p < .01$ ; Age  $\times$  Session:  $F[1,36] = 5.7$ ;  $p = .02$ ). The two age groups showed considerable improvement in terms of latencies and errors. Old adults, however, were clearly outside the range of young adults both before and after practice. Nevertheless, as indicated by the significant interactions, old adults did profit somewhat more than young adults from practice. The picture is very similar for latency data of the first and the last practice session. Significant effects for Age ( $F[1,36] = 66.7$ ;  $p < .01$ ), Session ( $F[1,36] = 151.9$ ;  $p < .01$ ), and for the Age  $\times$  Session interaction ( $F[1,36] = 14.3$ ;  $p < .01$ ) were revealed. Again, both age groups exhibited considerable gains. Although old adults showed somewhat more improvement in absolute terms, age effects were stable throughout practice.

With respect to errors, the effects of Age ( $F[1,36] = 18.9$ ;  $p < .01$ ) and Session ( $F[1,36] = 14.5$ ;  $p < .01$ ) were highly significant and the interaction ( $F[1,36] = 3.0$ ;  $p = .09$ ) marginally significant. Old adults made more errors than young adults in Sessions 1 and 8, and there was a slight overall increase in error rates between Sessions 1 and 8 (from 17% to 19%), which probably was due to the adaptive regulation of presentation times. The

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<sup>14</sup>For all ANOVAS of latencies reported in this section the assumption of homogeneous variances between groups was violated (Bartlett-Box  $F > 15.7$ ;  $p < .01$ ). As can be seen in Figure 9, interindividual variability is much larger among old adults than among young adults. Therefore, Age  $\times$  Session interactions should be interpreted with care.

**Figure 9**  
**Mean Response Latencies and Error Percentages of Young and Old Adults Across**  
**the Baseline (B), the Prepractice (Pre), the Eight Practice Sessions, and the**  
**Postpractice (Post) Assessments Collapsed Across Task Conditions**



*Note.* Vertical lines indicate standard deviations. Only those conditions from the Prepractice- and Postpractice Assessments which were used during practice sessions are included. Assessments before and after practice are kept separate from the practice sessions because they differed in mode of presentation.



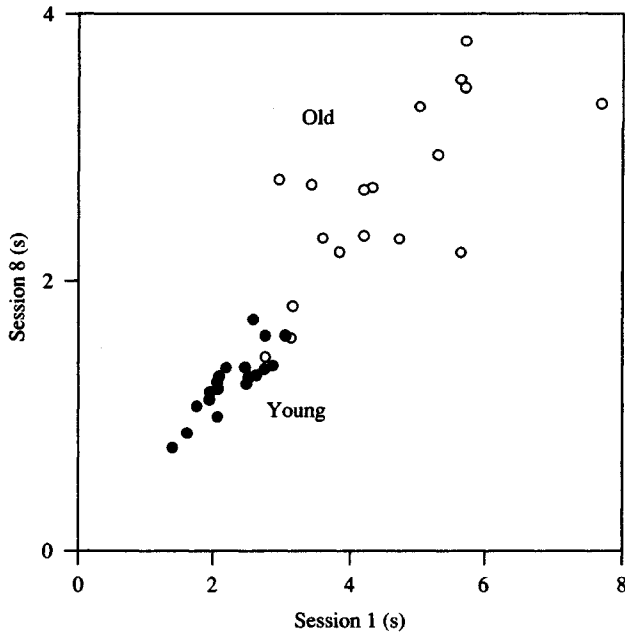
adaptive procedure was also responsible for the higher error rate in the practice sessions compared to the Prepractice and Postpractice Assessments in which items were presented with liberal presentation times of 30 s per item (see Figure 9). During practice, presentation times were regulated through an error criterion of about 17 percent (not more than one incorrect yes-item and one incorrect no-item per 12-item block) which comes very close to the error rates observed for the two age groups. The fact that old adults exhibited somewhat more errors throughout practice than young adults indicates, however, that the adaptive process did not completely eliminate differences between age groups. This aspect will be taken up again in a later section.

In summary, the results were consistent with Predictions 1a and 1b, suggesting both large general learning gains for both age groups and clear limits of plasticity for old adults: (1) Both age groups showed large increments in performance indicating *a considerable amount of learning capacity in young as well as in old adults*. Expressed in percentages, both age groups showed a speed-up of more than 50 percent (young: 57%; old: 54%) between Prepractice and Postpractice Assessment and of about 40 percent (young: 42%; old: 40%) between Sessions 1 and 8. (2) At the same time, old adults did not reach the level of performance displayed by young adults before practice suggesting *sizeable age-related limits of plasticity*. Old adults were about twice as slow as young adults and made significantly more errors throughout the extensive practice procedure. Note again that these results are based on the general age trends averaged across all task condition used in the practice procedure.

Additional information about the separation of age groups and the effect of practice on individual and age differences in overall response time is provided in Figure 10. Individual subjects' latencies collapsed across all conditions from the first practice session were plotted against those from the eighth session. Two aspects are important: First, age groups were almost entirely separated both at the beginning and at the end of practice. Only two old adults were within the range of young adults at both measurement occasions. Second, the overall predictability of performance in Session 8 on the basis of performance in Session 1 is high (81%), but somewhat lower when considering the two age groups separately (70% common variance for young and 52% for old adults) indicating that, especially for old adults, some restructuring of individual differences occurred.

The emphasis of this study was not so much on the achievement of a declarative knowledge-base, but rather on the refinement of a procedural skill (Anderson, 1983). Therefore, the above analyses which focused on

Figure 10  
Response Latencies from Session 1 versus Response Latencies from Session 8  
Collapsed Across all Task Conditions (Individual Data)



performance changes subsequent to the tutor-guided learning-to-criterion procedure are the relevant ones with respect to Predictions 1a and 1b. For the interpretation of the forthcoming results, however, the effect of the tutor-guided learning-to-criterion phase also has to be considered. The learning-to-criterion module between Baseline and Prepractice Assessment was successful in increasing accuracy of old adults' performance considerably—but not to the performance level of young adults<sup>15</sup> (see Figure 9). Thus, the goal of this procedure, to eliminate the baseline differences between young and old adults with respect to their principle ability to solve the task, was met only partly. This result must be qualified, however, by the pattern of errors throughout the whole practice and training procedure. The fact that, despite extensive instruction and prac-

<sup>15</sup>An Age (2)  $\times$  Session (2) ANOVA was conducted for both latencies and errors in Baseline and Prepractice assessments. For latencies significant main effects for Age ( $F[1,36] = 95.7; p < .01$ ) and Session ( $F[1,36] = 31.4; p < .01$ ) but a nonsignificant interaction effect ( $F[1,36] = .12$ ) were revealed. For errors, both the main effects Age ( $F[1,36] = 44.3; p < .01$ ) and Session ( $F[1,36] = 47.0; p < .01$ ) and the interaction ( $F[1,36] = 25.9; p < .01$ ) were significant.

tice, error rates of old adults were higher than those of young adults at every measurement occasion (see Figure 9) indicates a more fundamental processing limitation than one that could easily have been compensated by experiential factors. Nevertheless, in particular with respect to the question of age-differential improvement across practice, the low initial level of performance displayed by old (but not by young adults), will have to be taken into consideration.

### **Limits of Plasticity as a Function of Sequential and Coordinative Complexity (Predictions 2a, 2b, 2c, 2d)**

The previous data analysis focussed on performance averaged across task conditions. The focus of the main predictions (2a, 2b, 2c, 2d) centered on age-related limitations of plasticity as a function of task conditions. In particular, it was expected that old adults would exhibit processing deficits beyond an effect of general slowing in coordinative complexity conditions but not in sequential complexity conditions. *Sequential complexity was manipulated by a variation of the number of object transformations in the absence of spatial transformations. Coordinative complexity was expected to be high in conditions containing at least one spatial transformation and particularly in those containing both spatial and object transformations.*

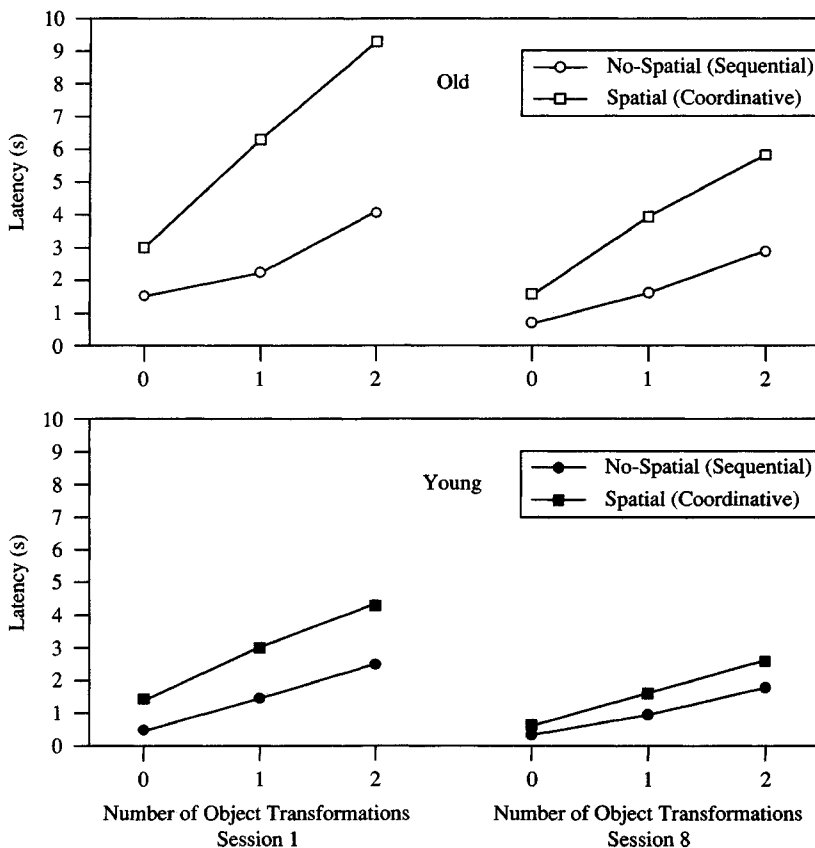
In the following, first, the main condition-specific effects will be portrayed in the traditional way, namely in terms of raw response latencies. Subsequently, Predictions 2a, 2b, and 2c suggesting a dissociation between sequential and coordinative complexity with respect to age effects will be put to test. Three different data-analytical approaches will be presented which all are tailored to distinguish the proposed condition-specific effects (sequential versus coordinative complexity) from a uniform age  $\times$  complexity interaction (Predictions 2a, 2b, 2c). Then, Prediction 2d implying that in coordinative complexity conditions latency distributions of old adults are stretched towards long latencies will be investigated. In the last part of this section, results of control analyses will be reported.

#### *Analysis of Raw Latencies*

Figure 11 shows the raw response latencies (based on correct responses) from Sessions 1 and 8 of old and young adults from the six task conditions used during practice. Predictions were formulated with respect to what

can be achieved given extensive practice. Nevertheless, data from Sessions 1 and 8 will be considered here in order to convey a comprehensive picture of the results. All forthcoming analyses were also carried out for data from Session 8 only and, unless otherwise indicated, the pattern of results remained the same. Figure 11 shows that old adults performed with considerably larger latencies than young adults in each task condition and that every task variation had a stronger effect on response latencies of old adults than on those of young adults. Overall, age effects

Figure 11  
Response Latencies from Sessions 1 and 8 in all  
Task Conditions and Both Age Groups



*Note.* Sequential complexity was manipulated through variation of the number of object transformations in the absence of a spatial transformation; coordinative complexity was supposed to be high in conditions with one spatial transformation and especially when both spatial and object transformations had to be performed.

were reduced across practice, but the general response time pattern did not change.

Most of the interactions between age and the task factors (including practice) were significant (Age  $\times$  Object—first contrast:  $F[1,36] = 28.84$ ;  $p < .01$ ; second contrast:  $F[1,36] = 27.17$ ;  $p < .01$ ; Age  $\times$  Spatial:  $F[1,36] = 37.0$ ;  $p < .01$ ; Age  $\times$  Object  $\times$  Spatial—first contrast:  $F[1,36] = 34.4$ ;  $p < .01$ ; second contrast:  $F[1,36] = 5.3$ ;  $p < .05$ ; Age  $\times$  Object  $\times$  Session—second contrast:  $F[1,36] = 4.2$ ;  $p < .05$ ; Age  $\times$  Spatial  $\times$  Session:  $F[1,36] = 4.2$ ;  $p < .05$ ; Age  $\times$  Session  $\times$  Spatial  $\times$  Objects—first contrast:  $F[1,36] = 5.0$ ;  $p < .05$ ). It also has to be noted that the age groups differed considerably in terms of interindividual variability.<sup>16</sup>

Analysis of variance of raw latencies represents the traditional way of looking at potential condition-specific age differences in cognitive aging research. For the evaluation of the present predictions, raw latencies are, however, not very informative. From a methodological point of view, this situation, in which old adults are both slower and exhibit more variability indicates a possible measurement inequivalence (e.g., Kausler, 1991; Labouvie, 1980; Salthouse, 1985). Thus, it can be questioned whether a latency difference between conditions of a certain magnitude means the same across age groups. Also, a pattern of slower response times, larger variability, and larger condition effects for old than for young adults is exactly what one would expect on the basis of a general slowing model: All of the above age  $\times$  condition interactions obtained with raw response times could be a function of a general complexity effect due to cognitive slowing. Thus, an unspecific reduction in processing speed has to be considered as a baseline for any condition-specific processing constraints (Cerella, 1990; Kausler, 1991; Salthouse, 1985).

Three alternative approaches were chosen to evaluate Predictions 2a, 2b, and 2c suggesting that age effects will be larger in coordinative complexity conditions than in sequential complexity conditions: Analysis of logarithmic transformed latencies, age-simulation, and the old-young plot analysis, each providing somewhat different perspectives on the present results.

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<sup>16</sup>The assumption of homogeneous variances between groups—which is critical for the application of analyses of variance—was violated in a rather dramatic way (the Bartlett-Box test was significant for all conditions: Bartlett-Box  $F > 4.3$ ;  $p < .05$ ). Old adults exhibited larger variability than young adults throughout. This is not surprising, rather it is exactly what one would expect given the large variation of response times in this experiment and the fact that latencies usually have skewed distributions. For reasons of comparability with traditional cognitive aging research the analysis of raw latencies is conducted as a first step despite potential problems of interpretation.

### *Analysis of Log-Transformed Latencies (Predictions 2a, 2b, 2c)*

According to Predictions 2a, 2b, and 2c, age effects in sequential complexity should be in line with general slowing whereas larger age differences are expected for coordinative complexity conditions. As described in the literature review of this research (*Speed as an Age-Related Processing Resource*), the main assumptions of the cognitive slowing model are the following: (a) Response times represent a composite of an age-invariant number of processing steps. (b) In old adults, every processing step is slowed by a constant proportion compared to young adults.<sup>17</sup> From these assumptions follows that, given that the simple general slowing model holds, age differences in raw response latencies should increase as a function of complexity while the ratios between latencies of young and old adults remain constant. A logarithmic transformation of latencies rescales absolute latency differences in terms of ratios (Tukey, 1977). Thus, in an ANOVA using log-transformed latencies, only those age  $\times$  condition interactions should become significant which cannot be explained by a proportional effect of general slowing (Cerella, 1990). Also, logarithmic transformation stretches the scale near zero and compresses it for larger values leading to an elimination or at least reduction of heterogeneity of variances and thus provides a better basis for analysis of variance (e.g., Busemeyer, 1980; Levine & Dunlap, 1982; Luce, 1986). Log-transformed latencies at the end of practice (Session 8) are shown in Figure 12 (results for Session 1 are similar).

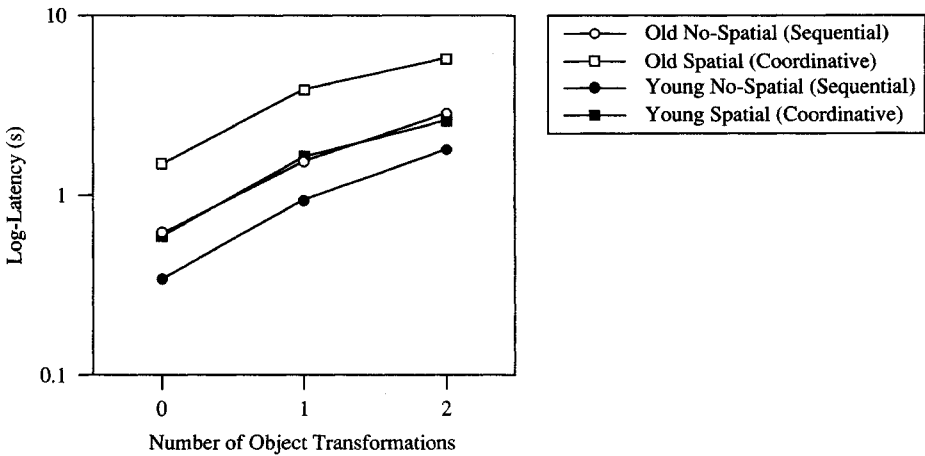
According to the figure, the dominant effect is the larger age difference in all spatial conditions compared to no-spatial conditions. At the same time, there seems to be no additional increase of age effects when both spatial and object transformations need to be performed.

This observation was supported by the statistical analysis. As expected, the log transformation of latencies led to a considerable reduction of heterogeneity between young and old adults. The Bartlett-Box test was significant for the 1-spatial/1-object transformation condition in Session 8 only (Bartlett-Box  $F = 5.8$ ;  $p < .05$ ). Consistent with the dual assumption of a general slowing effect in sequential complexity conditions (Prediction 2a) but an effect larger than general slowing in all spatial conditions

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<sup>17</sup>The assumption of constant proportions of slowing across processing steps holds for the proportional slowing model only (e.g., Cerella, Poon, & Williams, 1980; Salthouse, 1985). This model has proven very successful in accounting for age-differential reaction time data. In a later section, the present data will also be considered from the perspective of recent models assuming an overproportional increase of age differences with complexity (e.g., Cerella, 1990; Myerson et al., 1990).

Figure 12  
Log-Transformed Latencies from Session 8 for Old and Young Adults



Note. Sequential complexity was manipulated through variation of the number of object transformations in the absence of a spatial transformation; coordinative complexity was supposed to be high in conditions with one spatial transformation and especially when both spatial and object transformations had to be performed.

(Prediction 2b), the ANOVA revealed a highly significant Age  $\times$  Spatial interaction ( $F[1,36] = 14.8; p < .01$ ) indicating larger effects in the spatial than in the no-spatial conditions. Also, there was an Age  $\times$  Spatial  $\times$  Session ( $F[1,36] = 14.05; p < .01$ ), an Age  $\times$  Object (first contrast:  $F[1,36] = 6.3; p < .05$ ), an Age  $\times$  Spatial  $\times$  Object ( $F[1,36] = 13.9; p < .01$ ), and an Age  $\times$  Spatial  $\times$  Object  $\times$  Session interaction ( $F[1,36] = 5.6; p < .05$ ). Inspection of data revealed that the latter effects could be attributed to the large age differences in the design-inherent baseline condition during Session 1 (0-spatial/0-object).<sup>18</sup> When replacing this condition by the baseline response time task, most of these effects were eliminated. Only the theoretically relevant Age  $\times$  Spatial interaction ( $F[1,36] = 24.7; p < .01$ ) and a marginally significant effect for the Age  $\times$  Spatial  $\times$  Session interaction ( $F[1,36] = 3.9; p = .06$ ) remained. The latter effect indicated

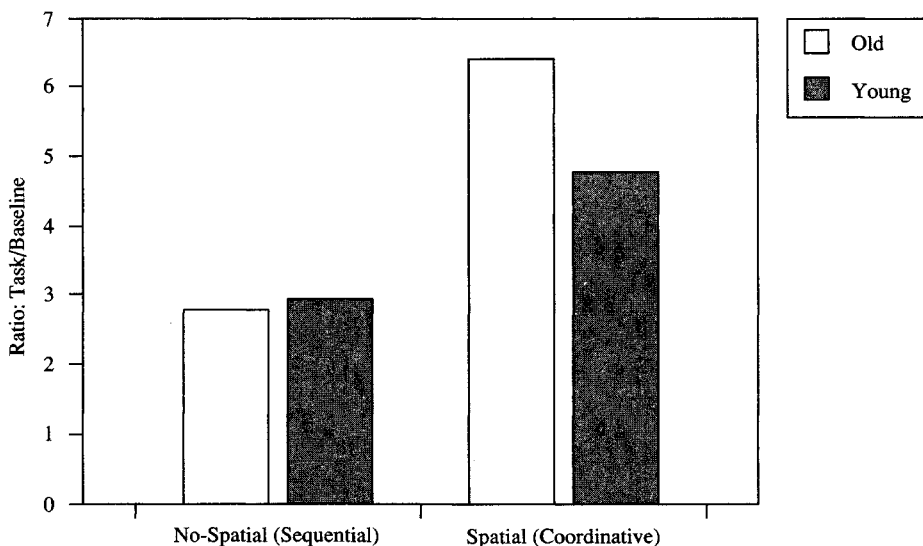
<sup>18</sup>At this point, the puzzling effect that old adults' performance in the 0-spatial/0-object condition was overproportionally slowed can be reconsidered in the light of the present main finding of an Age  $\times$  Spatial interaction. A possible reason could be that the distractors for the physical match of the entire array which had to be conducted in this condition consisted of spatially transformed arrays. As the above results indicated, old adults had particular problems with spatial transformations and thus possibly also with quick decisions between physically identical and spatially transformed arrays.

that age differences in the spatial conditions showed a slight increase across practice sessions.

Consistent with the impression gained from inspection of Figure 12, there was no indication of an Age  $\times$  Spatial  $\times$  Object interaction: Age differences in spatial-plus-object transformation conditions were not larger than in the single-spatial transformation condition. Thus, Prediction 2c, implying that coordinative complexity is especially large when both object and spatial transformations have to be considered, had to be rejected on the basis of these results.

To summarize, analysis of log-transformed latencies, which is specifically tailored to distinguish effects of proportional slowing from condition-specific effects, revealed that the current pattern of results cannot be accounted for by an unspecific reduction of processing speed. Age differences in response latencies were considerably larger in spatial than in no-spatial conditions indicating age-related processing deficits beyond general slowing in coordinative complexity conditions. This aspect can be illustrated another way by presenting age differences while controlling for the effect of general slowing. In Figure 13, response latencies for old and young adults averaged for spatial and no-spatial conditions are depicted after dividing them through latencies in the baseline response time task on

Figure 13  
Latencies in the Spatial and No-Spatial Conditions in Units of the Baseline  
Response Time Task for Old and Young Adults in Session 8





an individual basis. This way, the effect of general slowing should be eliminated for no-spatial conditions but not for spatial conditions. As shown in Figure 13, this is exactly what happened: After “factoring out” general slowing, age effects in sequential complexity conditions (no-spatial) have disappeared. However, in coordinative complexity conditions (spatial), age effects are still present.

Results obtained with log-transformed latencies also suggest that, contrary to Prediction 2c, age-differential processing limitations in the spatial-plus-object transformation conditions did not exceed those observed in the 1-spatial/0-object condition. As can be seen in Figure 12, latency slopes as a function of the number of object transformations are parallel across age groups and both spatial and no-spatial conditions. This suggests that the spatial-plus-object conditions were implementations of coordinative complexity, however, not to a larger degree than the single-spatial transformation condition. In other words, the present data can be regarded as an indication of *two proportional age effects*. The first and smaller one can be found in the no-spatial conditions (sequential complexity), the second and larger one, in the spatial conditions (coordinative complexity).

Finally, it should be noted that there was also a strong indication in the first analysis of log latencies (including the 0-spatial/0-object condition) and a weaker one in the second analysis (including the external response time condition) that practice in the spatial transformation conditions led to a condition-specific magnification of age differences. This latter aspect will be dealt with again in the section on age-differential learning.

### *Age Simulation (Predictions 2a, 2b, 2c)*

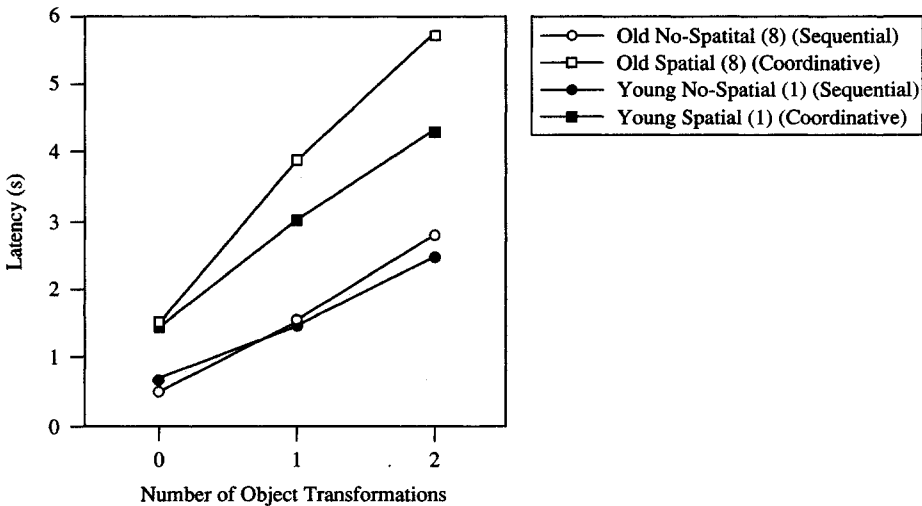
The second approach to the identification of condition-specific limitations of old adults' plasticity follows the idea of age simulation (Baltes & Goulet, 1971; Baltes, Reese, & Nesselroade, 1977; Goulet, 1972). The rationale of this technique is to equate age groups with respect to a construct that theoretically is of key relevance for the dependent variable under consideration, for example, processing speed. In the present case, this requires the identification of points of age-equivalent performance in young and old adults' learning curves for conditions which theoretically are governed by general processing speed only (no-spatial conditions). Given such points of equivalent performance, they can serve as a baseline for conditions representing additional processing constraints (spatial conditions).

Full equivalence between young and old adults for the no-spatial conditions was not achieved within the eight sessions of this experiment. In Session 8, however, latencies and errors of old adults in these conditions differed only slightly from those of young adults in Session 1. Old adults' performance was highly similar to that of young adults in the 0-spatial/1-object condition (latencies:  $t[36] = .89$ ;  $p = .38$ ; errors:  $t[36] = -1.07$ ;  $p = .28$ ); but in the 0-spatial/2-object condition there was a marginal significant difference with respect to latencies ( $t[36] = 1.90$ ;  $p = .06$ ; errors:  $t[36] = -1.35$ ;  $p = .18$ ). Latencies of old adults from Session 8 and latencies of young adults from Session 1 are presented in Figure 14.

A clear picture emerged: Whereas age differences were slight in the no-spatial conditions, old adults in Session 8 were slowed down in the two task conditions containing both object and spatial transformations to a much larger degree than young adults in Session 1. The only exception is the 1-spatial/0-object condition: In contrast to the result obtained with log-transformed latencies, in the present analysis, age groups were similar in this condition.

Statistical analysis confirmed these observations: An Age (2)  $\times$  Object (3)  $\times$  Spatial (2) ANOVA revealed Age  $\times$  Spatial ( $F[1,36] = 8.1$ ;  $p < .01$ ) and Age  $\times$  Object interactions ( $F[1,36] = 10.2$ ;  $p < .01$ ). Post-hoc t-tests indicated that these effects can be attributed to age differences in the

Figure 14  
Young Adults' Latencies from Session 1  
Compared to Old Adults' Latencies from Session 8



1-spatial/1-object ( $t[36] = 2.4; p = .01$ ) and the 1-spatial/2-object transformation conditions ( $t[36] = 2.9; p < .01$ ). Age groups did not differ significantly in the 1-spatial/0-object condition ( $t[36] = .63; p > .5$ ). Thus, in no-spatial conditions and in the condition with a single spatial transformation, old adults were able to come very close to young adults' initial level of performance. However, they remained slower in the more complex conditions involving both object and spatial transformations. This result also shows that, contrary to predictions of a strong general slowing account (e.g., Cerella, 1991), the aging cognitive system could not be converted into a "young system" through a general practice-related speed-up.

*Latencies of Old Adults as a Function of Latencies  
of Young Adults (Predictions 2a, 2b, 2c)*

As described earlier (*Speed as an Age-Related Resource*) an attempt has been made in recent cognitive slowing models to subsume age changes across a wide range of complexity under one single aging process. This process is assumed to increase in its decrementary effect in a continuous, but nonlinear manner, as complexity unfolds (Cerella, 1990; Myerson et al., 1990). In contrast, in the present research, a discontinuity with respect to age differences between task conditions which are low and high in coordinative complexity was proposed.

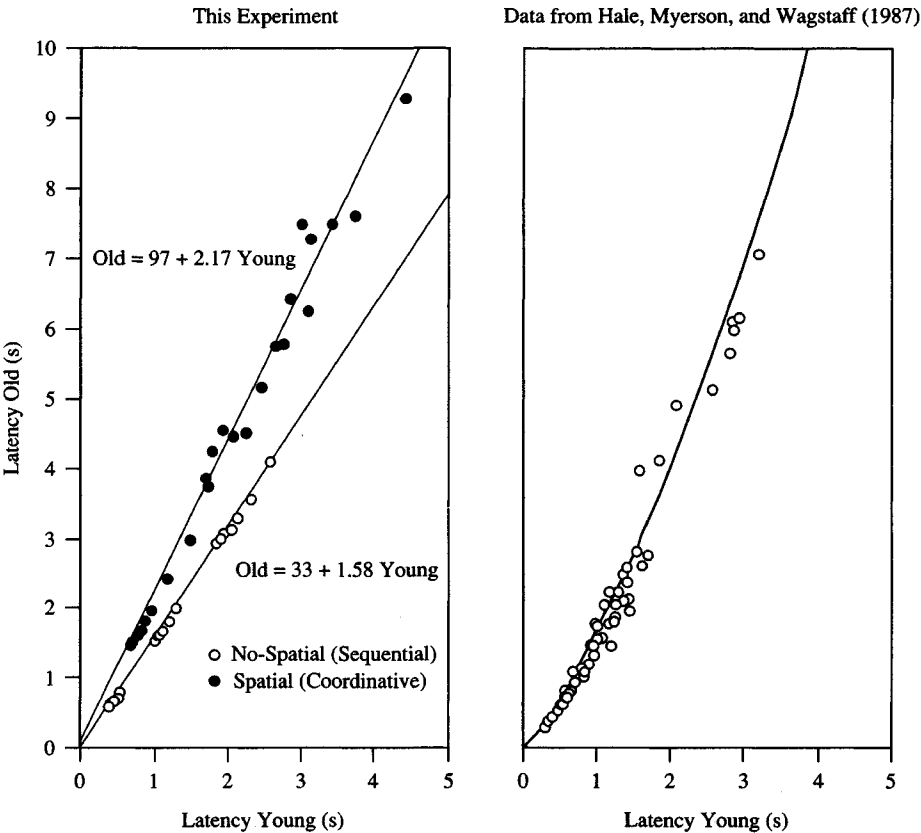
Analysis of log-transformed latencies allows to test condition-specific age differences against effects of proportional slowing, not, however, against nonlinear (i.e., overproportional) slowing. A straightforward test whether the current results are produced by more than one, discontinuous slowing processes or by a nonlinear, continuous process, is the technique of representing old adults' latencies as a function of young adults' latencies. If the larger age effects—which in this study were found in the conditions of high coordinative complexity—are the product of a continuous process, the old-young function should be described best by one single power function (Myerson et al., 1990) or quadratic function (Cerella, 1990). If, however, in conditions of high coordinative complexity, an additional processing limitation comes into play, at least two slowing functions—linear or nonlinear—should be obtained.

This method also serves two further goals. First, it yields a concise summary of response latencies from all conditions and practice sessions. Second, using this method, the present data can be compared easily with

the results from meta-analytic research on general slowing (e. g., Cerella, 1990; Hale, Myerson, & Wagstaff, 1987).

Figure 15 shows in the left panel the results of plotting mean latencies of old adults from the six task conditions in each of the eight practice sessions (total: 48 data points) against the respective latencies of young adults. For comparison, the result of the only meta-analysis using a large complexity range (Hale, Myerson, & Wagstaff, 1987; as used in Myerson et al., 1990) is shown in the right panel of Figure 15. For the old-young function of the present experiment, 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 13).

Figure 15  
Latencies of Old Adults Plotted Against Latencies of Young Adults  
for all Task Conditions and Practice Levels



Observations from all eight practice sessions were used because enough data points could be obtained by these means for estimating slowing functions reliably. This, of course, is warranted only when—as proponents of the general slowing model claim (Cerella, 1990; Myerson et al., 1990)—age differences across practice and complexity levels can be described by the same function.

As obvious from Figure 15, and in contrast to the Hale et al. (1987) meta-analysis, data points from this experiment fall nicely along two lines. The line with the shallow slope represents conditions without spatial transformations. Conditions containing spatial transformations fall on the line with the steeper slope. Also, within each of the two domains, practice and complexity exert similar proportional age differences. In line with the main predictions of this research, this finding clearly indicates a discontinuity between the no-spatial and the spatial conditions.

A hierarchical analysis of regression was conducted in order to further test the condition-specific hypotheses about age differences in the spatial and the complex multiple-transformation conditions (Predictions 2b, 2c) against the simple proportional slowing model (Table 4).

In a first step, mean latencies of old adults from all 48 conditions were regressed on latencies from young adults; this accounted for 94 percent of the variance. In a second step, the main effect Spatial was included. A highly significant change in  $R^2$  of .03 was obtained, indicating larger age differences for spatial conditions than for no-spatial conditions. In a third step, the interaction between latencies of young adults and the Spatial factor was entered. This interaction should explain additional variance in case of a difference in slopes between no-spatial and spatial conditions.

Table 4  
Hierarchical Analysis of Regression: Old Adults' Latencies as a  
Function of Young Adults' Latencies and Task Factors

Step	Predictor	$R^2$ -Change	$p$	$R^2$
1. Enter	$L_Y$	.943	< .01	.943
2. Enter	S	.035	< .01	.978
3. Enter	$L_Y \times S$	.011	< .01	.989
4. Enter	O, $L_Y \times O$	.003	< .01	.992
5. Enter	$S \times O$ , $L_Y \times S \times O$	.01	> .1	.993

The highly significant change in  $R^2$  was .01, indicating two different slowing factors for the two categories of task conditions.

This result fits very well with the impression derived from inspection of Figure 15 and, again, supports Predictions 2a (age effects in line with general slowing in sequential complexity conditions) and 2b (age effects beyond general slowing in coordinative complexity conditions with at least one spatial transformation). In additional steps, Prediction 2c implying particularly large age differences in conditions with both object and spatial transformations was tested. Two steps were necessary to test the respective interaction effect. First, the main effect Object and its interaction with young adults' latencies were included. A significant but very slight change in  $R^2$  of .003 was obtained. Then, in a final step, the critical two-way interaction Spatial  $\times$  Object and the three-way interaction including the latencies of young adults were entered. Here no significant increment of  $R^2$  was found.

Using parsimony as a selection criterion and given that it is very difficult to make valid judgments about increments in the amount of variance explained when approaching 100 percent, the third-step model (including young adults' latencies, Spatial, and Spatial  $\times$  young adults' latencies) can be regarded as the best representation of the data (see Table 4). It demands minimal information about task conditions; produces a substantive increment in explained variance over the proportional slowing model, and with a  $R^2$  of nearly .99 leaves very little remaining variability to be explained. This model with four parameters (including the intercept) accounts for about the same amount of variance as an eight parameter model including all information about the task conditions. The coefficients for latencies of young adults and their interaction with the Spatial factor were highly significant ( $t[44] = 22.0$ ;  $p < .01$ ;  $t[44] = 6.7$ ;  $p < .01$ ), but not the intercept and the coefficient for the Spatial factor ( $t[44] = .2$ ;  $p > .7$ ;  $t[44] = .8$ ;  $p > .4$ ).

*The main message of these analyses is that the effect of age in the current data set can best be described by two different slowing functions depending on the task conditions.* In the no-spatial conditions the slowing factor was 1.59. Since the Spatial factor was dummy coded (no-spatial: 0, spatial: 1) the respective slowing factor for the spatial condition can be derived by adding the two coefficients for  $L_Y$  (1.59) and  $L_Y \times S$  (.58) which yields 2.17. Slowing factors of these magnitudes have been reported in the literature so far (e.g., Myerson et al., 1990; Table 2). The smaller factor was found mainly in simple tasks and the larger factor was found when complex conditions were included in the analysis. The second important aspect of this finding is that there seems to be little additional effect of the

Table 5  
Model Equations and Fit Statistics

Type of Function	Equation	$R^2$
Linear function	$L_O = .35 + 2.2 L_Y$	.943
Two slowing functions	$L_O = .028 + 1.59 L_Y + 0.117 S + .58 L_Y \times S$	.989
Full task model	$L_O = 2.06 S + 1.58 O - .002 \text{ Session} + 1.57 S \times O - .16 S \times \text{Session} - .07 O \times \text{Session} - .06 S \times O \times \text{Session}$	.987
Power function	$L_O = 1.88 L_Y^{1.12}$	.946
Information-loss model	$L_O = ((.41 L_Y + 1)^{5.56} - 1) / 2.28$	.933
Overhead model	$L_O = L_Y + .38 L_Y^2$	.890

*Note.* Coefficients printed bold were significant.

complex spatial-plus-object transformation conditions beyond the difference between no-spatial and spatial conditions. Thus, in line with the analysis of log-transformed latencies, Prediction 2c is not supported by the results of this analysis.

Concerning the distinction between linear and nonlinear slowing functions, the results are also very clear. When fitting a power law model to the data, the amount of explained variance is 94.5 percent which is only slightly better than the simple proportional slowing model, but considerably worse than the model with two slowing functions introduced above (Table 5). Cerella (1990) has proposed a mathematical model of age-related slowing which also predicts a nonlinear function very similar to the power function (see right panel of Figure 15), and Cerella (1990) proposed a quadratic function assuming a single parameter representing costs of coordinating multiple processing steps. The first accounted for 93 percent, the second for 89 percent of the variance (Table 5). These results also fit the impression conveyed by Figure 15. Although the current data set represents a large variation on the complexity continuum, there is no indication for nonlinearity.<sup>19</sup> Thus, these results clearly support the notion of a condition-specific limitation of old adults' processing provided coordinative complexity is high.

<sup>19</sup>Also, when two nonlinear functions were estimated, one for no-spatial and one for spatial conditions, there was no increase in amount of variance explained.

### *Analysis of Latency Distributions (Prediction 2d)*

According to Prediction 2d, latency distributions of old adults should be skewed more towards large latencies than those of young adults in conditions of high coordinative complexity. In the preceding analyses, the Spatial factor was identified as the sole source of condition-specific age effects. Therefore, the analysis of latency distributions focused on this task variation only. Furthermore, only data from Session 8 will be analyzed here.

Sophisticated methods are available for distributional analysis (Heathcote, Popiel, & Mewhort, 1991; Townsend, 1990). These, however, require a large number of trials. A very straightforward technique is to represent an individual subject's latency distribution in terms of latencies from various percentiles of the distribution. Long latencies within a distribution would be indicated by the latency values found for high percentile ranks, shorter latencies would be indicated by the value for lower ranks.

The 10th, 30th, 50th, 70th, and 90th percentile of the latency distribution of each subject (using correct responses only) was computed on the basis of each condition (separately for yes- and no-items) and then averaged for no-spatial<sup>20</sup> and spatial conditions. Thus, if latency distributions are similar across age groups, age effects should not vary across different percentiles. If, however, according to Prediction 2d, distributions of old adults contain a large proportion of long latencies in spatial conditions, age effects should increase for larger percentiles in the spatial but not in the no-spatial conditions.

Figure 16 shows the relevant data. The figure indicates that, in line with Prediction 2d, latencies of old adults in the spatial condition increased with higher percentiles to a larger degree than in the no-spatial condition. In contrast, differences between conditions for young adults seemed to be very slight.

Latencies were log-transformed<sup>21</sup> and submitted to an Age (2)  $\times$  Spatial (2)  $\times$  Percentiles (5) ANOVA. In four nonorthogonal contrasts, each level of the Percentile factor was tested against the next higher one. Since

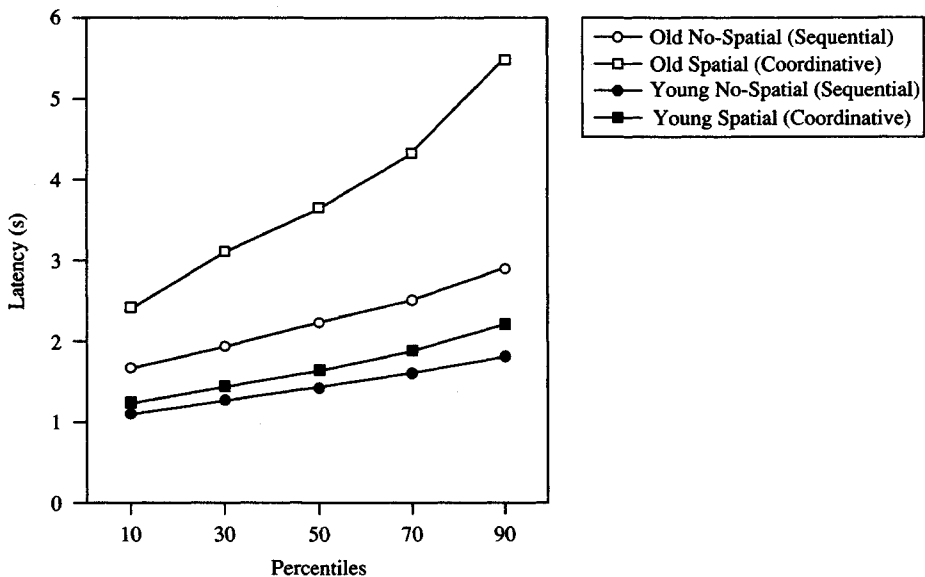
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<sup>20</sup>Because of the problems with the 0-spatial/0-object transformation condition, only the one-object and two-object transformation conditions were used here. The overall pattern was, however, affected only slightly when this condition was included.

<sup>21</sup>Log latencies were used here for the same reason as in the earlier analyses presented in this section: Log transformation accounts for proportional slowing and compensates for the skewness of the latency distribution. It therefore can be regarded as a very conservative test of condition-specific or percentile-specific age differences (Cerella, 1990).



Figure 16  
Response Latencies of Young and Old Adults from Session 8  
in Spatial and No-Spatial Conditions as a Function of Percentiles  
from Individual Latency Distributions



contrasts were not orthogonal,  $\alpha$ -level was adjusted to  $p = .05/4 = .0125$ . All main effects and two-way interactions were highly significant ( $F[1,36] = 10.2$ ;  $p < .01$ ). Critical with respect to the expectation of a large proportion of long latencies for old adults in the spatial condition (Prediction 2d) are the three-way interactions Age  $\times$  Spatial  $\times$  Percentiles. Except for one marginally significant effect for the contrast between the 30th and the 50th percentile ( $F[1,36] = 4.5$ ;  $p < .05$ ), the three-way interactions for the other three contrasts were significant ( $F[1,36] > 6.9$ ;  $p < .01$ ). These interactions suggest that, in spatial conditions, latencies of old adults increased towards higher percentiles to a larger degree compared to the no-spatial conditions and to young adults in both spatial and no-spatial conditions.

In order to decompose this effect further, two additional analyses were performed which tested whether latency distributions were similar (a) for the no-spatial conditions between age groups and (b) within young adults between spatial and no-spatial conditions. The first, comparing young and old adults in no-spatial conditions, yielded only one significant Age  $\times$  Percentiles interaction, namely, between the 70th and the 90th percentile

( $F[1,36] = 10.3; p < .01$ ). Also in the second analysis focusing on the effect of the Percentiles factor within young adults, there was only one significant interaction between the Spatial and the Percentiles factor. This effect, again, was obtained for the contrast between the 70th and the 90th percentile ( $F[1,19] = 51.7; p < .01$ ). Thus, except for the 90th percentile, distributions were similar across age groups for the no-spatial conditions and for young adults between spatial and no-spatial conditions. Only for the 90th percentile did young adults exhibit some deviation from the predicted pattern in the direction of larger latencies. However, as the significant three-way interaction for this contrast shows, here also old adults were slowed down to an overproportionally larger degree than young adults.

To summarize, the individual latency distributions followed the predicted pattern: Distributions were highly similar for young adults in both no-spatial and spatial conditions and old adults in the no-spatial conditions. In spatial conditions, latencies of old adults, however, became disproportionately larger for higher percentiles. For example, for the 10th percentile, latencies of old adults in the spatial conditions were about two times slower than those of young adults, whereas for the 90th percentile the respective ratio was about 2.5. In contrast, for no-spatial conditions the respective ratios were 1.53 and 1.63. In other words, latency distributions of old adults in the spatial conditions contained a larger portion of long response times than the latency distribution of young adults. According to a working memory account for age differences in complex tasks, one can interpret this as an indication of time-consuming processes after loss of relevant information or algorithmic breakdown in a certain proportion of items.

### *Control Analyses*

#### *Analysis of Errors in Sessions 1 and 8*

The main focus of this study is on latencies of correct responses. It has to be considered, however, whether the above described age-differential effects with respect to latencies have to be qualified by effects found in errors.

An innovative feature of this study was that during practice, participants worked under the regime of a criterion-referenced adaptive process regulating presentation times per item. When a participant responded above a certain criterion of correct items, the presentation time was shortened for the next block; if the criterion was not met, the presentation

time was prolonged by a fixed proportion. The rationale for this procedure was that participants who traded high accuracies for long response times should be forced into a faster mode of processing. Participants, however, who made many errors were granted longer presentation times in the hope that this would produce a higher emphasis on accuracy. Because of this particular procedure, two types of errors need to be distinguished: (a) Of substantive interest are the “true errors” which are reflected by incorrect responses. (b) Time-out errors reflect the degree to which the adaptive process constrained presentation times.

In Table 6 both types of errors are presented for all conditions, Sessions 1 and 8, and both age groups.

For true errors (i.e., incorrect responses), an analysis of variance revealed a main effect for Age ( $F[1,36] = 10.6; p < .01$ ), an Age  $\times$  Spatial ( $F[1,36] = 105.3; p < .01$ ) and an Age  $\times$  Spatial  $\times$  Object interaction (first contrast:  $F[1,36] = 21.6; p < .01$ ) as dominating effects. Also, there was an Age  $\times$  Session interaction ( $F[1,36] = 8.3; p < .01$ ) indicating that, overall, age differences declined between Sessions 1 and 8. According to post-hoc t-tests (see Table 6), old adults made more errors than young adults in all conditions from Sessions 1 and 8 which contained both object and spatial

Table 6  
Mean Error Percentages (*SD*) and Significance Levels of T-Tests  
(Comparing Age Groups within Conditions)  
for Time-Out and True Errors

Session	Error	Age	Conditions (Spatial-Object)					
			0-0	0-1	0-2	1-0	1-1	1-2
1	Time-Out	Young	7.6 (4.4)	6.9 (2.0)	8.3 (3.1)	5.3 (2.6)	5.6 (3.7)	6.2 (3.2)
		Old	6.9 (3.2)	9.0 (3.1)	7.6 (3.9)	6.0 (3.4)	3.9 (3.5)	4.0 (3.7)
	True	Young	3.8 (2.9)	7.6 (4.9)	4.6 (3.7)	9.0 (6.6)	10.5 (5.9)	8.2 (4.7)
		Old	2.2 (2.7)	6.9 (4.0)	6.5 (6.5)	11.6 (6.2)	24.3 (7.8)	22.2 (5.5)
8	Time-Out	Young	9.6 (4.8)	7.4 (5.0)	7.8 (3.8)	5.4 (2.6)	5.4 (3.3)	6.2 (4.0)
		Old	13.4 (4.8)	10.6 (3.6)	10.7 (3.5)	6.0 (3.4)	3.3 (4.2)	4.9 (3.6)
	True	Young	8.2 (5.0)	9.9 (7.0)	7.2 (4.6)	10.5 (5.4)	12.6 (6.3)	10.4 (6.7)
		Old	5.4 (4.6)	5.6 (3.7)	3.8 (3.0)	11.3 (7.0)	23.2 (7.3)	19.2 (6.7)

Note. +  $p < .1$ ; \*  $p < .05$ ; \*\*  $p < .01$ .

transformations. In no-spatial conditions from Session 8, however, young adults performed with slightly less accuracy than old adults.

For time-out errors, an Age  $\times$  Session ( $F[1,36] = 4.1; p < .05$ ), an Age  $\times$  Spatial ( $F[1,36] = 25.0; p < .01$ ) and an Age  $\times$  Spatial  $\times$  Session ( $F[1,36] = 4.5; p < .05$ ) interaction was found. Overall, age differences were not very pronounced for time-out errors, which indicates that time limits were quite similar for both age groups. The only major effect, the Age  $\times$  Spatial interaction, can be attributed to the fact that old adults, in general, were exposed to more severe time limits in no-spatial conditions in Session 8 than young adults (Table 6). This can be regarded as a compensatory reaction of the adaptive process to accuracy differences favoring young adults (as reflected in true errors) in the respective conditions.

Overall, the adaptive process did not succeed in equating old and young adults with respect to accuracies. This was the case, although the adaptive process did, as expected, exert a compensatory influence: In four out of six conditions in Session 1, and in all conditions of Session 8, time-out errors and true errors were correlated negatively.<sup>22</sup> Thus, time limits were more severe for those participants who made fewer incorrect responses. One can only speculate, as to why the adaptive process, nevertheless, did not fulfill its intended goal. A simple explanation might be that it only works if participants have available all relevant cognitive processes for high-accuracy performance. It is possible that in the complex conditions of the Figural Transformation Task, many old adults did not reach this level of routinized performance during the eight practice sessions. Another reason might be that the control exerted by the adaptive regime over the participants' behavior was asymmetric: It is relatively easy to bring participants into a mode of processing in which the emphasis is on speed and not so much on accuracy by imposing strict time limits through a reduction in presentation times (Baron & Matilla, 1989). However, it is more difficult to ensure that participants use all the time available. In the current study, participants (a) were informed about presentation times for each block and (b) were instructed to use all the time provided. Beyond that, however, there was no control over participants' behavior. Thus, the adaptive process can counteract overcautiousness, but it probably was less successful in bringing participants into a careful, high-accuracy mode of processing.

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<sup>22</sup>Correlations between time-out and true errors for the six task conditions (0-0, 0-1, 0-2, 1-0, 1-1, 1-2) in Session 1 were -.0, -.15, -.43, -.42, -.46, -.52. The Session 8 correlations were -.47, -.44, -.62, -.24, -.61, -.60.

Irrespective of the issues related to the adaptive procedure, it is important to evaluate the accuracy differences between age groups with respect to the interpretability of response latencies. The crucial question here is whether there were tradeoffs between latencies and accuracies implying that old adults strived for higher accuracy and therefore worked slower than young adults (e.g., Salthouse & Somberg, 1982b). With respect to the no-spatial conditions, this actually seemed to be the case, at least for Session 8. In this session, old adults exhibited somewhat less true errors than young adults. Also, in Session 8, correlations between true errors and latencies were negative in these conditions which indicates a tradeoff between both measures.<sup>23</sup>

For spatial conditions, however, age differences reflected in true errors and latencies were in the same direction indicating a positive relationship between the two measures. The respective correlations partly confirm this (see Footnote 23). Except for the 1-spatial/0-object condition in Session 8, correlations between latencies and true errors in those conditions involving spatial transformations were of moderately positive size (range: .33–.63).

Does the main finding obtained with response latencies—the particularly large age-related slowing in the spatial conditions—have to be qualified in the light of the relationships between latencies and errors? This does not seem to be the case. If anything, the joint occurrence of a negative relationship between latency and error scores in the no-spatial conditions and a positive one in the spatial-plus-object transformation conditions counteracts the critical condition-specific effect obtained with response latencies: In no-spatial conditions, age differences, very likely, were overestimated because old adults placed larger emphasis on accuracy than young adults. In contrast, in those conditions, containing both object and spatial conditions, old adults, probably, would have needed even more time to reach a level of accuracy comparable to that of young adults. Interestingly, these were those conditions for which, according to Prediction 2c, especially large age differences with respect to latencies had been expected. Thus, it is possible that Prediction 2c was not confirmed because old adults, in the spatial-plus-object transformation condition, did not succeed in reaching the same accuracy level as young adults.

One could make an additional argument with respect to the high error rates of old adults in the spatial-plus-object transformation conditions. It is possible that they are indicative of a qualitatively different and less

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<sup>23</sup>Correlations between errors and latencies for the six task conditions (0-0, 0-1, 0-2, 1-0, 1-1, 1-2) in Session 1 were -.27, .01, .09, .33, .65, .63 and in Session 8: -.24, -.31, -.34, .08, .51, .55.

efficient strategy, so that comparisons in terms of latencies do not lead to valid interpretations in terms of processing speed. Irrespective of whether or not this argument is valid in the current context, it is important to determine to what degree latencies, compared to errors, represented age-relevant variability. Or to restate the question: Did only those old adults who, in spatial conditions, showed high error-rates, exhibit long response times?

To identify the amount of variance unique to response latencies an analysis of covariance (ANCOVA) was conducted using log latencies<sup>24</sup> as dependent variable and each condition's error rate (true errors) as varying covariates.<sup>25</sup> Whereas there was a main effect for Age ( $F[1,36] = 72.8$ ;  $p < .01$ ), the critical Age  $\times$  Spatial interaction failed to reach the significance level ( $F[1,36] = 3.0$ ;  $p < .1$ ). However, there was a highly significant Age  $\times$  Session  $\times$  Spatial interaction ( $F[1,36] = 13.8$ ;  $p < .01$ ) which was due to the fact that in Session 8, age differences were larger in spatial conditions than in no-spatial conditions even after controlling for error rates. In a separate ANCOVA of log latencies from Session 8 only, the Age  $\times$  Spatial effect was highly significant ( $F[1,36] = 15.4$ ;  $p < .01$ ). The respective effect size was .31 compared to .44 when conducting the same analysis as an ANOVA (i.e., without controlling for error rates).

To summarize, the results obtained with true errors (incorrect responses) and response latencies both point to a particular age-specific processing deficit in spatial conditions. The two measures share a large portion of the theoretically relevant condition-specific variance in Session 1. At the end of practice, however, log latencies did carry unique, age-related information. The central age-by-condition effect obtained with latencies does not have to be qualified in the light of the analysis of true errors; however, one can have doubts with respect to the preciseness to which response latencies reflect age-specific limitations in sequential and coordinative complexity conditions. In particular, it is possible, that old adults would have exhibited even longer latencies in the spatial-plus-

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<sup>24</sup>Log latencies were used because they yielded the best and most conservative representation of the condition-specific results.

<sup>25</sup>It is somewhat problematic to use measures as covariates which are affected by the treatment or vary between groups (Cochran, 1957; Porter & Raudenbush, 1987; Smith, 1957). In the current context, however, it is not intended to interpret the covariates as causal factors. Rather, including errors as a covariate is used as a technique for estimating proportions of variance not related to error rates. The assumptions of homogeneous and significant regression coefficients (Glass, Peckham, & Sanders, 1972) were tested by regressing hierarchically each condition's log latency on (1) errors, (2) age, and (3) the age  $\times$  errors interaction. Overall, coefficients were parallel between age groups, but were significantly different from zero in only 7 of the 12 conditions.

object transformation conditions, if accuracies in these conditions would have been more similar between age groups.

### *Influence of Sample Characteristics*

The main result obtained from the analyses so far is the especially large age difference in all conditions containing spatial transformations. In the light of present cognitive aging research, this finding of a condition-specific age effect is nontrivial (e.g., Cerella, 1990). Therefore, special care has to be taken to verify the fact that it represents a true effect and not the product of the particular sample used in this study. The following control analyses will address this issue.

*Knowledge.* Young adults scored slightly better than old adults on the Vocabulary test (after Wechsler, 1964) which, in cognitive aging research, is usually regarded as an indicator of crystallized ability and thus as a proxy for educational background. The optimal pattern is one of equal performance between age groups.

As there were negative correlations between the Vocabulary score and the response latencies in the Figural Transformation Task (range:  $-.20$ – $-.48$ ), an ANCOVA using log latencies<sup>26</sup> as dependent variable was conducted to test whether the theoretically relevant age-related effects could be accounted for by the Vocabulary score. The critical Age  $\times$  Spatial interaction became highly significant ( $F[1,36] = 24.9$ ;  $p < .01$ ). The respective effect size was .41 compared to .44 when Vocabulary was not included as a covariate. Thus, this result indicates that the age difference in Vocabulary is only slightly related to the main condition-specific age effect.

*General cognitive status.* It is possible that the critical Age  $\times$  Spatial interaction is not a general age-specific phenomenon but is produced by a subgroup of low-ability subjects among the sample of old adults. This possibility seems particularly plausible as, in general, the variability in performance was very high among old adults (see Figure 9). To test this hypothesis old adults were divided into two equally-sized groups of low and high-ability subjects based on a simple composite of standardized scores in Digit Symbol Substitution, Card Rotation, and Analogies. These three tests were administered during the first session and represent measures of fluid/mechanical aspects of intelligence. An analysis of variance was conducted in which young adults were contrasted against high-ability old adults and in a second step high-ability old adults were

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<sup>26</sup>Since the two contrasts were not orthogonal the  $\alpha$ -level was set to  $p = .05/2 = .025$ .

contrasted against low-ability old adults (see Footnote 26). Log latencies were deployed as dependent variable (see Footnote 24). The interaction of the Spatial factor with young versus high-ability old adults became significant ( $F[1,36] = 8.7; p < .01$ ), as did the respective interaction contrasting high-ability old adults with low-ability old adults ( $F[1,36] = 10.2; p < .01$ ). Thus, the critical condition-specific age difference is not a function of the general cognitive status of old adults. Rather, it can be found even when contrasting young versus high-ability old adults. Yet, as the significant interaction for the contrast between low-ability and high-ability old adults shows, there was a very large variation among old adults indicating that a certain portion of the general Age  $\times$  Spatial interaction was caused by low-ability old adults.

*Age.* The same argument can be put forward with respect to ability could also be made with respect to age. The age variation was large in the present sample of old adults ( $SD = 5.2$  vs.  $SD = 2.0$  for young adults). Also, the mean age of the current sample of old adults ( $M = 74$  years) was slightly higher than typically used in cognitive aging research. Thus, it is possible that a subgroup of very old adults is responsible for the main age-specific effect. Old adults were separated into two equal-sized groups with respect to age (the cut-off was 75). In an ANOVA contrasting the young against the young-old and then the young-old against the old-old (see Footnote 26), only the interaction between the two younger groups and the Spatial factor reached the significance level ( $F[1,36] = 16.2; p < .01$ ). Thus, the critical effect is not tied to very old age, but can be observed in old adults below an age of 75.

To conclude, the central effect obtained in the present study, the particularly large slowing of old adults in spatial conditions (coordinative complexity), does not have to be qualified with respect to intellectual-educational background as indicated by a test of vocabulary or the general cognitive status of the old adults as indicated by a composite of three measures of fluid intelligence. Also, the main complexity-specific effect is not restricted to old adults above 75 years of age.

### *Summary* (Predictions 2a, 2b, 2c, 2d)

The sequence of analyses aimed at the identification of condition-specific age differences in response time can be summarized in the following way:

First, consistent with Prediction 2a suggesting age effects in line with general slowing in sequential complexity conditions, the age-differential



effects of the Object factor in the absence of a spatial transformation were relatively small. Moreover, they could be eliminated almost completely by simulating age-equivalent processing speed through practice or by dividing response latencies through an indicator of general processing speed. In addition, the old-young plot technique revealed that slowing in no-spatial conditions was comparable in terms of magnitude to the amount of slowing found in meta-analytic summaries of age differences in simple speeded tasks. Thus, consistent with Prediction 2a, these results suggest that, apart from the design-inherent baseline condition (see Footnote 13), *age-differences in the no-spatial conditions could be accounted for completely by a relatively general slowing factor.*

Second, according to Prediction 2b, age differences in spatial conditions should be larger than in no-spatial conditions. This prediction was verified in the analysis of log latencies and—with one exception—also in the analysis of latencies stemming from age-equivalent points in the learning curves. In addition, the old-young plot technique revealed that the large effects in spatial conditions could be explained neither by proportional slowing nor by nonlinear slowing models. Analysis of errors showed that this effect is neither the product of a speed-accuracy trade-off nor of particular sample characteristics. *The notion that old adults exhibit processing constraints beyond general slowing in coordinative complexity conditions (Prediction 2b), was strongly supported by the present results.*

Third, according to Prediction 2c, even larger age differences than in the condition containing one spatial transformation were expected for the complex conditions containing both spatial and object transformations. However, neither with the analysis using log-transformed latencies nor using the Brinley plot technique the critical Age  $\times$  Spatial  $\times$  Object interaction could be found. Thus, on the basis of response latencies, Prediction 2c has to be rejected: The demand of coordinating multiple transformations seemed to contribute only little in terms of age-differential processing constraints beyond the effect obtained when a single spatial transformation was to be performed. This conclusion has to be qualified somewhat in the light of the considerable negative age differences in the spatial-plus-object transformation conditions. It is possible that the processing limitations predicted for these conditions affected accuracy rather than response latencies.

Finally, confirming Prediction 2d, latency distributions of old adults were shown to contain a particularly large proportion of long latencies in spatial conditions (coordinative complexity) but not in no-spatial conditions (sequential complexity). This result is in line with the assumption that the performance of old adults in these conditions is characterized by

working memory failures which have to be compensated by time-consuming recursions through the sequence of processing steps.

### **Age-Differential Learning (Prediction 3)**

According to Prediction 3, old adults should exhibit a slower rate of learning than young adults in conditions of high coordinative complexity. The various analyses, reported so far, on response latency as a function of task conditions encompassed measurement occasions both at the beginning and at the end of practice and yielded different outcomes with respect to the question of age-differential improvement. For example, using raw latencies, an overall reduction of age differences was found which was somewhat larger in spatial conditions than in no-spatial conditions. In contrast, using log-transformed latencies, old adults seemed to exhibit somewhat less learning than young adults in the spatial conditions, a finding that would be consistent with Prediction 3.

The above diversity of results with respect to age-differential learning can be attributed to differences in the quality of the measurement scales used. Practice-related change in the speed of performance can be portrayed in different ways—each implying certain assumptions regarding the indicator-construct relationship (Labouvie, 1980; Salthouse, 1985). Although there is no final solution to the issue of how to analyze training-related improvements, it is widely accepted among students of learning and skill acquisition that learning data can be represented, extremely well, by power functions (Anderson, 1987; Charness & Campbell, 1988; Logan, 1988; Newell & Rosenbloom, 1981; Shrager, Hogg, & Huberman, 1988). Power functions reflect the fact that learning proceeds with negative acceleration in almost every case reported in the literature. Also, based on the power function representation, there have been several theoretical attempts to account for learning and automatization phenomena (Logan, 1988; Newell & Rosenbloom, 1981; Shrager, Hogg, & Huberman, 1988). For example, the power function has been interpreted by Newell and Rosenbloom (1981) as the outcome of one uniform, steady-state chunking mechanism. Of importance in the current context is the fact that the rate parameter in the power function is interpretable as an indicator of learning speed (Newell & Rosenbloom, 1981) which can be used as an individual difference parameter (Charness & Campbell, 1988; Woltz, 1988). Finally, power functions are estimated on the basis of log latencies and log sessions and thus, account for any effects of proportional slowing (see *Analysis of Log-Transformed Latencies*).

Two-parameter power functions were fitted to the eight-session learning curves of each individual subject by computing linear regressions of log reaction times on log sessions. The two parameters are the intercept, that is, the initial level of performance and the slope, that is, the learning rate. Mean  $R^2$ s, the intercept, and the learning rate parameters from each condition and age group are listed in Table 7.

The degree of fit as a function of age group and conditions was tested with an ANOVA using the amount of variance explained for each individual subject ( $R^2$ ) as dependent variable. A significant effect for Age ( $F[1,36] = 18.4; p < .01$ ), Spatial ( $F[1,36] = 11.7; p < .01$ ), and an Age  $\times$  Spatial interaction ( $F[1,36] = 6.8; p < .05$ ) were revealed. Power law fits of old adults were lower than those of young adults in all conditions, but particularly in those involving spatial transformations. This implies that the representation of the learning curves of old adults in spatial conditions through power functions was better for young adults than for old adults. A similar finding was also obtained in a study by Charness and Campbell (1988).

An ANOVA with learning rates as dependent variables revealed three significant within-subject effects (Objects—first contrast:  $F[1,36] = 160.6; p < .01$ ; second contrast:  $F[1,36] = 10.8; p < .01$ ; Spatial  $\times$  Objects—first contrast:  $F[1,36] = 23.04; p < .01$ ). The first two effects indicate that, in general, learning was slower the more object transformations were to be performed. The Spatial  $\times$  Object interaction can be attributed to the fact that learning rate was greater in spatial conditions with at least one object

Table 7  
Means (*SD*) of Power Function Fit ( $R^2$ ), Intercept,  
and Learning Rate for each Task Condition and Age Group

Variable	Age	Conditions (Spatial-Object)					
		0-0	0-1	0-2	1-0	1-1	1-2
$R^2$	Young	.89 (.09)	.87 (.07)	.89 (.15)	.93 (.06)	.80 (.20)	.88 (.02)
	Old	.74 (.25)	.78 (.18)	.83 (.17)	.74 (.25)	.62 (.30)	.63 (.07)
Intercept <sup>1</sup>	Young	.70 (.29)	1.45 (.24)	2.75 (.41)	1.50 (.29)	3.20 (.80)	4.87 (1.08)
	Old	1.71 (.58)	2.19 (.38)	4.22 (1.11)	3.01 (1.09)	6.31 (2.49)	9.87 (3.73)
Rate	Young	-.40 (.15)	-.20 (.06)	-.17 (.05)	-.40 (.12)	-.29 (.14)	-.24 (.06)
	Old	-.55 (.24)	-.17 (.07)	-.13 (.12)	-.34 (.14)	-.24 (.06)	-.19 (.14)

Note. <sup>1</sup>Intercepts are expressed in the units of seconds by computing the anti-logs of the estimated intercepts.

transformation than in no-spatial conditions; the reverse was true for conditions containing no object transformations. Three age-specific effects were significant: the Age  $\times$  Object (1) interaction ( $F[1,36] = 6.11$ ;  $p = .02$ ), the Age  $\times$  Spatial interaction ( $F[1,36] = 11.1$ ;  $p < .01$ ), and the Age  $\times$  Object (1)  $\times$  Spatial interaction ( $F[1,36] = 6.4$ ;  $p < .05$ ). Inspection of the data revealed that these effects could be attributed mainly to the fact that old adults exhibited a larger amount of improvement in the 0-spatial/0-object condition than young adults (see Footnote 18). Only in this condition, age groups differed significantly from each other ( $t[36] = 2.24$ ;  $p < .05$ ). When computing an ANOVA where the 0-spatial/0-object condition is omitted (thus contrasting the remaining two sequential against the three coordinative complexity conditions), the critical Age  $\times$  Spatial interaction was not significant ( $F[1,36] = .87$ ;  $p > .3$ ).

To conclude, the analysis of individual power functions did not reveal reliable learning differences between young and old adults with the exception of the 0-spatial/0-object condition. Thus, Prediction 3 was not supported. The learning curves of old adults were less regular in the spatial conditions, but otherwise *very similar to those of young adults, irrespective of task conditions*. The present results are also in line with those obtained in the old-young plot analysis of response times from all conditions and sessions. There, within spatial and no-spatial conditions, the ratios between young and old adults were found to be invariant throughout practice which indicates that relative changes due to practice were highly similar across age groups.

## Testing-the-Limits (Prediction 4)

### *Accuracy in the Transfer Conditions*

In Prediction 4, the expectation was formulated that, both before and after practice, large age-differential limitations with respect to the reserve capacity for coping with complex testing-the-limits situations should become apparent. Thus, this prediction refers to the ability of maintaining high-level performance as complexity unfolds.

A large complexity variation was established by orthogonally varying the Spatial factor from zero to two spatial transformations<sup>27</sup> and the

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<sup>27</sup>The original design also contained conditions with three spatial transformations. There were reasons to believe that old adults were penalized by the time limit of 30 seconds more than young adults in these conditions. Therefore they were excluded from the analyses. The overall pattern of results is not affected by this step, but the interpretability of the current analysis is increased.

Object factor from zero to three object transformations. Thus, the design included the six conditions used during practice and, in addition, six moderately complex to very complex transfer (testing-the-limits) situations. Aside from the condition with three object transformations, all other transfer conditions can be regarded as implementations of coordinative complexity. Different from the practice procedure, items from all conditions were presented in a mixed format using fixed presentation times of 30 seconds per item. Participants were exposed to 24 items per condition at each measurement occasion.

Percentages of correct solutions are presented in Figure 17 (at this point only the data points denoted as “observed” are relevant; the “predicted” data points will be explained below). The figure shows that old adults exhibited considerable performance breakdown in the complex conditions both before and after practice, whereas young adults’ level of performance was high at both measurement occasions.

In line with this observation, an Age (2)  $\times$  Session (2)  $\times$  Spatial (3)  $\times$  Object (4) ANOVA of accuracy scores revealed as age-differential effects a main effect for Age ( $F[1,36] = 103.5; p < .01$ ), an Age  $\times$  Session interaction ( $F[1,36] = 7.0; p = .01$ ) representing somewhat larger overall accuracy gains for old adults than for young adults, and an Age  $\times$  Spatial interaction ( $F[2,72] = 79.1; p < .01$ ) indicating considerably larger age differences as a function of the number of spatial transformations.

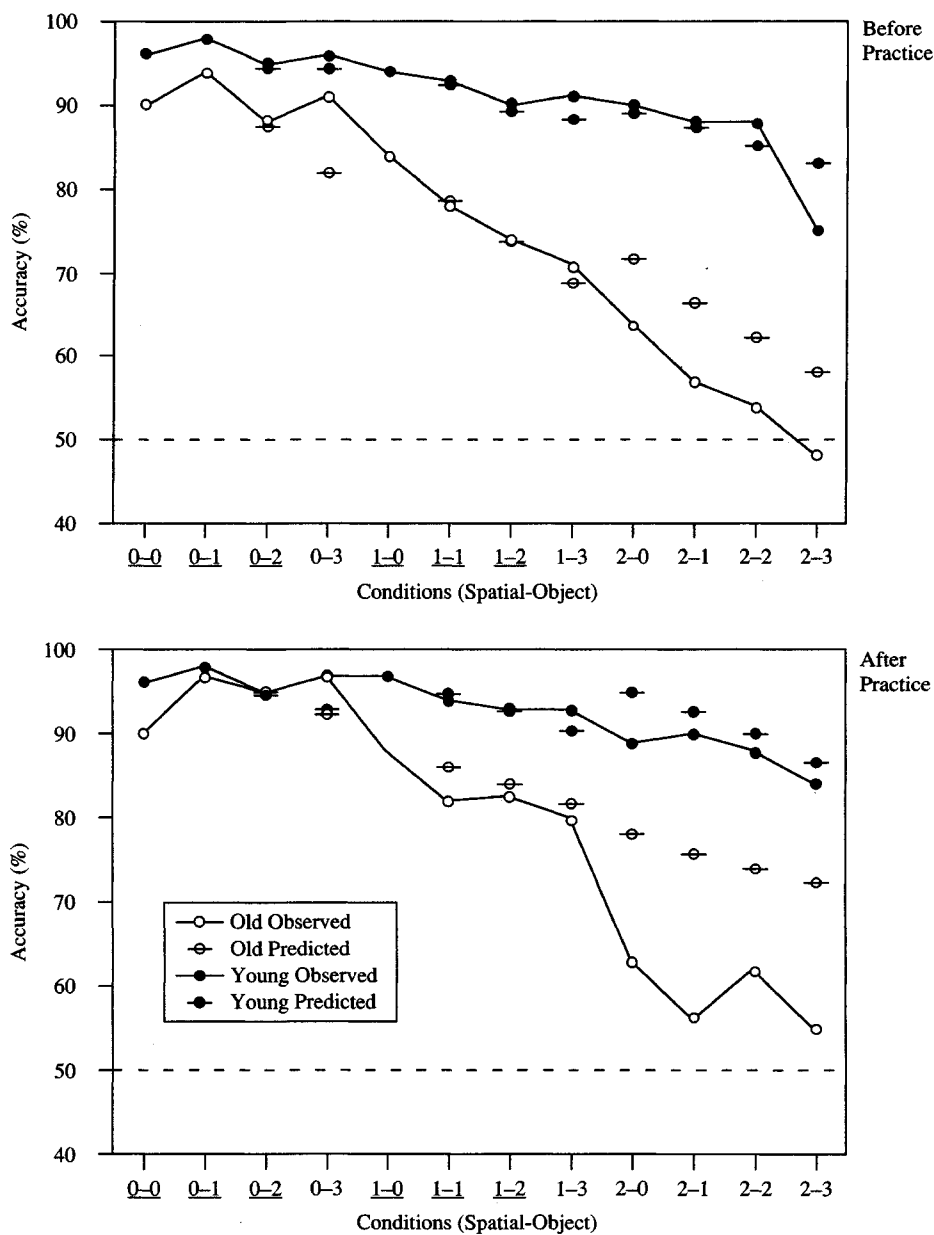
Finally, there was an Age  $\times$  Spatial  $\times$  Object interaction ( $F[6,216] = 2.7; p = .01$ ): In particular before practice, age differences increased to a somewhat larger degree as a function of object transformations in the presence of spatial transformations than in the no-spatial conditions. In post-hoc t-tests significant age differences were found for all conditions containing at least one spatial transformation (all  $ts[36] > 3.12; p < .01$ ).

Thus, this analysis shows that whereas young adults were able to sustain a relatively high level of functioning despite a considerable increase of (coordinative) complexity, old adults exhibited breakdown of performance at both measurement occasions.

#### *Probabilistic Error Model: Distinguishing Different Sources of Processing Limitations*

Within the pattern of age-differential results of the above analysis, the Age  $\times$  Spatial interaction is the dominating effect. According to Figure 17, especially the two-spatial conditions seemed to be more difficult for old adults than for young adults. Performance of old adults in these

Figure 17  
 Empirical and Predicted Percentages of Correct Solutions for each Condition,  
 Measurement Occasion, and Age Group



Note. Underlined conditions were used during practice. Data points denoted as “predicted” will be explained below.

conditions was only slightly above chance level both before and after practice.

There is, however, one important question that cannot be answered at this level of analysis: Do the large age differences in the complex conditions represent age-specific limitations in reserve capacity that go beyond what can be predicted on the basis of the single transformation conditions? One has to take into account that the accuracies in the complex conditions could be a result of the fact that errors in the constituent task components are connected in a multiplicative way. This means, if only one component is wrong, the whole solution of the item will be incorrect (Duncan, 1980; Mulholland, Pellegrino, & Glaser, 1980). Assuming independence between errors in the single task components (object transformations and spatial transformations), the baseline model for predicting percentages of correct solutions for each task condition consisting of more than one single transformation can be expressed in the following way:

$$(1) \quad \begin{array}{ll} p_{s,o} = p_1^s & \text{for } s > 0 \text{ and } o = 0; \\ p_{s,o} = p_2^o & \text{for } s = 0 \text{ and } o > 0; \\ p_{s,o} = p_1^s * p_2^o & \text{for } s > 0 \text{ and } o > 0; \end{array}$$

whereby  $p_1$  is the empirical probability for correct solutions of the single spatial transformation and  $p_2$  of the single object transformation;  $s$  and  $o$  denote the number of spatial and object transformations in the condition for which accuracy scores are to be predicted. The predictions of this model (expressed as percentages) for the task conditions consisting of more than one transformation are shown in Figure 17. The model explained 82 percent of the variability in the observed group means for both age groups. As one can see, deviations from the predicted accuracies were slight for young adults. For old adults, deviations were small as long as not more than one spatial transformation had to be solved. However, in the two-spatial-transformation conditions, old adults performed at a considerably lower level than predicted from the baseline model. For statistical tests of deviations from the predicted values, the mean predicted accuracies for the respective age group<sup>28</sup>, measurement occasion, and condition were taken as the reference. Deviations of young adults' observed scores from predicted values were in four conditions significantly positive (before and after practice: 0-spatial/3-object and

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<sup>28</sup>Group means instead of individual error probabilities were used because the relevant unit of observation are the age groups. The mean error probabilities were regarded as the more reliable estimate for this purpose.

2-spatial/3-object) and in two conditions negative (before practice: 2-spatial/3-object, after practice: 2-spatial/0-object).<sup>29</sup> For old adults only in two conditions, deviations were positive (before and after practice: 0-spatial/3-object), but in eight conditions there were negative deviations: In all of the two-spatial transformation conditions old adults exhibited significantly more errors than predicted before and after practice. Whereas younger adults' mean deviations from the predicted values in the two-spatial conditions were 2.8 percent before practice and 2.9 percent after practice, old adults performed 8.6 and 15.7 percent below the predicted accuracies.

To further test the age-differential deviations of observed scores from predicted scores, an Age (2)  $\times$  Session (2)  $\times$  Condition (9) ANOVA was conducted on the difference score between observed and predicted values.<sup>30</sup> The main effect Age ( $F[1,36] = 5.1$ ;  $p < .05$ ) and the Age  $\times$  Condition interaction were significant ( $F[8,288] = 4.9$ ;  $p < .01$ ). In subsequent t-tests, the observation that old adults deviated to a larger degree than young adults from the predicted values in conditions containing two spatial transformations could be verified. In almost all conditions with two spatial transformations, old adults exhibited either marginally or significantly larger deviations from the predicted values than young adults (before practice: 2-spatial/0-object,  $t[36] = 2.5$ ;  $p < .05$ ; 2-spatial/1-object,  $t[36] = 3.0$ ;  $p < .01$ ; 2-spatial/2-object,  $t[36] = 3.9$ ;  $p = .01$ ; after practice: 2-spatial/0-object,  $t[36] = 1.9$ ;  $p < .1$ ; 2-spatial/1-object,  $t[36] = 4.0$ ;  $p < .01$ ; 2-spatial/2-object,  $t[36] = 2.4$ ;  $p < .05$ ; 2-spatial/3-object,  $t[36] = 3.1$ ;  $p < .01$ ). Old adults showed a larger positive deviation from the predicted value than young adults only in one condition, namely, the 0-spatial/3-object condition before practice ( $t[36] = 2.7$ ;  $p < .05$ ).

The error analyses provided two important results: First, the probabilistic error model based on errors from single-transformation conditions could account for almost all age-differential effects in conditions that contained not more than one spatial transformation. Second and consistent with Prediction 4, old adults exhibited a severe breakdown in terms of accurate performance in high-coordinative complexity conditions even after practice. These processing limitations could be attributed to the need for *coordinating* two spatial transformations.

<sup>29</sup>Deviations were regarded as significant when the predicted score was outside the 95 percent confidence interval of the respective observed score.

<sup>30</sup>An ANOVA with a factorial design was not possible here, because there were no predicted values for the no-spatial/no-object, one-spatial/no-object, and no-spatial/one-object transformation conditions.



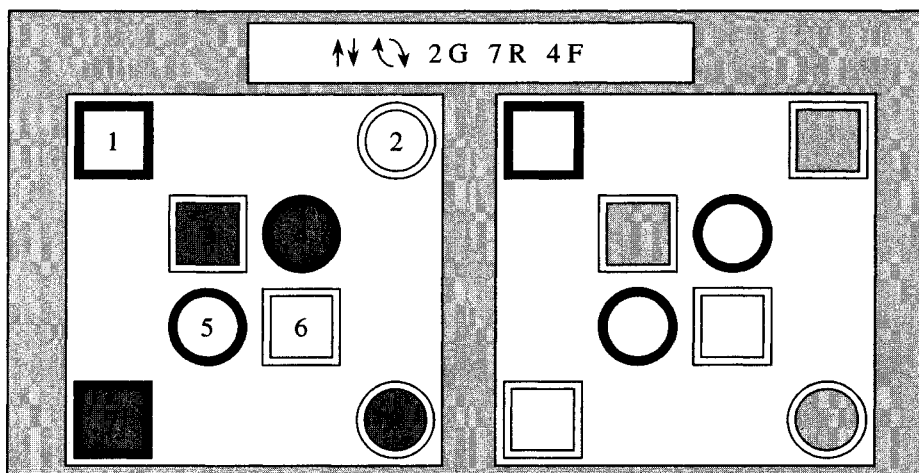
There are, however, two potential problems with this interpretation. First, maximum presentation times per item were restricted to 30 seconds, and old adults might have been more accurate with longer presentation times. To test this possibility, participants were exposed to two of the testing-the-limits conditions again, namely, the 2-spatial/0-object and the 2-spatial/3-object transformation condition in the last session of this experiment. Items were presented with an extremely liberal presentation time of 120 seconds. Also, high accuracy was emphasized in the instruction: Participants were explicitly told that the reason for this assessment was to find out whether these items were solvable in principle given a maximum amount of time. Old adults took significantly more time per item in these conditions than in the respective conditions of the Postpractice assessment of the full transfer continuum (2-spatial/0-object: 11.3 s vs. 7.7 s,  $t[17] = 2.8$ ;  $p = .01$ ; 2-spatial/3-object: 19.1 s vs. 13.2 s,  $t[17] = 2.4$ ;  $p < .05$ ). There was, however, no increase in terms of accuracy (2-spatial/0-object: 63% vs. 62.5% accuracy,  $t[17] = .1$ ;  $p > .9$ ; 2-spatial/3-object: 56% vs. 55.4% accuracy,  $t[17] = .2$ ;  $p > .8$ ). Thus, age-specific processing limitations observed in the two-spatial transformation conditions cannot be explained by too severe time constraints; more likely, they reflect a fundamental age-related deficit.

A second aspect to consider is the fact that the preceding analyses involving the whole continuum from simple to very complex conditions contained a confound between level of experience and complexity: In general, the less complex items were those used during the practice procedure. Therefore, one has to be careful about attributing old adults' lower performance level solely to the manipulation of task complexity. It is an open question whether more experience with the complex conditions would have increased old adults' accuracy of performance. It is, however, a valid inference that extensive practice in constituent task components did not benefit old adults' performance in highly complex conditions.

Even with this interpretational constraint, it seems defensible to conclude that the results of the error analyses point to two distinct sources of age differences in the accuracy pattern. First, old adults were less accurate than young adults in single transformations, especially in spatial transformation. As shown in Figure 17, the results of the probabilistic error model suggest that the multiplicative combination of these basic inaccuracies could account for nearly all of the age-differential effect in conditions with up to one spatial transformation.

Second, in line with Prediction 4, old adults exhibited performance breakdown in conditions with two spatial transformations. This breakdown was larger than predicted by the error probabilities based on the

Figure 18  
Sample Item from the Testing-the-Limits Condition with Two Spatial  
and Three Object Transformations



*Note.* According to the symbolic rules, the array should be reflected on the horizontal axis and rotated, object 2 should change the form, object 7 the frame, and object 4 the color. The correct solution to this item is "yes."

single-transformation conditions. Figure 18 shows a sample item with two spatial conditions and three additional object transformations. It should become clear from this figure that solving such items requires a considerable amount of coordinative activities, including simultaneous processing and storage of products from earlier steps. Thus, this finding supports the notion that coordination efficiency of old adults is constrained because of reduced working memory capacity. The processing limitations of old adults were stable despite the fact that all components used in the complex conditions had been practiced extensively. Thus, even though there was a considerable speed-up in the easy to moderate complex conditions during practice, there was no comparable benefit with respect to the reserve capacity of old adults for coping with the very complex conditions.

## 6. Discussion

### Synopsis

In this research the assumption was put to test that a model distinguishing between two dimensions of task complexity (sequential and coordinative) leads to a better understanding of adult age differences than models proposing a single, unspecific dimension. Systematic manipulations of sequential complexity and coordinative complexity were conducted—each corresponding to a theoretical limitation of old adults' cognitive plasticity. Moderate age differences governed by *general slowing* were expected in conditions involving sequential checks of independent figural transformations (i.e., sequential complexity). More severe age-related decrements—both in terms of performance level and learnability—were predicted for conditions requiring *coordination of cognitive processes in working memory* (i.e., coordinative complexity). Such conditions were implemented through items involving spatial transformations and the combination of both object and spatial transformation.

The predictions and the respective results are summarized in Table 8. Of the eight single predictions, six were supported. In line with *Predictions 1a* and *1b*, results revealed substantial learning gains for both age groups. At the same time, stable age-related processing limitations were obtained in each task condition: Although both age groups exhibited learning gains of about 50 percent, old adults were generally about two times slower than young adults, even after practice.

In agreement with the main set of predictions, age differences in terms of response latencies (a) were moderate when only sequential complexity was varied (*Prediction 2a*), but (b) were twice as large in coordinative complexity conditions involving a spatial transformation (*Prediction 2b*). This pattern of results is consistent with the notion that *age-related slowing* is responsible for age effects in sequential complexity conditions whereas *cognitive slowing plus an age-related reduction in working memory capacity* produces age differences in coordinative complexity conditions.

Table 8  
Synopsis of Predictions and Results

Prediction	Content	Outcome	Figure
1a	Large general practice-related performance gains for both age groups across practice sessions	confirmed	8
1b	Stable age effects throughout practice sessions	confirmed	8
2a	Age effects in line with general slowing in sequential complexity conditions (no-spatial conditions)	confirmed	15
2b	Age effects not accountable for by general slowing in coordinative complexity conditions with one spatial transformation	confirmed	15
2c	Particularly large age effects in coordinative complexity in spatial-plus-object conditions.	rejected	15
2d	Latency distributions of old adults but not of young adults are skewed towards long latencies in coordinative complexity conditions	confirmed	16
3	Old adults' rate of learning is reduced compared to that of young adults in coordinative complexity conditions	rejected	–
4	Clear performance limits in terms of accuracy for old adults in highly complex testing-the-limits conditions	confirmed	17

In addition, analysis of individual latency distributions revealed that in spatial conditions (coordinative complexity), the distributions of old adults but not those of young adults were particularly stretched towards long latencies (*Prediction 2d*). This finding fits the assumption that in coordinative conditions old adults had to perform time-consuming recursions and rechecking activities with higher probability than young adults in order to compensate working memory failures.

In testing-the-limits conditions requiring the coordination of two spatial transformations, old adults exhibited clear “losses” in plasticity in terms of very high error rates (*Prediction 4*). The application of a probabilistic failure rate model to the data in order to delineate the “sequential” and the “coordinative” sources of errors revealed that the performance breakdown of old adults could be attributed largely to high coordinative demands.

Two findings were counter predictions. (a) The combination of both spatial and object transformations did not produce age-related deficits in addition to those apparent with only a single spatial transformation (*Prediction 2c*). (b) Practice-related improvement was similar for both age groups and across both dimensions of task complexity (*Prediction 3*).

Thus, the central findings of this research was that old adults performed particularly slow in all conditions containing spatial transformations. Spatial transformations were considered to be an operationalization of high coordinative complexity and thus of high working memory requirements. This result is in line with the assumption of two distinct dimensions of task complexity (sequential and coordinative). The following discussion will focus mainly on possible qualifications and theoretical implications of the main finding. In the last part, the question of age-differential learning will be considered.

### **Qualifications and Alternative Interpretations**

The main findings of this study, the particular problems of old adults under high coordinative complexity, is potentially of considerable theoretical importance. Therefore, before turning to its theoretical implications, possible limitations with respect to its interpretability need to be discussed. The following issues deserve consideration: (a) Potential methodological problems related to response latencies, and (b) the possibility of alternative interpretations resulting from the particular choice of tasks and subjects.

#### *Validity of Response Latencies*

##### *Performance and Strategic Differences Between Age Groups*

In the present research, age differences in response times were assumed to reflect differences in terms of processing speed or working memory capacity which are aspects of the basic "implementational" (Anderson, 1987; Marr, 1982) or "hardware" (Charness, 1981) level of the cognitive architecture. Such interpretations rest on the assumption that age groups are equivalent with respect to the level of "strategies," "algorithms," "software," or performance factors (e.g., Bower & Clapper, 1989; Cerella, 1990; Myerson et al., 1990). In complex tasks, such as those used in the present study, this is a difficult requirement to fulfill (Charness & Campbell, 1988).

One special case of a performance factor which already has been dealt with extensively in the results section is the trade-off between speed and accuracy. It is known that subjects can exchange speed for accuracy (e.g., Lohman, 1989; Wickelgren, 1977), and it is possible that groups differ in terms of this trade-off. It would be particularly critical if old adults were more cautious than young adults, thus putting a higher emphasis on

accuracy than on speed (Baron & LeBreck, 1987; Okun, 1976; Okun, Siegler, & George, 1978). As the analysis of error patterns shows, this was not the case. In the spatial conditions (coordinative complexity) old adults exhibited decrements on both variables—accuracy and latency. Thus, it seems highly unlikely that age differences in response times were overestimated because of a negative trade-off constellation. If anything, there was the reverse problem: It is possible that high error rates of old adults in the spatial-plus-object conditions led to an underestimation of the “true” age effects in terms of latencies. This aspect has to be considered with respect to the question whether the old-young function is linear or nonlinear (e.g., Cerella, 1990; see Figure 15). In this case not only the global age-differential effect but the precise differences between latencies of old and young adults are important. Thus, it would be of interest to measure the time old and young adults require to perform conditions differing in terms of coordinative complexity when error rates are invariant across age. In the two recent experiments, in which adaptations of the Figural Transformation Task were used, this was achieved by assessing the presentation times needed to perform a certain accuracy criterion in an extensive adaptive training and testing procedure (Kliegl, Mayr & Krampe, in press; Mayr & Kliegel, in press).<sup>31</sup> The results of this study completely replicated the main finding of the present research: Slowing was larger in coordinative conditions than in sequential conditions and completely linear in both cases.

The high error rates of old adults in spatial conditions rule out a trade-off situation; it is possible, however, that they point to another potential problem limiting the validity of response latencies: The substantial age-differential slowing in the spatial conditions could be a result of old adults using qualitatively different, less efficient strategies than young adults. A number of features of the present study were meant to counteract age differences in strategy use: (a) Participants were carefully instructed and informed about all aspects relevant for solving the Figural Transformation Task. (b) A tutor-guided learning-to-criterion procedure was conducted prior to testing and practice in which old adults received up to two or three times more training than young adults. (c) Most importantly, eight practice sessions were conducted bringing participants close to their performance limits. The likelihood that substantial age differences in strategies persist, despite such a large amount of task-related experience, should be relatively small. With the exception of one

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<sup>31</sup>The Mayr and Kliegl (in press) article reports both the current experiment and a follow-up experiment in which the adaptive assessment procedure was used.

condition (see below), no major changes in the overall pattern of age effects occurred, neither with respect to response latencies nor in terms of accuracy. Nevertheless, generalizability of the present results is limited to the amount of instruction and practice provided in this study. It is an open question whether more experience with the task would have eliminated the condition-specific processing deficits of old adults.

With respect to the relatively high error rates of old adults, it is interesting to note that such a finding is not at all unusual in spatial tasks. Some of the clearest results with respect to latencies in mental rotation tasks using complex stimulus material comes from studies in which error rates of 20 to over 30 percent were obtained for young adults (e. g., Folk & Luce, 1987). Errors in this context have been interpreted as evidence for the decay of the stimulus representation during the execution of mental transformations (Kosslyn, 1981). Thus, high error rates may indicate less efficient processing but not necessarily qualitatively different processing.

In one condition of the Figural Transformation Task, age groups probably did differ in a qualitative way: The 0-object/0-spatial condition, which was included in the design as the most simple one in terms of processing requirements, turned out to be surprisingly difficult for old adults. A possible explanation of this puzzling phenomenon might be that spatially transformed arrays were used as distractors for the physical match of the stimulus array, which was required in this condition. Instead of using the optimal strategy of comparing only one single object, old adults probably—in the same way as was necessary for the items containing one spatial transformation—conducted comparisons between several objects. The fact that this was more a strategic than a fundamental difference between age groups was indicated by two aspects: (a) Old adults' limitation in this condition was a transient phenomenon. Whereas old adults were about three times slower than young adults at the beginning of practice, the ratio was reduced to about 1.8 at the end of practice (in all other conditions ratios between old and young adults remained relatively stable across practice). (b) There was a zero-correlation between old adults' response latencies in Sessions 1 and 8 indicating a reorganization of the skill. In all other conditions, considerable correlations between Session 1 and 8 were obtained.

All in all, and apart from the above mentioned 0-object/0-spatial condition, old adults probably did not differ in terms of strategies. It is important to note, however, that the term strategy only refers to processes that can either be chosen optionally or are at least within the range of a subject's possible modes of processing given instruction and practice. The possibility remains that old adults needed more processing steps than

young adults in certain conditions, because their cognitive algorithms were more error-prone. As will be argued in a later section, this could be one possible effect of working memory deficits on processing.

### *Representation of Age Effects in Response Latencies*

The main finding of the present research stems from analyses of transformed response latencies. Using transformed data instead of raw data is an unusual practice and thus requires justification.

Aside from purely statistical reasons (e.g., Levine & Dunlap, 1982; Srivastava, 1959), transformations may be indicated when serious doubts exist about the linearity of the relation between the raw dependent variable and the underlying theoretical construct (e.g., Baron, 1985; Labouvie, 1980; Salthouse, 1985). Statistical tests of interactions are meaningful only when linearity is given (e.g., Busemeyer, 1980). Very often, there is no good way of deciding whether a transformation is appropriate or not.

In the present case, however, the situation is different. The main reason for transforming latencies was that raw response latencies were not informative with respect to the theoretical issues of the current research. When the effects of processing speed and additional kinds of age-related resources need to be distinguished, the relevant unit of measurement have to be latency ratios between young and old adults. Why? Age differences remain invariant across conditions with respect to the old-young ratio as long as processing speed is the only relevant age-related resource (e.g., Cerella, 1990; Salthouse, 1978, 1988a). Thus, to scrutinize the question of additional age-related resources, task variations need to be identified that not only produce an increase in age differences with respect to raw latencies—which was the case for every task variation applied in the present study—but also in terms of latency ratios. This reasoning is not based on statistical arguments, but on the knowledge that global slowing exerts a proportional effect on age differences in response latencies which has to be taken as a baseline for any additional effect.

The main technique chosen to identify those age effects that were larger than the proportional complexity effect was logarithmic transformation of latencies. With log latencies age-differential interactions are significant only when old-young ratios differ between conditions, as it was the case for the spatial versus the nonspatial conditions. It is also important to note that log latencies usually meet the homogeneity-of-variance assumption of the ANOVA in a far better way than raw latencies. Thus, following Cerella (1990), log transformation of latencies can be advised whenever “true” age  $\times$  condition interactions need to be distinguished from a general, slowing-based complexity effect. Aside from log transformation,



two additional methods of analysis were used. In the first, equivalence across age groups in terms of processing speed in sequential complexity conditions was simulated through practice. With this method, plasticity limitations in the two conditions involving spatial and object transformations could be demonstrated. The second method was the old-young function technique which is especially suited to identify deviations not only from a proportional slowing model but also from models assuming an overproportional increase of age effects as a function of complexity (e.g., Myerson et al., 1990).

The above techniques of representing age differences in latencies are clearly quite conservative, leaving only those effects that cannot be accounted for by general slowing. Also, the different methods yielded highly similar outcomes. Therefore, the main finding in this study, the fact that old adults are particularly slowed in coordinative complexity conditions, can be considered to be quite robust.

### *Conclusion*

The main age-differential effect found in the present study—the slowing of old adults in spatial conditions (i.e., coordinative complexity)—cannot be explained as the result of a speed-accuracy trade-off, qualitative different (optional) strategies between age groups, or the particular choice of data transformation. Rather, the fact that the effect was stable despite conservative methods of analysis and that it showed no tendency to become smaller after eight sessions of practice points to a fundamental limitation in old adults' processing.

### *Potential Effects of Cohort and Sampling*

An additional methodological factor needs to be considered. Ideally, groups in age-differential research should not differ in anything but age. As in most age-comparative studies, however, the current research is cross-sectional. Therefore, a confound between age and cohort may impose a severe threat to the internal validity of the design (Baltes, Reese, & Nesselroade, 1977). Could the main finding, the substantial age difference in the spatial conditions, be explained by factors other than age as an indicator of organismic change? A prime candidate for such an alternative factor are experience differences between young and old adults. In the area of intellectual functioning, the major research program allowing a distinction between the effects of cohort and age is Schaie's cohort-sequential study (Schaie, 1979, 1983). Of relevance in the current context

is the fact that in this study spatial ability and reasoning ability were found to show considerable “historical” increments as a function of cohort. Thus, later cohorts displayed on average higher levels of performance than earlier cohorts.

There is no way of resolving the principle interpretational ambiguity produced by the age-cohort confound in cross-sectional studies. Only plausibility arguments can be put forward. In this research, extensive instruction, training, and practice were used to bring participants close to their performance asymptote. It is one of the propositions of the testing-the-limits approach that near limits of plasticity biological constraints are more important than pre-experimental knowledge factors (Baltes, 1987; Baltes & Kliegl, 1992; Kliegl & Baltes, 1987). In other words, as practice unfolds cohort and age differences in experience are reduced. In addition, control analyses were conducted which proved the robustness of the main finding across variations of old adults’ age (below 75 vs. above 75), general cognitive status, and verbal knowledge. Thus, it is plausible to assume that the age  $\times$  condition interaction revealed in the present study can be attributed to ontogenetic development rather than to cultural change. The outcomes of the control analyses also provide evidence against the possibility that the present finding is a function of selection biases affecting the sample of old and young adults in different ways.

A question regarding external validity remains, however: To what degree is the finding obtained in this study generalizable beyond the present positive selection of young and old adults? It cannot be ruled out that different results would have been obtained for comparisons between different levels of ability within and between age groups, such as between less able young and old adults. For example, it is possible that less able young adults would be impaired in the spatial conditions in the same way as old adults. Also, it has to be acknowledged that generalizability of the present finding is limited to the contrast between young and old adults. It is an open question to what degree “young-old” (50 to 60 years) or middle-aged adults would exhibit a similar pattern of performance deficits.

### *Age Deficits in Working Memory versus Age Deficits in Spatial Processing*

In the preceding sections it was argued that the main finding is likely to represent a true effect of age as an indicator of organismic change. Even when taking this for granted, one can still question the significance of the

main finding for the theoretical distinction between sequential and coordinative complexity.

A proposition of this research is that high coordinative complexity (a) corresponds to high working memory requirements and (b) can be operationalized through spatial transformations of complex stimuli or the combination of both spatial and object transformations. Results pointed to the spatial transformation as the dominant source of age-differential constraints. Contrary to predictions, the combination of both spatial and object transformations did not produce additional age effects.

The fact that the main age  $\times$  condition interaction was produced solely by spatial transformations raises doubts as to whether the amount of working memory activities really is the critical aspect constraining old adults' performance. As an alternative, a domain-specific interpretation could be put forward. In general discussions regarding the organization of intelligence it has been argued that relatively independent faculties or subsystems corresponding to different domains of functioning can be distinguished (e.g., Detterman, 1986; Gardener, 1983). Some researchers, for example, have suggested that mental transformations in the two- or three-dimensional space constitute a unique processing domain governed by mechanisms differing from those underlying discrete, propositional processing (Kosslyn, 1981; Shepard & Metzler, 1971). Spatial processes by these researchers are assumed to be tied to an analogous medium in which spatial and metric relations between parts are preserved (e.g., Kosslyn et al., 1979; Shepard, 1982). Moreover, neuropsychological evidence points to neurological subsystems involved in mental imagery and spatial processing (Farah, 1988; Farah et al., 1985; Kosslyn, 1988). Kosslyn et al. (1985), for example, presented evidence for the existence of a specific module responsible for the mental integration of parts into a whole—a process which certainly is involved in many spatial tasks using complex stimuli. Finally, even from the working memory perspective, arguments have been presented for a visuo-spatial subsystem which is assumed to be distinct from the storage system for verbal information and the central executive (Baddeley, 1986; Baddeley & Lieberman, 1980).

On the basis of such a multidimensional view of intellectual functioning, one could argue that subsystems related to spatial processing and mental imagery are subject to a more pronounced age-related decline than other abilities. Thus, the results of the current study could represent age-specific limitations due to processing requirements in a specific cognitive and neuropsychological subsystem, rather than due to the more general, domain-unspecific dimension of coordinative complexity.

There is, though, also research which highlights the coordinative aspects and general working memory demands involved in complex spatial processing (Hertzog & Rypma, 1991; Just & Carpenter, 1985; Kyllonen, Lohman, & Woltz, 1984; Lohman, 1988; Yuille & Steiger, 1982). Even researchers proposing an analogous processing medium acknowledge the fact that spatial tasks often require a stepwise mode of processing and parallel retainment and transformation of stimuli (Bethell-Fox & Shepard, 1988). Finally, in comparison to other complex abilities, age differences in spatial processing do not stand out as being particularly pronounced. Salthouse (1985), for example, listed age correlations or effect sizes from numerous studies on age differences in memory, reasoning, and perceptual-spatial abilities. In general, it seems that the age effects in the various domains are quite similar in size.

The interpretational ambiguity between a domain-specific and a complexity-based interpretation cannot be resolved in the current study. Given the present results, the hypothesis that high coordinative complexity limits plasticity of old adults is plausible, but is not the only one possible. More research is needed in which the present confound is avoided. As a follow-up to this study, an experiment was conducted in which both spatial and no-spatial manipulations of coordinative complexity (implemented within a figural transformation task) were contrasted with a large variation in terms of sequential complexity (Mayr & Kliegl, in press). The results of this experiment revealed particularly pronounced slowing for *both* conditions high in coordinative complexity and less slowing when only sequential complexity was varied. Thus, this evidence lends support to the assertion that—within the domain of figural transformations—the present finding can be generalized beyond the domain of spatial processing.

### *General Conclusion*

Possible threats to the internal and external validity of the main outcome of this study were discussed at some length in the preceding sections. It can be concluded that the condition-specific age effect is difficult to explain in terms of strategic factors or cohort effects. In addition, even though a domain-specific interpretation of the main results cannot be ruled out completely, the central claim of this study, that old adults' processing was particularly constrained because of high coordinative complexity seems plausible. The following section will focus on the theoretical aspects of this finding and relate the study to the state of the

field as described in the introductory sections. In particular, issues related to general slowing and working memory will be considered.

## **Cognitive Slowing and Age-Related Working Memory Deficits**

### *Limitations of General Slowing*

As elaborated in the opening sections of this dissertation, prominent models in the current research on old-age intellectual functioning specify a general reduction in task-unspecific processing speed as a major cause of age-related changes in cognition (e.g., Cerella, 1985; Cerella, Poon, & Williams, 1980; Salthouse, 1985). All slowing models share the assumption that the cognitive system of old adults functions exactly the same way as that of young adults (i.e., the number of processing steps for a given task is age-invariant) except for a loss in *general* speed of processing.

Early models assumed that old adults, compared to young adults, are slowed by a constant factor of about 1.6. Based on recent meta-analyses (Cerella, 1990; Hale, Myerson, & Wagstaff, 1987), two newly introduced models, the information-loss model (Myerson et al., 1990) and the overhead model (Cerella, 1990), claim that slowing is nonlinear. Specifically, ratios between old and young adults are assumed to increase as complexity unfolds. In the present context, these latter models are of particular interest, because (a) they attempt to account for age differences across a wide range of complexity and (b) they specify the locus of age-related dysfunctioning in parameters of mathematical models. According to the information-loss model, old adults lose a larger amount of information with every single processing step than young adults. Cerella, in his overhead model proposes that with every processing step the organizational requirements increase for old but not for young adults.<sup>32</sup> Thus, both of these models hypothesize that nonlinear slowing is produced by an age-related increment to processing time requirements which increases with every step within a processing algorithm.<sup>33</sup>

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<sup>32</sup>Cerella's assumption of an "organizational" overhead has some similarities with the present conceptualization of age-differential working memory functioning in coordinative complexity conditions. However, whereas this overhead is unconditionally linked to each processing step, in the present research the assumption is made that age-sensitive coordinative activities are tied to particular task conditions (e.g., involving parallel storage and processing of information).

<sup>33</sup>In both models the term processing steps refers to an unobservable activity occurring at a very basic level of processing. In the information-loss model actually the transmission of information between neurons is specified as the relevant level.

What is the message of the present findings with respect to models proposing an unspecific reduction of processing speed? The first aspect is that a single slowing parameter cannot account for the pattern of results obtained in this study. Old adults were slowed twice as much in coordinative complexity conditions (spatial conditions) than in sequential complexity conditions (nonspatial conditions). As shown in Figure 15, two slowing functions emerged instead of one. Thus, the present finding qualifies the major claim of general slowing models, namely, that one single proportional or overproportional slowing process is sufficient to explain age effects in nearly all speeded tasks (e.g., Cerella, 1990).

The second important aspect is that the results of this study are in clear dissent with models proposing nonlinear slowing: Figure 15 shows that latencies can be represented almost perfectly by *two linear* functions. Thus, there is no evidence of overproportional slowing towards more complex conditions. Even when taking into account that there is some ambiguity concerning the precise age effects in the spatial-plus-object conditions because of old adults' high error rates, *there is no indication of a nonlinear process between sequential and coordinative complexity*.

How can the divergence between the present results and the data in the literature which propose one (nonlinear) slowing function be explained? Evidence in favor of the general slowing model reported so far was based on meta-analytic integrations of multiple data sets from a variety of different conditions (Cerella, 1990; Myerson et al., 1990). As already mentioned in an earlier section (*Critique of the General Slowing Account*), two aspects could be especially critical: (a) In the meta-analysis showing nonlinear slowing, long latencies were obtained mostly from mental rotation tasks, so that there is a confound between complexity and type of tasks. Thus, the nonlinear function might actually be a mixture of two linear ones, a shallow function for simple tasks and a steeper one for more complex (mental rotation) tasks. Note, that in the present study, spatial transformations as an implementation of coordinative complexity produced particularly large slowing. (b) All experiments incorporated in the meta-analyses used one-session assessments with minimal instruction and practice. Therefore, it is possible that large age effects responsible for the nonlinear function reflect less efficient strategies of old adults rather than slow processing speed (Charness & Campbell, 1988).

Thus, the current data suggest that coordinative complexity constitutes a boundary condition for any model assuming general slowing. The data are not, however, a complete refutation of the notion that a relatively unspecific decline in processing speed is an important factor in cognitive aging. In the sequential complexity conditions presented in this research,

a linear slowing factor of about 1.6 was obtained. This is very similar to the value reported in prior surveys of the literature (Cerella, 1985, 1990; Cerella, Poon, & Williams, 1980; Salthouse, 1985). The repeated finding of a slowing of this magnitude suggests that aging does correlate with a relatively general reduction of processing speed. It very likely can be attributed to changes on an implementational (i.e., hardware or physiological) level of processing and it seems to exert a proportional effect on age differences as long as coordinative activities are not involved (see Cerella [1990] for an elegant model of an implementational level decrement leading to linear slowing).

With the rejection of models assuming a single (nonlinear) slowing process, the current results challenge the reductionist approach of specifying a very general, implementational, and purely quantitative aspect of processing as the *only* locus of age-related cognitive decline. More fruitful might be a perspective which focuses not only on processing speed as an implementational parameter of a cognitive system but also on the possibility of additional age effects as a function of the *algorithmic and working memory demands* of the task. In the following section, such a view will be applied to the present data.

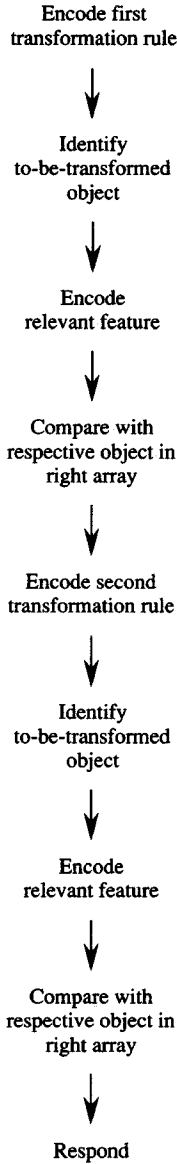
### *Working Memory Functioning in Speeded Tasks*

How can the finding of two different “slowing factors” be explained? Assuming that coordinative complexity requires working memory activities, which aspect of working memory functioning could be responsible for the large age effects in terms of response latencies? The interpretation offered here rests on the following two assumptions: (a) In sequential complexity conditions, age differences in response times reflect a relatively general, proportional slowing. (b) In coordinative complexity conditions, however, the long response latencies of old adults indicate additional time-consuming compensatory activities after loss of information from working memory. Working memory failures are assumed to occur with higher probability for old adults than for young adults.

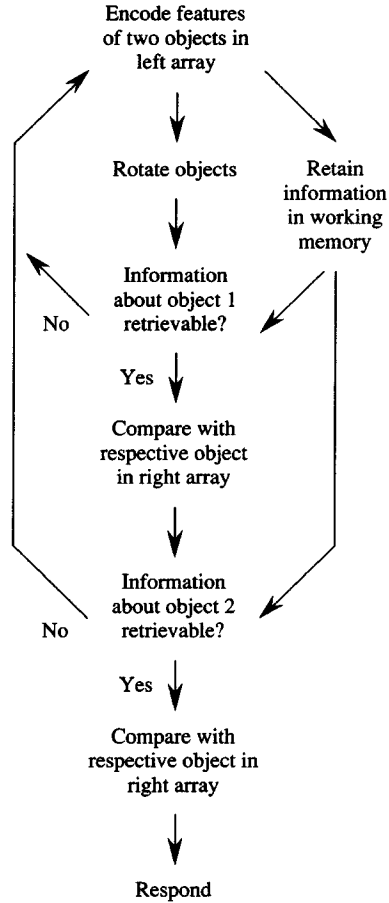
Figure 19 (right panel) illustrates in a simplified way how working memory constraints could influence processing in an item with a rotation (see Figure 6b). Note, that this transformation required attending to two objects (with three relevant features each). Thus, six features from left-array objects had to be encoded and stored in working memory while identifying the rotated or reflected counterparts in the right array. Very likely, young adults, because of their presumably larger working memory

**Figure 19**  
**Simplified Flowcharts of an Item with Two Object Transformations**  
**and an Item with a Single Rotation (Yes-Items)**

*0-Spatial/2-Object*



*1-Spatial/0-Object*



*Note.* The upgoing arrows in the right panel reflect recursions through the processing sequence and are assumed to be mainly a characteristic of old adults' processing. Note, that these are not necessarily the only possible "algorithmic paths" through the items.



capacity, could retain and transform all necessary information in a fluent sequence and maybe even simultaneously.

Assuming an age-related reduction in working memory capacity, old adults probably experienced loss of relevant information more often forcing them into additional recursions through the processing sequence. Age-related increase in the tendency to lose information within complex tasks has been reported by numerous studies (e.g., Hertzog & Rypma, 1991; Light, Zelinski, & Moore, 1982; Offenbach, 1974; Salthouse et al., 1989; Young, 1966). Within the algorithmic sequence presented in Figure 19 (right panel), there are two occasions at which loss of information requires recursions through the processing sequence. Note also, that flowcharts for the other coordinative complexity items (i.e., a spatial transformation and one or two additional object transformations) would contain even more potential "break-points" at which recursions due to information loss could become necessary.

Such a view of the role of working memory in spatial processing is in line with observations from cognitive research on spatial ability. For example, Kyllonen, Lohman, and Woltz (1984) showed that high-ability subjects in a complex visualization task processed much information simultaneously and in an integrative way. In contrast, low-ability subjects deployed more step-by-step processing and more often required recovering of information earlier processed. In a similar vein, Just and Carpenter (1985) demonstrated that low-ability subjects often need several attempts and a piecemeal mode of processing to rotate complex figures, which the authors attributed to working memory constraints.

In contrast to the flowchart of a coordinative complexity item, consider the flowchart of a "complex" item from the sequential complexity conditions, an item with two object-related transformations (Figure 19, left panel). The figure shows that such an item certainly requires more processing steps than an item with a single spatial transformation. This is indicated by the fact that the response times for the condition with two object transformations are longer than for the spatial transformation condition (about 1.9 vs. 0.6 s for young adults and 3 vs. 1.5 s for old adults in Session 8). However, in contrast to spatial transformations no parallel storage and processing of information is necessary here. The processing sequence contains no "break-points" leading to recursions through the sequence because of potential loss of information. Thus, aside from a basic slowing, old adults and young adults should perform items of this kind with similar efficiency.

It still needs to be shown that such a probabilistic "failure-plus-recursion" model is capable of accounting for the present finding of two linear

slowing functions. Formalization of the model can help to clarify this issue. Our assumptions are that (a) in coordinative complexity conditions information which 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

$$(1) \quad L_O = b * L_Y$$

where  $L_O$  is the time for old adults,  $L_Y$  is the time for young adults, and  $b$  is the basic slowing factor in the following way:

$$(2) \quad L_O = 1/p * b * L_Y$$

where  $p$  is the probability of not having to repeat processing steps (relative to young adults) because of information loss from working memory.<sup>34</sup> The value for the basic slowing factor  $b$  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 slope of 1.58 in sequential complexity conditions can be used as an estimate of the basic slowing value  $b$ . When setting  $L_Y$  to 1 and  $L_O$  equal to the slowing ratios in coordinative complexity conditions ( $L_O = 2.17$ ) a value for  $p$  of .73 is yielded. Thus, the assumption that in coordinative complexity conditions old adults with higher probability than young adults need to repeat the processing sequence is compatible with the pattern of results obtained in this experiment.

The main reason for this formalization was not to provide a detailed processing model for the present task (which would not be possible on the basis of present knowledge). Rather, the intention was to demonstrate that the assumption of probabilistic working memory failures above a general reduction of processing speed can, in principle, account for the present finding of two linear slowing functions.

There are a few additional pieces of evidence in the present data which support the view on age-differential working memory functioning pro-

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<sup>34</sup>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 yields:

$$L_O = b * L_Y + (1 - p) * b * L_Y + (1 - p) * (1 - p) * b * L_Y \dots$$

This series can be rewritten as  $L_O = 1/p * b * L_Y$ . A similar logic was used by Cerella (1990) to explain simple proportional slowing as a function of breakage of neural links.

posed here. For example, old adults produced higher error rates in two of the three coordinative complexity conditions throughout practice. This seems to be a plausible outcome assuming loss of information as a relevant source of age differences in response speed. It is likely that (old) participants were not aware of every loss of information from working memory so that a certain proportion of responses are incorrect because they are provided on the basis of false information.

A second set of results in support of this probabilistic recursion model comes from the percentile analysis of latency distributions. In coordinative complexity conditions, latency distributions of old adults contained a larger proportion of long latencies than the distributions from old adults in sequential complexity conditions and those of young adults in both sequential and coordinative conditions. The overproportional long response times of old adults can be interpreted as reflections of time-consuming recursions through the processing algorithm after information loss.

Finally, a third indication of the working memory problems of old adults in coordinative complexity conditions comes from the testing-the-limits assessment before and after practice. Old adults exhibited very low accuracy scores in items containing two spatial transformations. Using a probabilistic failure-rate model, performance breakdown of old adults could be attributed to the high coordinative demands in these conditions. Interestingly, young adults showed no comparable problems with coordinating spatial transformations.

The above support for the probabilistic recursion model is somewhat indirect. Thus, a final evaluation of this model is difficult on the basis of present evidence. The overall pattern of results suggests, however, that the long response times of old adults under high coordinative complexity are at least in part produced by working memory failures. Further research along these lines promises insights both into the nature of age differences in complex cognitive processing and the characteristics of working memory functioning. A task for future research will be to find better ways for assessing paths through a sequence of processing steps in order to distinguish speed-based explanations from algorithm-based explanations of age effects in complex tasks.

A final qualification referring to the relation between processing speed and working memory needs to be considered. The present data suggest that the two aspects constitute distinct sources of age-differential processing limitations. However, it may turn out in the future, that by some indirect linkage, age-related loss in speed produces age effects in working memory. On the one hand, there are some findings in the literature

suggesting that speed may be one determinant of certain aspects of working memory capacity, such as memory span (e.g., Baddeley, 1986; Hasselhorn, 1988; Nicolson, 1981). On the other hand, research on general interindividual differences suggests that the two aspects, speed and working memory, are connected only loosely (e.g., Kyllonen & Christal, 1990). Thus, final conclusions have to await further research on determinants of working memory functioning.

To summarize, a tentative model was proposed which explains age-differential effects in sequential and coordinative complexity conditions as a function of age-related decline in processing speed and working memory capacity. The main assumption of this model is that age effects in sequential complexity conditions are governed by a relatively general slowing process, while the number of processing steps is invariant across age groups. In coordinative complexity conditions, however, old adults are not only slowed but also require more processing steps than young adults because they have to compensate loss of information in working memory. The model can account not only for the finding of two linear slowing processes as a function of sequential and coordinative complexity but is also consistent with the results regarding the age-differential latency distributions and the error patterns obtained in this study. Future tests of this model will have to focus on the actual processing sequences of old and young adults and on the functional linkage between speed and working memory.

### **Aging and Learning**

The fact that participants were exposed to eight practice sessions, so far, was considered mainly from the viewpoint of a precise assessment of age effects at performance limits. However, an additional focus of the present research was on the substantive issue of potential age effects in terms of procedural learning. Specifically, old adults were predicted to exhibit learning rates similar to those of young adults in sequential complexity conditions. In contrast, a slower rate of improvement was predicted for old adults than for young adults in the coordinative complexity conditions. This expectation was based on the assumption that learning mechanisms constrained by working memory capacity should be more important in these conditions than in sequential complexity conditions (Anderson, 1987; Charness & Campbell, 1988; Woltz, 1988). Results did not support this prediction: *Highly similar rates of improvement across age groups were revealed in all task conditions.*

There is an ongoing discussion in the literature with respect to the question of age-specific learning deficits (Cerella, 1991; Fisk, McGee, & Giambra, 1988; Fisk & Rogers, 1991). Some researchers claim that particular learning mechanisms, such as automatization in visual search, are impaired in old adults (Fisk & Rogers, 1991). In contrast, proponents of cognitive slowing argue that most changes of age effects across practice can be portrayed in terms of a general slowing effect (Cerella, 1991; Myerson et al., 1990). Also, there is a growing body of evidence indicating that age effects in terms of procedural learning in simple tasks are small to nonexistent (e.g., Cerella, 1991; Madden & Nebes, 1980; Plude & Hoyer, 1981; Salthouse & Somberg, 1982).

The particular contribution of the present research is that compared to most other studies, complexity of the practice task was manipulated across a wide range. The fact that skill acquisition was age-invariant across conditions suggests that learning is "immune" against aging, even in highly complex tasks. This aspect is demonstrated nicely in the old-young function (see Figure 15): Within sequential and coordinative complexity conditions, common slowing functions emerged across practice sessions and the variation of the number of object transformations. Thus, the present findings constitute a qualified confirmation of the general slowing position: Proportional age effects are constant across practice, yet differ as a function of sequential versus coordinative complexity.

In one other study using a highly complex task, similar learning for old and young adults was obtained: Charness and Campbell (1988) trained young, middle-aged, and old adults in a mental squaring task for six sessions. Although there were some indications that old adults profited less in terms of working memory management than middle-aged adults, power function learning rates were highly similar between old and young adults irrespective of task complexity.

Theoretically, the accumulating evidence, indicating that procedural learning is unaffected by age, points to an independence between learning mechanisms and the broad spectrum of cognitive abilities known to be affected by age-related decrements. It needs to be taken into regard, however, that assessment of individual and age differences in learnability is difficult for a number of reasons (e.g., Ackerman, 1987; Cronbach & Snow, 1977; Flammer, 1975; Ruch, 1933; Snow, Kyllonen, & Marshalek, 1984; Thorndike et al., 1928). Thus, before accepting such a strong conclusion some possible qualifications of the present pattern of results need to be considered.

One important aspect is that age groups usually (also in this study) differ in terms of baseline performance (Goulet, 1972), and one can only

speculate what effect this has on the validity of learning parameters. Two features of the present study were meant to counteract the problem of age effects in baseline performance.

First, age-differential learning was analyzed by estimating individual power functions for learning curves in each condition (Charness & Campbell, 1988; Newell & Rosenbloom, 1981). The estimation of power functions is based on log transformations of latencies and sessions. This is important as old and young adults, because of the large initial age effects in terms of response latencies, operated in different regions of the measurement space which is known to be distorted for latencies (see *Representation of Raw Latencies*). Representing learning in terms of power function parameters (e.g., the learning rate) is equivalent with comparing proportional age differences and thus corrects for the measurement problems introduced by the fact that old adults are generally slower than young adults.

Second, an attempt was made to equate participants with respect to their principle ability to perform the Figural Transformation Task with high accuracy by deploying a tutor-guided learning-to-criterion procedure prior to testing and practice. However, although in certain conditions old adults received up to three times more guided practice and instruction than young adults, age differences in terms of accuracy were still observable in the coordinative complexity conditions at the beginning of practice. Thus, it cannot be excluded that age differences in terms of the task-related knowledge base prior to practice distorted the true pattern of age-differential learning.<sup>35</sup>

A final aspect to be mentioned here is that even the conditions used in the present research may still not be sufficiently complex in terms of providing a learning space large enough for individual or age differences to unfold (Cronbach & Snow, 1977). In this context, it is interesting to compare the present results with studies in which young and old adults were trained in an imagery-based mnemonic technique for remembering word pairs (method of loci; Kliegl, Smith, & Baltes, 1989; Kliegl, Smith, & Baltes, 1990; Thompson & Kliegl, 1991). The optimization of a knowledge-

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<sup>35</sup>For example, it is known that the largest amount of improvement occurs in the early stages of learning (e.g., Newell & Rosenbloom, 1981). It is possible that old adults needed the first encounters with the Figural Transformation Task (e.g., during the learning-to-criterion procedure or the Prepractice Assessment) to build up a basic knowledge base and, thus, experienced the large "initial" improvement after practice has started. In contrast, young adults might have exhibited this large speed-up in the first encounters with the task and thus were already much closer to their asymptote than old adults when entering practice. In this case, old adults' learning rate would be overestimated relative to that of young adults: It would reflect not only the gradual approach to the asymptote but also the large initial speed-up of performance.

base supporting fluent construction of interactive images constitutes probably a nearly open-ended task and learning space. Here, age effects increased across training and practice.

Given these qualifications, the question of age differences in procedural learning has to remain unresolved. It seems, however, that if age effects do exist they are relatively small within the range of complexity studied so far. On a theoretical level, this repeated finding of similar learning for young and old adults may indicate that large proportions of procedural learning mechanisms are applied automatically and thus are not affected by age-related cognitive resources. In this context, future research would profit from a precise taxonomy of learning mechanisms and their limitations. It is relatively easy to specify which tasks require working memory processes; it is, however, much more difficult to be specific about the question whether, in a particular task, *learning mechanisms* require working memory or not. In this research the assumption was made that in coordinative complexity conditions, a large amount of task-related knowledge needs to be considered. Therefore, based on Anderson's model of skill acquisition (e.g., Anderson, 1987; Woltz, 1988), the build-up of a stable declarative knowledge-base and the integration of single operators (i.e., productions) into efficient processing routines (i.e., composition) was proposed to be constrained by working memory capacity. The underlying idea was that of working memory as a "needle's eye" for highly efficient processing routines. This notion probably remains an interesting one even though it could not be confirmed in this study. Future research, however, should be aware of the fact that complexity alone is most likely not the sole critical aspect modulating difficulty of learning and thus of age differences in learnability (see also Charness & Campbell, 1988). Additional aspects to consider might be the degree of redundancy in the learning environment or the number of different routines to be acquired and applied across items.

### Conclusion and Outlook

The main contribution of this study to the longstanding search for mechanisms in cognitive aging is the demonstration that age-differential performance limits in speeded tasks are determined by at least two dimensions of task complexity (sequential and coordinative). On the one hand, this particular outcome adds to the converging evidence that age effects show a relatively large regularity across tasks conditions. This general finding can be attributed, most likely, to age-related changes in a

relatively small set of basic parameters of the cognitive system. On the other hand, this research qualifies the extreme reductionism of recent models proposing general slowing as the main source of age-related changes (e.g., Cerella, 1990; Myerson et al., 1990). Rather, the present finding draws attention to the possibility of additional age-specific constraints, such as working memory capacity.

This study offers a new perspective on the age  $\times$  complexity phenomenon, but, at the same time, is limited in design and selected measures. Therefore, a number of questions for further research emerge. An unsettled issue is, for example, the generality of the phenomenon observed: Does the present distinction between sequential and coordinative complexity hold also for larger variations of the two task dimensions? Can different complexity dimensions be distinguished in other processing domains, such as episodic memory (Kliegl, Mayr, & Krampe, *in press*)? Of equal importance is the question whether the dissociation between sequential and coordinative complexity would resist further practice and training (Baltes & Kliegl, 1992).

In addition, the interpretation put forward in this study that age effects in coordinative complexity conditions are a function of both slowing and working memory deficits needs further investigation. In the future, an attempt should be made to gain more information about working memory functioning in complex, speeded tasks. This could be established, for example, by using refined assessment techniques, such as the registration of eye movements (Carpenter, Just, & Shell, 1990; Just & Carpenter, 1985), which allow assessment of individual differences in cognitive algorithms.

This study was designed from a cognitive-experimental perspective. Therefore, the sole focus was on mean age effects. Additional important information could be gained by the analysis of covariations (e.g., Hertzog, 1989; Lindenberger, Mayr, & Kliegl, 1993; Salthouse, 1991). In particular, the claim that age effects in coordinative and sequential complexity conditions represent distinct age-related resources can be translated into hypotheses about covariation patterns. For example, working memory measures should explain additional age-related variance after accounting for measures of processing speed in coordinative complexity conditions, but not in sequential complexity conditions. The test of such hypotheses is an important task for future research.

Finally, shifting the viewpoint, the present research can be evaluated also from a more general interindividual differences perspective. Description and explanation of the faculties of mind is the main goal of this research tradition (e.g., Carroll, 1981; Cattell, 1971; Gardener, 1983;



Jensen, 1985; Hunt, 1978; Spearman, 1923; Sternberg, 1985; Thurstone, 1938). In particular, during the last 15 years there has been an effort from cognitive psychologists to identify the basic cognitive skills constituting the ability clusters which have emerged from the psychometric research tradition (e.g., Hunt, 1978; Mulholland, Pellegrino, & Glaser, 1980; Sternberg, 1983). This endeavour has yielded only moderate success (e.g., Keating, 1984; Kyllonen & Christal, 1990; Sternberg, 1990). It seems as if the segregation of complex performance into basic components eliminated critical aspects of complex functioning. In contrast, the present approach preserves important characteristics of complex processing and is analytic at the same time. Through the strategy of manipulating task complexity in a well-controlled and theoretically meaningful manner, two distinct sources of age differences could be identified. It seems promising to apply this perspective to interindividual differences research in psychometric intelligence. Such an approach might provide new insights into the way important aspects of interindividual variability emerge as task complexity unfolds. It is the hope of the author that research along these lines has the potential of contributing not only to our knowledge about mechanisms in cognitive aging, but also about complex functioning in general.

# Appendix

## Appendix A: Supplementary Tables

Table A-1  
Mean Latencies (*SD*) Broken Down by Session (1 vs. 8), Response Type (Yes/No), Group (Young/Old), and Task Conditions

Session	Response	Group	Condition (Spatial-Object)					
			0-0	0-1	0-2	1-0	1-1	1-2
1	Yes	Old	1,927 (705)	2,176 (389)	4,228 (1,094)	2,986 (916)	6,461 (2,719)	9,834 (3,514)
		Young	774 (299)	1,477 (251)	2,729 (433)	1,484 (394)	3,205 (824)	4,849 (1,204)
	No	Old	1,582 (430)	2,431 (466)	4,126 (1,381)	3,083 (1,692)	6,206 (2,462)	8,705 (3,366)
		Young	743 (193)	1,553 (267)	2,389 (492)	1,451 (307)	2,938 (741)	3,807 (1,014)
	Yes	Old	560 (144)	1,573 (288)	3,131 (611)	1,538 (546)	3,963 (1,399)	6,211 (2,009)
		Young	308 (71)	981 (131)	1,975 (293)	661 (203)	1,750 (363)	2,921 (595)
8	No	Old	565 (133)	1,616 (298)	2,641 (550)	1,573 (514)	3,916 (1,499)	5,295 (1,818)
		Young	315 (66)	1,022 (130)	1,698 (266)	681 (146)	1,603 (329)	2,250 (528)

Table A-2  
Mean Percentages (*SD*) for True Errors (False Responses) Broken Down  
by Session (1 vs. 8), Response Type (Yes/No), Group (Young/Old),  
and Task Conditions

Session	Response	Group	Condition (Spatial-Object)					
			0-0	0-1	0-2	1-0	1-1	1-2
1	Yes	Old	.77 (1.60)	6.33 (4.65)	4.63 (3.44)	7.87 (6.34)	18.36 (10.49)	22.07 (9.97)
		Young	3.89 (3.04)	7.78 (5.67)	3.33 (3.89)	9.31 (8.12)	5.56 (4.94)	6.67 (3.97)
	No	Old	3.70 (4.86)	7.41 (6.17)	8.33 (12.24)	15.28 (10.18)	30.25 (11.90)	22.38 (11.21)
		Young	3.75 (4.62)	7.36 (7.17)	5.83 (5.25)	8.61 (8.35)	15.42 (8.62)	9.72 (7.07)
	Yes	Old	4.63 (6.25)	4.32 (3.46)	2.62 (3.23)	9.41 (6.33)	12.81 (3.18)	18.52 (8.31)
		Young	9.31 (6.26)	11.39 (10.85)	3.89 (3.65)	11.25 (8.85)	6.53 (4.44)	6.67 (5.21)
8	No	Old	6.17 (5.09)	6.79 (5.65)	4.94 (4.62)	13.27 (9.88)	33.64 (14.60)	19.91 (9.63)
		Young	7.08 (4.89)	8.47 (6.01)	10.42 (7.59)	9.72 (5.66)	18.75 (10.58)	14.03 (9.68)

Table A-3  
Mean Percentages (*SD*) for Time-Out Errors Broken Down by Session  
(1 vs. 8), Response Type (Yes/No), Group (Young/Old), and Task Conditions

Session	Response	Group	Condition (Spatial-Object)					
			0-0	0-1	0-2	1-0	1-1	1-2
1	Yes	Old	7.25 (4.87)	6.94 (4.79)	6.17 (4.42)	5.25 (5.12)	3.55 (4.35)	3.40 (3.24)
		Young	6.11 (3.99)	6.39 (3.38)	10.00 (4.63)	4.86 (3.81)	5.97 (4.53)	7.64 (4.49)
	No	Old	6.64 (5.88)	11.11 (4.86)	8.95 (5.35)	6.79 (3.72)	4.32 (4.07)	4.63 (5.22)
		Young	9.17 (6.12)	7.36 (3.75)	6.67 (4.27)	5.69 (4.64)	5.14 (4.88)	4.72 (3.83)
	Yes	Old	12.50 (5.49)	9.57 (5.15)	11.88 (4.93)	5.40 (4.41)	3.24 (4.18)	5.09 (4.79)
		Young	8.61 (5.55)	6.53 (4.88)	8.75 (5.79)	4.03 (3.55)	6.11 (3.56)	7.22 (5.44)
8	No	Old	14.35 (6.27)	11.57 (4.18)	9.41 (5.81)	6.94 (4.97)	3.40 (4.72)	4.78 (4.13)
		Young	10.56 (5.74)	8.33 (6.05)	6.81 (4.27)	6.81 (3.87)	4.58 (3.64)	5.14 (3.85)

Table A-4  
Intercorrelations for all Six Task Conditions in Sessions 1 and 8,  
Cronbach's  $\alpha$  (in the Diagonals), and Stabilities between Sessions 1 and 8  
Separately for Old ( $N = 18$ ) and Young ( $N = 20$ ) Adults

		Session 1						Session 8						Stability
		Conditions (Spatial-Object)						Conditions (Spatial-Object)						
		0-0	0-1	0-2	1-0	1-1	1-2	0-0	0-1	0-2	1-0	1-1	1-2	
Old	0-0	.77	.18	.20	.10	.09	.40	.94	.58	.28	.38	.35	.38	-.02
	0-1		.90	.77	.13	.65	.67		.96	.83	.29	.59	.59	.69
	0-2			.95	.32	.71	.71			.97	.08	.55	.42	.70
	1-0				.94	.61	.45				.95	.40	.53	.74
	1-1					.94	.78					.95	.80	.59
	1-2						.93						.98	.58
Young	0-0	.95	.58	.48	.46	.56	.46	.98	.50	.46	.75	.61	.66	.61
	0-1		.92	.66	.61	.64	.65		.94	.80	.48	.77	.86	.70
	0-2			.95	.43	.63	.80			.96	.34	.73	.88	.88
	1-0				.94	.66	.60				.98	.59	.59	.53
	1-1					.94	.86					.95	.89	.59
	1-2						.95						.95	.84

## **Appendix B: Recruitment Process**

Most old adults were recruited from a pool of subjects who participated in an earlier study in which various personality and intelligence measures had been administered ( $N = 99$ ). In the feedback session to this larger study, general aspects of the present research were described and those subjects who wished to participate were asked to leave their names and telephone numbers. About 60 old adults volunteered to participate. The final sample was selected by using the following criteria: age of the subjects (equal number of subjects below and above 75 and not younger than 65 years), sex (as women were overrepresented in the sample, as many men as possible were selected), and fluid intelligence (respecting the criteria of age and sex, the best scoring subjects on the fluid ability factor were selected). Due to various reasons (e.g., bad eye sight, vacation, health problems), only 15 old adults could be selected this way. Five additional old adults were recruited who were referred by participants of earlier studies.

Young adults were recruited by an announcement which was posted at the campus of the Berlin Free University.

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## CURRICULUM VITAE

### Name

Ulrich Mayr

### Born

May 7, 1962      Ingolstadt, FRG

### Citizenship

German

### Education

1981

Abitur

Gymnasium Erding, Erding

1982 - 1988

Diploma in Psychology

Free University, Berlin

### Professional Experience

1986 - 1988

Research Assistant

Free University, Berlin

1988 - 1991

Pre-doctoral Research  
Fellow

Max Planck Institute for  
Human Development and  
Education, Berlin



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Gestalt und Funktion nichtstaatlicher Schulen im

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623 S. Stuttgart: Klett-Cotta, 1979.



**M**ayr untersucht am Beispiel figuralen Problemlösens altersbezogene Leistungsgrenzen der Intelligenz und des Gedächtnisses. Die Frage ist, ob die Bedingungen für kognitives Altern im Bereich der fluiden Intelligenz in einem einzelnen, unspezifischen Prozeß zu suchen sind, oder ob sich verschiedene Mechanismen unterscheiden lassen. Der Autor differenziert zwischen zwei Dimensionen der Aufgabenkomplexität, die mit jeweils unterschiedlichen, altersabhängigen Mechanismen im Zusammenhang stehen: sequentielle bzw. koordinative Komplexität. Mit dieser in der empirischen Untersuchung bestätigten Unterscheidung fügt Mayr einen wichtigen differenzierenden Aspekt zum Bild kognitiven Alterns hinzu. Altersabbau in verschiedenen intellektuellen Leistungen läßt sich demnach nicht auf einen einzigen, letztlich physiologisch zu begründenden, Parameter reduzieren. Vielmehr müssen die kognitiven Aspekte der Aufgabenbearbeitung (Reduktion der Arbeitsgedächtniskapazität) mit berücksichtigt werden.

