STUDIEN UND BERICHTE 58

Ralf Th. Krampe

Maintaining excellence

Cognitive-motor performance in pianists differing in age and skill level

Max-Planck-Institut
für Bildungsforschung

Ralf Thomas Krampe, geboren 1962 in Bochum, studierte Psychologie an der Ruhr-Universität Bochum und an der University of Colorado in Boulder (USA) als Fulbright-Stipendiat. Die Schwerpunkte seiner Studien waren Kognitive Psychologie und die Entwicklung von Expertise. 1988 Promotionsstipendium der Max-Planck-Gesellschaft; von 1991-1993 Post-Doctoral Fellow am Max-Planck-Institut für Bildungsforschung in Berlin; seit 1994 wissenschaftlicher Mitarbeiter am Psychologischen Institut der Universität Potsdam.

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Abstract

The study investigated the role of *deliberate* practice in the acquisition and maintenance of high-level skills as a pianist. The notion of deliberate practice is used to distinguish efforts directed at improving or maintaining specific skills from mere experience in a domain. Participants ($N = 48$) were four groups of pianists differing in age (young: $M = 24.7$ years; elderly: $M = 60.3$ years) and skill level (professionals vs. amateurs). Current levels of practice and involvement in other skill-related activities were measured with a detailed diary. Past amounts of training were derived from subjects' retrospective estimates. Piano playing skill was assessed through finger-tapping tasks, speeded bimanual coordination tasks, memorization of movement sequences, and the musical interpretation of a short piece.

General markers of cognitive-motor speed revealed similar age-related declines in both skill groups. Expert pianists were superior to amateur pianists in all skill-related tasks, and skill effects increased with task complexity. While elderly experts generally performed at the level of their young counterparts, typical age-related decline of speeded cognitive-motor functions was observed in elderly amateurs. Performance in non-speeded tasks, like memorization of movement sequences and the systematic variation of speed and loudness in musical performance showed no age-related decline.

Current involvement in skill-related activities was similar in young and elderly experts; however, elderly professionals had decreased their active practice to 40 percent of the weekly amount practiced by young experts at the time of investigation. A model based on a power-law relation between practice intensity during various life-phases and performance could account for group differences in skill-related tasks and explained additional interindividual differences within groups in the most complex task conditions. Maintenance practice (the amount of exercise during the last ten years) showed the strongest relation to interindividual differences in the elderly expert group. Results are taken as support for a model of selective maintenance of specific skills through deliberate practice.

Zusammenfassung

In der vorliegenden Arbeit wird der Einfluß jahre- oder jahrzehntelangen Trainings in einer natürlichen Fertigkeit (Klavierspielen) auf die Entwicklung kognitiv-motorischer Funktionen im Erwachsenenalter untersucht. Es wurden die Leistungen von Personen verglichen, die sich in den Dimensionen Alter und Können (Berufsmusiker vs. Amateurpianisten) unterschieden. Die vorliegende Arbeit verbindet somit Fragestellungen aus der Tradition der Erforschung besonderer Fertigkeiten *(Expertise)* und der Entwicklungspsychologie der Lebensspanne. Die zentrale These, die der Untersuchung zugrunde lag, war, daß interindividuelle Unterschiede in kognitiven und motorischen Leistungen, die eine hohe Relevanz für die untersuchte Expertise haben, wesentlich durch den gegenwärtigen und früheren Übungsaufwand für den Erwerb und Erhalt der Expertise bedingt sind. Die wichtigste Implikation dieser These ist, daß altersbedingte Veränderungen bei Fertigkeiten, die im Rahmen der Expertise trainiert werden, geringer ausfallen als bei solchen kognitiv-motorischen Funktionen, die keine direkte Relevanz für das Klavierspielen haben. Die untersuchte Problemstellung zielte darüber hinaus auf die Klärung der Frage, inwieweit altersbedingte Veränderungen in einfachen und komplexen kognitiv-motorischen Fertigkeiten durch gezieltes Training moderiert oder gar kompensiert werden können.

Der theoretische Hintergrund der vorliegenden Arbeit ist der „Peak Performance"-Ansatz, der die Entwicklung von Personen, die in ihrem speziellen Gebiet Höchstleistungen erbringen, zum Gegenstand hat (Ericsson, 1990; Ericsson, Krampe, & Tesch-Römer, 1993; Ericsson, Tesch-Römer, & Krampe, 1990). Im Vordergrund dieses Ansatzes steht die These, daß Personen, die außergewöhnliche Leistungen in einem Gebiet erbringen, über ihr ganzes Leben hinweg erfolgreich die Effizienz ihres Aufwandes an Zeit und Energie für den Erwerb und Erhalt spezieller Fertigkeiten optimieren. Können und Leistung wird in diesem Modell zu jedem Zeitpunkt des Lebens als eine Funktion früheren und gegenwärtigen Übungsaufwandes für die Entwicklung der Expertise erklärt. Die Betonung der Bedeutung adaptiver Prozesse während der gesamten Lebensspanne charakterisiert den Peak Performance-Ansatz als eine Integration von Ansätzen in der Entwicklungspsychologie der Lebensspanne (z. B. Baltes, 1987) und Konzepten aus der Expertise-Forschung. In ihrem Modell zur Entwicklung von außergewöhnlichen Leistungen in natürlichen Fertigkeiten betonen Ericsson, Krampe und Tesch-Römer den Unterschied zwischen *Übung* und *Erfahrung*. Übung wird von den Autoren nicht als der bloße Gebrauch von Fertigkeiten, sondern als gezielte Tätigkeit, mit dem Vorsatz, das eigene Können zu verbessern, definiert. Der Erwerb außergewöhnlicher Fertigkeiten setzt in diesem Modell die fortwährende Steigerung des Übungspensums bis zum Erreichen des optimalen Niveaus im frühen Erwachsenenalter voraus. Nur in wenigen Bereichen menschlichen Könnens gibt es

eine klare Abgrenzung zwischen Üben und anderen Tätigkeiten, die es Individuen erlauben würde, präzise Auskünfte über ihren Trainingsaufwand zu geben. Sport und musikalisches Instrumentalspiel sind solche Bereiche. Ericsson, Krampe und Tesch-Römer haben vor kurzem eine Studie vorgelegt, in der früherer und gegenwärtiger Übungsaufwand für das Violinespielen mit Hilfe retrospektiver Zeitschätzungen und eines Tagebuchs erfaßt wurden. Die Autoren konnten zeigen, daß die Leistungsunterschiede zwischen drei Gruppen von Studenten einer Musikakademie durch die so gewonnenen Messungen früheren und gegenwärtigen Übungsaufwandes erklärt werden konnten. In der Sportpsychologie sind Leistungsabbau sowie nachlassende Effizienz physiologischer Prozesse bei Athleten im mittleren Erwachsenenalter mit veränderter Trainingsintensität in Verbindung gebracht worden. In seiner Diskussion entsprechender Befunde kommt Ericsson zu dem Schluß, daß die Entwicklung besonderen Könnens im späteren Erwachsenenalter vor dem Hintergrund rein altersbedingter Effekte auf physiologische Prozesse, Veränderungen in Intensität und Ausmaß von Training und möglichen Interaktionen dieser beiden Faktoren zu sehen ist.

Die Verfügbarkeit von erworbenem Wissen und die Effizienz motorischer Fertigkeiten nehmen proportional zum zeitlichen Abstand vom Zeitpunkt ihres Erwerbs ab, wenn sie nicht durch fortgesetzten Gebrauch erhalten werden (Annett, 1979; Ericsson & Crutcher, 1988). In Studien über den Erhalt von Wissen, das vor längerer Zeit in natürlichen Kontexten erworben wurde, waren biographisches Alter und die Dauer des Behaltensintervalls naturgemäß konfundiert. Der Schwerpunkt bisheriger Untersuchungen lag auf der kognitiven Repräsentation der Gedächtnisinhalte, während ontogenetische Faktoren weitestgehend vernachlässigt wurden (z. B. Bahrick, 1984; Bahrick & Hall, 1991). Die in diesen Studien untersuchten Fertigkeiten waren durchweg auf einem geringen Könnensniveau und wurden während des Behaltensintervalls wenig oder gar nicht trainiert. Die zuverlässige Messung und statistische Kontrolle von Übungsaufwand während langer Zeiträume haben sich bei der Untersuchung des Erhalts von Wissen und Fertigkeiten als ein methodisches Problem erwiesen. Modelle aus der Tradition der Expertise-Forschung (Anderson, 1982; Fitts, 1954) führen zeitliche Stabilität auf den Erwerb spezifischer Mechanismen der Informationsverarbeitung zurück, die die erworbenen Fertigkeiten resistent gegen Interferenz machen. Die zunehmende Spezifität erworbener Mechanismen verringert auf der anderen Seite den Nutzen (Transfer) des entsprechenden Trainings für den Erhalt genereller Funktionen, die für die Expertise weniger wichtig sind.

Frühere Untersuchungen haben gezeigt, daß außergewöhnliche Leistungen in Kunst und Wissenschaft überwiegend von Individuen in den ersten vier Lebensjahrzehnten erbracht wurden (Lehmann, 1953). Diese Ergebnisse sind im Sinne eines Abbaus an Produktivität während der späteren Lebensjahrzehnte interpretiert worden. Längsschnittstudien fanden dagegen bei Wissenschaftlern und Künstlern nur sehr geringe Anzeichen für nachlassende Produktivität bis in das sechste und siebente Lebensjahrzehnt hinein (Cole, 1979; Dennis, 1966). Bei diesen Untersuchungen war allerdings nur die Menge und weniger die Qualität der Produkte ausschlaggebend. Der gegenwärtige Stand der Befunde zu Altersunterschieden in kognitiven und motorischen Leistungen bei Aufgaben, die hohe Anforderungen an Genauigkeit und Geschwindigkeit stellen, legt die Annahme eines generellen Abbaus von Fähigkeiten mit fortschreitendem Alter nahe (Salthouse, 1985a). Dieser Abbau beginnt praktisch mit dem dritten Lebensjahrzehnt und beschleunigt sich von der sechsten Dekade an noch einmal. Als Erklärung für den generellen Charakter dieser Veränderung werden häufig biochemische und physiologische Veränderungen im zentralen Nervensystem herangezogen (Cerella, 1990). Auf der Ebene kognitiver Verarbeitung werden die Auswirkungen genereller altersbedingter Veränderungen als eine Reduktion der Prozeßrate des Arbeitsgedächtnisses (Salthouse, 1985a) oder als eine erhöhte Unfähigkeit älterer Personen, irrelevante Information zu ignorieren (Hasher & Zacks, 1988), beschrieben. Im Rahmen des Ansatzes zur Entwicklungspsychologie der Lebensspanne werden Veränderungen in der Geschwindigkeit mentaler Prozesse („Mechanik") als eine Abnahme an *Plastizität* (im Sinne der oberen Leistungsgrenzen) mit fortschreitendem Alter erklärt. Betont wird aber auch das stets vorhandene Potential, neue Fertigkeiten zu erwerben und etwaige Verluste zu kompensieren (Baltes, 1987; Baltes & Baltes, 1990). Darüber hinaus wird hervorgehoben, daß sich der altersbedingte Abbau nicht auf alle Bereiche mentaler Funktionen beziehen muß. Besonders in solchen Aufgaben, die umfassendes Wissen erfordern, verlaufen Entwicklungen im Erwachsenenalter nicht durchweg negativ.

Experimentelle Studien mit Experten und untrainierten Versuchspersonen verschiedener Altersgruppen haben zu unterschiedlichen Befunden geführt. So fand Salthouse (1984) in seiner Untersuchung zum Schreibmaschine-Schreiben, daß einfache Maße kognitiver und motorischer Leistungen (Geschwindigkeit repetitiver Fingerbewegungen, Zahlen-Symbol-Test) einen anderen Zusammenhang mit Können und Alter aufwiesen als komplexe Funktionen, die für das Schreibmaschine-Schreiben relevanter sind. Charness (1981, 1983) konnte zeigen, daß versierte ältere Spieler beim Schach und beim Bridge zwar mehr Zeit zur Analyse der Spielsituation brauchen, die Qualität der getroffenen Entscheidungen hing letztendlich aber nur vom Könnensniveau und nicht vom Alter der Probanden ab. Die beschriebenen Befunde verdeutlichen die Komplexität der Interaktion von Alter und Expertise: Spezifische Verarbeitungsmechanismen erlauben es Experten, die prozessualen Limitationen untrainierter Personen bei bestimmten Anforderungen zu umgehen; der „normale" Alterungsprozeß, auf der anderen Seite, scheint zu einer allgemeinen Verringerung der Verarbeitungskapazität zu führen.

Das Klavierspiel eignete sich in hervorragender Weise für die Untersuchung der eingangs beschriebenen Fragestellung, da es zwei wesentliche Kriterien erfüllt: Erstens erlaubt das musikalische Konzept von „Üben" die präzise Erfassung des Trainingsaufwandes, da es klar von anderen musikalischen Tätigkeiten abgegrenzt ist; zweitens ließen sich im Klavierspiel Merkmale finden, bei denen in Untersuchungen an untrainierten Versuchspersonen Limitationen der Verarbeitungskapazität des kognitiven Systems und eine Zunahme dieser Beschränkungen mit dem Alter deutlich wurden. Die wenigen vorhandenen Ansätze zur Untersuchung pianistischer Fertigkeiten haben versucht, die enorme Geschwindigkeit und Präzision von Bewegungen in einer Analogie zu den Prozessen zu charakterisieren, die bei geübten Typisten eingehender untersucht wurden. Als zentrales Moment wurde in dieser Forschung die zeitliche Überlappung von Bewegungen durch optimale Vorbereitung der jeweils nächsten Bewegung *(advance preparation)* isoliert (Gentner, 1988). Entsprechende Modelle für Schreibmaschine-Schreiben (Rumelhart & Norman, 1982; Salthouse, 1984) und auch Klavierspielen (Shaffer, 1976) betonen die parallelen Aspekte zugrundeliegender Informationsverarbeitung im Unterschied zur seriellen Verarbeitung einzelner Stimuli, wie sie etwa bei Wahl-Reaktionszeitaufgaben stattfindet. Zahlreiche Untersuchungen haben gezeigt, daß simultane Bewegungen mit beiden Händen enormen Einschränkungen unterliegen (Kelso, Southard, & Goodman, 1979; Kinsbourne & Hicks, 1978; Klapp, 1979; Swinnen & Walter, 1988), besonders, wenn zeitlich oder kinematisch verschiedene Abläufe koordiniert werden müssen. In diesen Untersuchungen wurde stets spekuliert, daß Klavierspielen weitgehende Unabhängigkeit der Hände voraussetzt. Die überlegenen Koordinationsfähigkeiten von Pianisten wurden jedoch, bis auf wenige Ausnahmen (z.B. Shaffer, 1981; Summers u.a., 1993), kaum untersucht. Die Geschwindigkeit peripherer Funktionen, wie zum Beispiel die Rate repetitiver Bewegungen mit einem Finger *(finger tapping)*, haben Korrelationen mit der Anschlagsrate bei Typisten gezeigt (Salthouse, 1984). Eine frühere Studie fand eine höhere Rate bei Pianisten als bei Kontrollgruppen (Telford & Spangler, 1935), jedoch keinen zusätzlichen Vorteil für Pianisten in komplexeren Bedingungen. Als ein wesentliches Merkmal pianistischen Könnens wurde in mehreren Untersuchungen (Shaffer, 1981; Sloboda, 1983; Palmer, 1989) die intentionale (im Sinne von gezielter, aber nicht unbedingt bewußter) Kontrolle zeitlicher und dynamischer (d.h. Lautstärke) Variationen beim Klavierspiel herausgestellt. Die vorgängige Untersuchungsmethode bestand darin, Pianisten ein bestimmtes Stück mehrmals spielen zu lassen, mit der Instruktion, eine gewählte Interpretation möglichst genau zu replizieren. Frühere Studien haben in der Tat gezeigt, daß Abweichungen vom Metrum (zeitliche Gleichförmigkeit) und dynamische Variationen systematisch sind, das heißt dem Ausdruck musikalischer Ideen dienen. Ein systematischer Vergleich zwischen Pianisten verschiedener Könnensniveaus findet sich aber bisher nicht in der Literatur.

Eine Untersuchung der eingangs beschriebenen Problemstellung erforderte eine zuverlässige Erfassung des gegenwärtigen und vergangenen Übungsniveaus. In der vorliegenden Untersuchung kamen hierzu die von Ericsson, Krampe und Tesch-Römer (1993) entwickelten Verfahren zur Anwendung. Bei der Entwicklung der experimentellen Aufgaben waren zwei theoretische Motive maßgeblich: Erstens sollten die Aufgaben Schwierigkeiten reflektieren, die für die untersuchte Expertise (Klavierspielen) relevant sind und die in Untersuchungen an untrainierten Versuchspersonen Hinweise auf Beschränkungen des kognitiven Systems geliefert hatten. Zweitens sollten die Aufgaben kognitiv-motorische Funktionen reflektieren, bei denen aufgrund bisheriger Forschung ein Altersabbau zu erwarten war. Die Diskussion der bisherigen Forschung legte drei Komponenten der komplexen Expertise Klavierspielen nahe, die sich demnach zur Untersuchung der beschriebenen Fragestellung eigneten: (1) die Effizienz peripherer motorischer Prozesse (d.h. Beweglichkeit einzelner Finger); (2) die Effizienz komplexer bimanualer Bewegungen und deren Memorisierung; (3) die gezielte Variation zeitlicher und dynamischer Merkmale einer Interpretation.

Die quasi-experimentellen Faktoren Expertise (professionelle vs. Amateurpianisten) und Alter wurden als Vier-Gruppen-Design realisiert. Jede Gruppe bestand aus zwölf Teilnehmern; das mittlere Alter der jungen Teilnehmer war 24,7 Jahre (20–32 Jahre), das der älteren Teilnehmer war 60,3 Jahre (52–68 Jahre). Das mittlere Alter der

Amateure und Profis in den jeweiligen Altersgruppen war nahezu identisch. Professionelle Pianisten in der jungen Altersgruppe waren Studenten in den Meisterklassen für Klavier der Berliner Hochschule der Künste. Ältere Experten waren professionelle Pianisten, die noch aktiv konzertierten oder lange Zeit konzertiert hatten und die in ihrer Jugend ein vergleichbares Studium absolviert hatten. Amateure in beiden Altersgruppen waren Personen, die nur in ihrer Freizeit musizierten und anderen Berufen oder Studien nachgingen. Der Bildungshintergrund für die beiden Amateurgruppen war vergleichbar. Bezüglich des allgemeinen Gesundheitszustandes waren die vier Gruppen ähnlich. Die Einteilung in Experten und Amateure wurde durch Experten-Ratings von Tonbandaufzeichnungen der Interpretation eines kurzen Stückes validiert. Die Probanden wurden für ihre Teilnahme an der Studie entlohnt.

Im Rahmen der Tagebuchprozedur führten die Untersuchungsteilnehmer sieben Tage lang detaillierte Aufzeichnungen über ihren Tagesablauf. Die verwendeten Formbögen ermöglichten eine Differenzierung in 15minütige Einheiten. Nach Ablauf der Woche wurden die Aufzeichnungen dann von den Teilnehmern unter Verwendung einer Taxonomie von zwölf musikalischen und zehn anderen Alltagsaktivitäten kategorisiert. Die so gewonnenen Daten ermöglichten eine Berechnung des Zeitaufwandes für jede Tätigkeit für den Zeitraum einer Woche. Zur Erfassung des früheren Übungsaufwandes wurden mit Hilfe eines standardisierten Fragenkatalogs eine Anzahl von bedeutsamen Lebensereignissen im Laufe der musikalischen Entwicklung ermittelt. Diese Ereignisse halfen den Probanden dann bei der retrospektiven Schätzung des zeitlichen Übungsaufwandes für jedes Jahr ihres Lebens.

Die Untersuchung fand an zwei verschiedenen Tagen statt. Aufgaben und Prozeduren wurden für alle Teilnehmer in derselben Reihenfolge administriert. Eine Zwei-Wahl-Reaktionszeitaufgabe und der Zahlen-Symbol-Test wurden als globale Maße für die Geschwindigkeit zentraler kognitiv-motorischer Prozesse verwendet. Diese Aufgaben dienten gleichzeitig als Kontrollaufgaben zur Validierung der expertiserelevanten Maße.

Für die Experimente wurde ein Yamaha CB-300 Klavier verwendet. Der Klang des Instruments ähnelt weitgehend dem eines normalen Klaviers, die Tonerzeugung geschah jedoch elektronisch, so daß die Datenaufzeichnung und die Versuchssteuerung computerisiert werden konnten. Die Tastatur ist mit einer gewichteten Mechanik verbunden und ermöglichte so die weitgehende Imitation eines Repetierverhaltens normaler Klaviere.

Die Effizienz peripherer motorischer Funktionen wurde mit drei „finger-tapping"-Aufgaben gemessen, die das Repetieren mit dem rechten bzw. linken Zeigefinger oder das Alternieren beider Finger erforderten. Den Schwerpunkt der experimentellen Untersuchung bildeten zwei Experimente zur Koordination komplexer Fingerbewegungen mit beiden Händen. Kurze Bewegungssequenzen von jeweils neun Tastenanschlägen auf der Klaviertastatur mußten mit möglichst großer Geschwindigkeit akkurat ausgeführt werden. Eine dreistufige Komplexitätsmanipulation wurde eingeführt: Die Sequenzen mußten entweder mit nur einer Hand (rechts oder links), parallel in beiden Händen (identische Abfolge der Finger in beiden Händen), oder synchron, bei verschiedenen Abfolgen der Finger in beiden Händen, ausgeführt werden. Im ersten Experiment stand den Versuchspersonen während der Ausführung der

Aufgabe ein Display mit der jeweiligen Fingerabfolge zur Verfügung. Das zweite Experiment erforderte die Ausführung der jeweiligen Aufgabe nach vorherigem Auswendiglernen. Die motorischen Anforderungen der einzelnen Sequenzen waren in den verschiedenen Bedingungen identisch, da die komplexeren Aufgaben aus entsprechenden Kombinationen der einfachen Aufgaben konstruiert waren. Zur Erfassung der Fähigkeit zur gezielten Variation von zeitlichen und dynamischen Merkmalen einer Interpretation wurden die Versuchsteilnehmer gebeten, ein Präludium von J. S. Bach einzuspielen und die gewählte Interpretation dreimal möglichst identisch zu replizieren.

Die folgenden Hypothesen wurden überprüft (Zusammenfassung):

1. Der gegenwärtige zeitliche Aufwand für Üben (gemessen durch Tagebuch) am Klavier sollte bei den professionellen Pianisten wesentlich höher ausfallen als bei den Amateuren, jedoch sollte das Ausmaß der Übungsaktivität bei den älteren Profis im Vergleich zu den jüngeren Pianisten deutlich reduziert sein.

2. Leistungen in den Kontrollaufgaben zur Messung globaler Verarbeitungsgeschwindigkeit bei kognitiv-motorischen Prozessen (Zwei-Wahl-Reaktionszeit und Zahlen-Symbol-Test) sollten signifikante Unterschiede zwischen Altersgruppen, jedoch keine Unterschiede zwischen professionellen und Amateurpianisten aufweisen.

3. Die Leistungen der professionellen Pianisten in den expertise-relevanten Aufgaben zur Koordination komplexer Bewegungen sollten sich signifikant von denen der Amateurgruppe unterscheiden. Gleichzeitig sollte die Performanz der älteren Amateure im Vergleich zur jungen Amateurgruppe schlechter ausfallen. Die Leistungsunterschiede zwischen jungen und älteren Profis sollten demgegenüber geringer ausfallen (signifikante Interaktion der Faktoren Alter und Expertise).

4. Höherer bimanualer Koordinationsaufwand für Bewegungen in den Tapping-Aufgaben und den beiden Experimenten mit komplexen Bewegungen sollte die Geschwindigkeit der Performanz beeinträchtigen. Dieser Effekt sollte jedoch für die professionellen Pianisten deutlich geringer ausfallen als für die Amateure und auch altersdifferentiell wirksam sein. Aus Vorhersage 3 folgte die Vorhersage einer dreifachen Interaktion zwischen Alter, Expertise und Komplexität.

5. Es wurde angenommen, daß die konsistente Interpretation eines Stückes musikalisches Wissen, und weniger Geschwindigkeit in der Ausführung, erfordert. Es wurde daher vorhergesagt, daß professionelle Pianisten eine gewählte Interpretation besser replizieren können, da sie dynamische und zeitliche Variationen gezielter kontrollieren. Altersunterschiede sollten auf dieses Maß keinen Einfluß haben.

6. Mit Hilfe regressionsanalytischer Verfahren sollte die Rolle des Übungsaufwandes während verschiedener Lebensphasen geklärt werden. Es wurde vorhergesagt, daß das Maß für den Übungsaufwand während verschiedener Lebensphasen die Unterschiede in der Performanz der vier Gruppen erklären könne. Darüber hinaus sollten die Übungsvariablen Varianz aufklären, die über die Anteile der Gruppenunterschiede (Haupteffekte) in bezug auf Alter und Expertise hinausgeht, das heißt interindividuelle Unterschiede innerhalb der vier Gruppen erklären können. Es wurde angenommen, daß ein Modell, das lediglich auf Übungsintensität basiert, bessere Vorhersagen für die Experten als für die Amateure liefert. Aufgrund des vergleichs-

weise geringen Trainingsniveaus in der Amateurgruppe wurden hier die Effekte „normalen“ Alters erwartet.

Die Auswertung der Tagebuchdaten bestätigte Hypothese 1: Pianisten verwandten mehr Zeit auf expertise-bezogene Aktivitäten als Amateure. Es gab keine Altersunterschiede in beiden Gruppen in bezug auf das generelle Maß. Ältere Experten wiesen jedoch ein aktives Übungspensum auf, das auf 40 Prozent des Übungsaufwandes der jungen Pianisten reduziert war, die 26 Stunden pro Woche übten. Die Auswertung der retrospektiven Schätzungen des früheren Übungsaufwandes ergab vergleichbare Verläufe für junge und ältere Experten während der ersten 20 Lebensjahre. Es zeigte sich jedoch, daß ältere Pianisten ihren effektiven Übungsaufwand seit dem Ende ihres Studiums kontinuierlich verringert hatten. Eine genauere Auswertung der anderen Aktivitäten während der Tagebuchwoche ergab, daß der größte Teil der 60-Stunden-Woche älterer Berufspianisten für Unterrichten verwandt wurde. Die beiden Amateurgruppen unterschieden sich nicht in ihrem Übungspensum zum Zeitpunkt der Untersuchung.

Hypothese 2 wurde ebenfalls bestätigt: Beide Tests globaler Verarbeitungsgeschwindigkeit wiesen signifikante Unterschiede zwischen Altersgruppen, jedoch keine Unterschiede zwischen Experten und Amateuren auf. Die Auswertung der „finger-tapping“-Aufgaben ergab eine signifikant höhere Repetitionsrate für Pianisten, jedoch keine Altersunterschiede. Professionelle Pianisten konnten ihre Anschlagsrate in der komplexen Bedingung, die das Alternieren beider Finger erforderte, überproportional im Vergleich zu den Amateuren erhöhen. Diese Befunde bestätigen die Hypothesen 3 und 4 in bezug auf die Unterschiede zwischen Experten und Amateuren und den differentiellen Effekt von Aufgabenkomplexität. Die Hypothesen wurden jedoch nicht in bezug auf die erwarteten Altersunterschiede bestätigt.

Die Auswertung der beiden Experimente zur bimanualen Koordination komplexer Bewegungen erbrachte klare Unterschiede zwischen Experten und Amateuren. Die Manipulation der Aufgabenkomplexität führte zu einer Reduktion der Performanz (Geschwindigkeit) in allen Gruppen. Dieser Effekt war jedoch bei Amateuren stärker als bei professionellen Pianisten. Die Unterschiede zwischen jungen und älteren Amateuren waren signifikant und nahmen mit steigender Komplexität der Aufgabe zu. Unterschiede zwischen jungen und älteren Experten waren nur in der komplexesten Bedingung des ersten Experiments reliabel. Dieser Befund konnte im zweiten Experiment nicht repliziert werden. Die Ergebnisse bestätigten im wesentlichen die Vorhersagen 3 und 4 für diese Aufgaben. Alter zeitigte einen deutlichen Effekt auf die Leistungen der Amateure in den komplexeren Bedingungen; dieser Effekt war jedoch in der Gruppe der Experten minimal.

Die Analyse der Übereinstimmung der drei Interpretationen des Präludiums ergab, daß professionelle Pianisten eine gewählte Interpretation besser replizieren können. Experten verwandten ihre dynamischen Variationen im Tempo und in der Lautstärke konsistenter im Vergleich der drei Einspielungen. Hypothese 5 durfte damit als bestätigt gelten.

Die in den Experimenten gefundenen Unterschiede zwischen den vier Gruppen ließen sich im Rahmen der Regressionsanalysen weitestgehend durch Maße des gegenwärtigen und vergangenen Übungsaufwandes erklären. Es verblieben jedoch in einigen

Aufgabenbedingungen kleine, aber signifikante Varianzanteile, die mit Alter oder Expertise assoziiert waren, auch, wenn die Effekte von Übungsaufwand statistisch kontrolliert wurden. Es zeigte sich auch, daß die Maße des Übungsaufwandes zusätzlich zu den Faktoren Expertise, Alter und der Interaktion dieser Variablen interindividuelle Unterschiede in den komplexesten Koordinationsaufgaben aufklären konnten. Das bedeutet, daß interindividuelle Unterschiede in der Leistung bei expertiserelevanten Aufgaben vom Übungsaufwand abhingen, über die Tatsache hinaus, daß eine Person ein Experte, Amateur, jünger oder älter (im Rahmen der angewandten Kriterien) war. Hypothese 6 konnte demnach in wesentlichen Teilen bestätigt werden. Weitere Analysen ergaben, daß ein Modell, das Performanz nur auf der Basis von früherem und gegenwärtigem Übungsaufwand erklärt, signifikant bessere Vorhersagen für die Gruppe der Experten als für die der Amateure liefert. Nach Kontrolle des Übungsaufwandes verblieben signifikante Effekte von Alter für die Amateurgruppe in den komplexen Koordinationsaufgaben, aber keine Alterseffekte in der Expertenstichprobe. Unter den Maßen für Übungsintensität erwies sich das Ausmaß an Training während der letzten zehn Lebensjahre als der beste Prädiktor für Performanz. Dies galt besonders für die älteren Experten und verweist auf die Rolle von Übung beim Erhalt von Fertigkeiten.

Die vorgestellte Arbeit liefert Befunde, die wichtige Komponenten pianistischen Könnens erhellen. Aus entwicklungspsychologischer Perspektive wurde gezeigt, daß die Entwicklung von Expertise im späteren Erwachsenenalter mit einer deutlichen Verschiebung der Schwerpunkte in den Aktivitäten einhergeht. Trotz ihres vergleichsweise geringen Übungsaufwandes gelingt es den älteren Experten, ihre Fertigkeit auf einem beeindruckenden Niveau zu erhalten. Dieser Erhalt ist spezifisch, da sich die Performanz älterer Experten in globalen Tests nicht von der älterer Amateure unterscheidet. Das geringe Trainingsniveau von Amateuren führt dazu, daß sich die Funktionen, die für das Klavierspiel relevant sind, gemäß „normalen" Alterungsprozessen entwickeln. Die verwandten Maße von Übungsintensität während verschiedener Lebensphasen erwiesen sich als brauchbar zur Aufklärung von interindividuellen Unterschieden in komplexen Fertigkeiten. Letztendlich ist es jedoch nicht gelungen, alle Unterschiede zwischen Alters- und Expertisegruppen durch diese Variablen zu erklären. Bei der Bewertung der Befunde muß berücksichtigt werden, daß ein sehr einfaches Modell des Zusammenhangs zwischen Üben und Können vorausgesetzt wurde: Das Summieren von Übungszeit über längere Lebensphasen und die Annahme einer Potenzfunktion für den Zusammenhang zwischen Übung und Können (in allen Regressionsanalysen wurden Log-Log-Modelle verwendet) erscheinen als eine gute Annäherung, können aber nicht etwaigen Änderungen in der Qualität des Übens gerecht werden. Zukünftige Forschung sollte Aspekte von selektivem oder kompensatorischem Training besonders bei älteren Professionellen berücksichtigen und darüber hinaus Fragen nach den motivationalen Ursachen der Veränderungen im Übungsniveau aufgreifen.

Introduction

On the occasion of his 75th birthday, Claudio Arrau, a world-famous pianist, amazed his audience with a recital in which he played flawlessly the technically strenuous Sonata No. 3 in F-Minor by Brahms (Kausler, 1982). Wilhelm Kempff continued to perform in front of large audiences until old age, before he finally decided to give up public performances because he felt that his finger dexterity was deteriorating and that his memory became less reliable. At that time he was 85 years old! A few years before his early death (he died at the age of 50), Glenn Gould recorded Johann Sebastian Bach's "Goldberg Variations" for a second time. His technical and musical realization was very different from his first interpretation of the same opus recorded more than 20 years before. There is general agreement that both of Gould's interpretations are among the most outstanding performances recorded in this century.

Playing the piano constitutes a highly practiced complex skill. Performers at all levels of proficiency invest enormous amounts of time in improving their abilities. Only a few individuals, however, are considered by the public to be outstanding performers. The above accounts, though a little anecdotal in character, illustrate that even at older ages, some artists continue to amaze their audiences with their skill, which can undergo dramatic developments over decades even if extreme levels of ability had already been reached. The technical and musical abilities reflected in the virtuosity of elderly pianists are well beyond those which most piano students ever achieve. What is it that enables these individuals to reach such outstanding levels of performance and often maintain them throughout their life courses?

The research presented here attempts to shed some light on this question. The basic premise adopted for this purpose is that acquisition and maintenance of real-life skill is a matter of long-term commitment to the development of specific abilities. It is assumed that long-term commitment is best reflected in the extensive amounts of time and energy invested in practice. Practice is defined as a deliberate, effortful activity motivated by the goal of improving specific abilities. Playing the piano is conceived as a highly practiced skill, relying on complex cognitive-motor processes. The observable phenomena of interest in this context relate to the subtle control of timing and force in the fluent generation of keystrokes. Skilled pianists combine rapid movements with different fingers while at the same time maintaining a steady beat. The most difficult aspect of this rapid execution of keystrokes is the combination of opposite hands. Timing and force of single strokes have to be optimally integrated into the performance context in order to convey musical phrases and patterns of coherence in timing and volume. The ultimate goal of performance is to communicate this expression of musical ideas to an audience.

The principal methodological approach to the study of maintaining the skill of playing the piano described here was a comparison of young and elderly subjects at different levels of proficiency. Professional pianists were compared to capable but less skilled amateurs with respect to their performance in a number of cognitive-motor tasks presumably reflecting specific mechanisms underlying piano performance. The strategy pursued in the research described here aimed at decomposing the complex skill into several components, which were relevant to the development of experimental tasks. The decomposition was governed by two theoretical perspectives. The first perspective relates to the isolation and reflection of skilled processing mechanisms, which allow expert pianists to circumvent the limitations evident in the cognitive-motor performance of unskilled individuals. The second perspective on constituent skill components was their relation to abilities which have been found to deteriorate with age in normal subjects. Based on earlier work on the acquisition of exceptional levels of performance in musicians (Ericsson, Krampe, & Tesch-Römer, 1993), methods of assessing past and current amounts of training were used in order to scrutinize the individual development with respect to the effort and training invested in acquiring and maintaining skills as a pianist. The strength of the correlation between measures of training level and performance in different experimental tasks provided a test for the basic claim underlying this research, namely, that performance at each stage of development is a function of past and current practice intensity.

Three major aspects will be addressed by the research presented here: The first aspect relates to the changes in the structure and amount of skill-related activities in experts during adult development. The second aspect concerns the developmental changes in expert and amateur pianists with respect to cognitive-motor abilities of different complexities. The third aspect refers to the correlation between past and current training levels and performances at different ages and levels of skill.

Outline of Chapters

This thesis is organized into two major parts: The first part includes a review of the existing literature on the development of skills, with a focus on cognitive-motor abilities and playing the piano. The second part of this thesis is a description of an empirical study on cognitive-motor performance in four groups of pianists differing in age and skill level. References to the literature and three appendices with additional illustrations and materials are included at the end.

The theory section is organized along two main topics. The first half of the literature review is centered around the expertise approach to the study of skill at different phases of development. The second half deals with performance constraints in simple and complex movements and the study of real-life cognitive-motor skills. The theory section starts out with a brief introduction of basic concepts and research strategies characteristic of the expertise approach. Studies of long-term retention of knowledge and skills are reviewed, and the theoretical as well as the methodological problems of studying the development of a certain skill across years or even decades are highlighted. The need to incorporate perspectives on ontogenetic development into the study of long-term skill retention is discussed, and the focus of review is shifted toward changes throughout the adult life course. After summarizing the main findings on age-related changes in productivity and creativity, issues concerning age-related decline in more basic mental and motor functions are raised. A life-span developmental framework (Baltes & Baltes, 1990) is described, which focuses on the developmental potential at each stage of development while also stressing the increasing constraints of age on this potential. The importance of developmental potential and its possible limitations in elderly individuals are illustrated with three studies with trained young and elderly subjects in a mnemonic technique. Accounts which attribute age-related decline in basic cognitive functions to disuse are contrasted with models assuming a global age-related deterioration of basic processing capacities. The few studies which have carefully analyzed the interplay of age and skill factors are then described in some detail in order to illustrate the central issues related to the research problem approached in this study. The study of the acquisition of exceptional levels of performance in real-life skills rounds up the review of literature on skill and developmental issues. The assumption of general dispositions or talents has played a major role in research on this topic. The talent concept is contrasted with an extended skill acquisition perspective recently proposed by Ericsson, Krampe, and Tesch-Römer (1993). This framework integrating developmental perspectives within the expertise approach is described, and findings from two recent studies on expert violinists are reported. The adaptation to large amounts of training and intensive practice over decades as the model's main account for high levels of real-life skill is discussed in its implications for the study of the development of skilled individuals.

The second part of the literature review is concerned with skill in the coordination of complex movements. The focus of consideration is on constraints evident from the performance of unskilled subjects and evidence for mechanisms allowing experts to surpass these constraints in skilled performance. Performance constraints resulting from finger dexterity, handedness, and mental control of simple motor tasks are discussed. Research on bimanual movements is described in more detail with a focus on the severe constraints on coordinating movements in opposite hands resulting from the inherent structure of the human motor system. The description of research on simpler tasks sets the stage for a review of results from research into more complex cognitive-motor skills. Typing as a well researched domain is discussed more extensively. Several analogies between typewriting and playing the piano are outlined, and their scope and limitations are discussed in order to provide guidelines for a theoretical decomposition of the skill of playing the piano. Three aspects of skill are derived from this discussion and proposed for the empirical study of expertise in playing the piano: the efficiency of peripheral motor components, the ability to control complex finger movements requiring the coordination of opposite hands, and the ability to intentionally control timing and force variation in expressive performance. An outline of the statement of the research problem with its implications for the design of the empirical study are found at the end of the theory section.

The review of the literature and the discussion of theoretical implications are motivated by four goals. First, the descriptions of the expertise approach and the developmental approach to the study of age-related performance changes are intended to illustrate the differences in basic theoretical concepts. Second, it will be documented from the review of earlier research that specific components of a complex skill can show trajectories of developmental change which are different from those of "normal aging." Third, a model of the acquisition of real-life skills focusing on the role of lifelong adaptation to the demands of training will be proposed as a framework for the investigation of the development of skilled performance. Fourth, a review of the existing literature on complex cognitive-motor skills shall provide theoretical grounds for a decomposition of the skill of playing the piano into several subcomponents.

Part II is introduced by an overview of the empirical investigation of cognitive-motor performance in four groups of pianists varying in age and proficiency. Following a brief description of the design and the experimental tasks, the research predictions are listed. The method section includes a detailed description of participants and procedures. The results section is organized along the main line of investigation: Age-related changes with respect to involvement in skill-related activities are first described with a focus on the amount of time spent for solo practice at the piano. Following that, subjects' performance in general markers of cognitive-motor speed will be compared between groups. The major part of the results section deals with the analysis of performance in skill-related tasks. Two different approaches will be described. The first set of analyses refers to the mean differences between groups and is based on analyses of variances. The second approach to the analysis of performance in skill-related tasks involves the use of multiple regression techniques. Measures of past and current amounts of training will be related to performance in the experimental tasks. The purpose of this second approach is to investigate how many of the differences between expert and amateur pianists, on the one hand, and young and elderly subjects, on the other, can be attributed to differences in the degree of past and current practice intensity.

The main findings are summarized at the beginning of the discussion section. Results are evaluated with respect to the predictions, and the conclusions which can be drawn regarding the developmental changes in cognitive-motor performance are summarized. The compatibility of the findings with alternative accounts is discussed, followed by a consideration of the limitations of this study with respect to the research problem under investigation. Based on the discussion of the research presented, some future perspectives are developed regarding further analysis of the data, and an outline for new investigations following along the line of the proposed research problem is suggested. The discussion section is brought to a close by some concluding remarks on the maintenance of high-level skills across the life span.

Theoretical Background

The Maintenance of Skill in Adulthood

Overview

The study of individuals who are especially distinguished by their performance in a certain domain *(expertise)* has provided numerous insights into the cognitive mechanisms underlying high-level skills. While it is widely assumed that the learning mechanisms isolated in laboratory research are equally relevant to the acquisition of real-life skill, there has been a clear neglect of developmental perspectives in the literature on expertise. Our knowledge of the developmental precursors of expertise is far less elaborated than the body of findings on skilled processes. This neglect is even more pronounced when it comes to the development in later phases of life. The study of age-related changes in professional expertise was dominated by sociological or psychometric perspectives and had not drawn the attention of experimental psychologists until recently. The heavy focus on processing mechanisms rather than developmental processes is typical for theorizing in cognitive psychology in general and expertise research at a more specific level. However, there are also pragmatic reasons for the neglect of aspects concerning developmental perspectives: Acquisition of expert-level performance takes considerable time, and the number of individuals who eventually succeed in excelling in a domain is by definition small. Researchers therefore tend to select individuals who are already experts in their field. As a result, theories on developmental precursors of real-life skill must necessarily rely on correlational evidence. Common sense often attributes exceptional achievements in a domain to specific innate talents. Interindividual differences in achievement have been accounted for by stable, or even innate, specific talents or dispositions. This approach is somewhat at odds with the expertise approach which is based on domain-specific mechanisms acquired in the course of learning.

The literature review in the first part of the theory chapter starts with a brief introduction to the expertise approach. The role of skill-specific mechanisms acquired through training is highlighted together with the implications for the preparation necessary to attain expert-level performance in a natural skill. The following review of findings on long-term retention of knowledge and skills suggests a progressive deterioration in rarely used abilities unless initial training exceeds a certain level of accomplishment. The occupational aspects of aging and the relation between age and peak performance are reviewed briefly. The available empirical work addressing issues of maintaining skills through frequent usage and potential moderating mechanisms is discussed. Finally, a model of the acquisition of real-life skills which focuses on the role of extended adaptation to a specific task domain is proposed (Ericsson, Krampe, & Tesch-Römer, 1993). Two studies derived from this model are described in more detail. The implications of the model for skill maintenance will be discussed.

The Skill Perspective

Starting with de Groot's (1978, original work published 1946) pioneering work on chess masters, research on high-level skills in specific domains *(expertise)* has become a major source of theoretical stimulation for psychology. The general approach in expertise research encompasses the identification of individuals who perform far above the average population or who are distinguished by some other external criterion in a specific domain. Salthouse (1991), among others, has made a case for the distinction between *expertise* and *experience.* He pointed out that familiarity with a domain does not necessarily imply competence and stressed the need for external validation of presumed levels of skill.

The traditional methodological approach common in expertise research is to design laboratory tasks especially developed to scrutinize the processing mechanisms underlying expert performance. The prevailing assumption is that the differences in processing mechanisms between experts and novices reflect acquired skills specific to the domain of expertise. Theories of skill acquisition and expertise claim to model the human potential for improving performance by means of cognitive processes and adaptive mechanisms. Research on expertise and skill in many domains has provided considerable evidence for *qualitative* differences between experts and novices with respect to the cognitive processes mediating task behavior (cf. Chi, Glaser, & Farr, 1988; Ericsson & Smith, 1991). The processing limitations apparent in unskilled performance do not seem to apply to skilled behavior in the same manner. In their classic study on memory for chess positions, Chase and Simon (1973) demonstrated that grandmaster chess players were able to recall briefly presented displays better than less skilled players. This advantage, however, was only evident for meaningful game positions. There was no recall advantage for random positions related to expertise. Chase and Simon claimed that grandmaster chess players relied on an extensive knowledge of game positions which enabled them to encode displays more efficiently. This knowledge base is built up during the long-term acquisition of chess skills. A number of related findings were later integrated into the theory of *skilled memory* (Chase & Ericsson, 1981; Ericsson, 1985). The skilled memory theory assumes that expert performance in various domains relies on an extensive knowledge base of relevant encodings. This knowledge base is highly organized into efficient *retrieval structures* allowing rapid access to relevant contents.

A central proposition of skilled memory theory is that qualitative differences in processing do not exist as a prerequisite of skill acquisition, but occur in the course of practice. The most impressive demonstration of exceptional memory skills acquired as a result of intensive long-term practice has been provided by Ericsson, Chase, and Faloon (1980). Their subject S.F. improved his digit span from 7 to over 80 digits in the course of over 250 hours of laboratory training and testing. S.F.'s memory performance prior to training was average. Chase and Ericsson (1981, 1982) were able to replicate and extend these findings. They showed that performance was based on specific encoding and retrieval strategies developed in the course of practice.

The relation between practice and performance level has been studied deploying a wide range of laboratory tasks. The general picture emerging from numerous studies is that the attained level of performance is a monotonic function of the amount of practice (Anderson, 1982; Newell & Rosenbloom, 1981) and can be adequately described by a negatively accelerated function or, more specifically, by a power function. When it comes to natural skills, the relation between practice and attained level of performance is less well investigated. Complex natural skills differ dramatically from skills trained in the laboratory in terms of the sheer amount of practice involved. Salthouse (1984) compared exercise in terms of the number of keystrokes executed by a typist in a normal working situation with the amount of training administered in a laboratory setting. According to his estimates, the amount of experience a professional typist gains during less than two weeks matches 50 hours of laboratory training in a perceptual-motor task. Along the lines of this comparison the number of keystrokes executed during extensive training in a choice reaction time task amounts to less than 17 minutes of a typist's normal work routine. By now typing is probably one of the best researched skills in the field of expertise. Salthouse (1986) provided impressive evidence for the amount of training necessary before critical changes in typing performance emerge: After 20 hours of intense practice in a keying task which shared important features with typewriting, his subjects showed considerable improvement; however, none of his subjects had begun to exhibit the processing characteristics found in skilled typists. Subjects were still limited in speed by processing constraints typical for novice behavior. Gentner (1988) provided estimates for the amount of practice involved in becoming even a moderately skilled typist. He calculated an accumulation of 600 hours of typing experience until completion of business school. At this time, average subjects perform at a speed of 56 gross words per minute, barely meeting employment standards. Professional typists have been found to perform at rates above 100 words per minute. Dvorak et al. (1936) have reported that even experienced typists showed considerable improvements after engaging in systematic practice besides their normal work routine. This indicates that adult typists may often improve long after formal training has ended. An important implication of the finding that individuals do not normally perform at their highest levels of skill in the working context is that job-related experience may not automatically lead to maximum improvement.

Extraordinary levels of skill require an extensive phase of preparation for these mechanisms to develop. Simon and Chase's (1973) estimate of ten years of training prior to achieving grandmaster level of performance in chess has been taken up by Ericsson and Crutcher (1990) and was shown to apply to a number of different domains. The duration of this preparatory phase is well beyond the scope of practice administered in laboratory studies. These differences in terms of duration of practice also imply enormous differences with respect to the motivation supporting long-term engagement in practice activities. Extension of the expertise framework toward the acquisition of exceptional real-life skills clearly requires the additional consideration of developmental perspectives. The focus of the research presented here centers on the maintenance of high-level expertise. Little attention has been paid so far to this topic in the context of expertise research. There are, however, a number of studies which tried to investigate the retention of knowledge and skills during various times of disuse. Relevant findings and their implication for the maintenance of expertise are discussed in the following section.

Retention of Knowledge and Skills

Usually it is taken for granted that knowledge and skills acquired by people remain at their disposal for a very long time, possibly throughout their lifetimes. Educational systems and training programs in many domains are based on the implicit assumption that the teaching contents of courses provide a basis for later performance in related areas. This perspective appears very optimistic in the light of research on episodic memory (Loftus & Loftus, 1980). The presumed long-term availability of learning gains does not rest on the assumption of maintenance through frequent usage; rather, the optimistic perspective is built on the hypothesized stability of previously acquired skills as such. Several well-known phenomena are not easy to explain for contemporary theories of learning and memory. Among the most intriguing puzzles in this context is that once someone has learned how to swim, he never forgets this skill although he may never use it. Neisser (1967) cites playing the piano, riding a bicycle, and well-rehearsed verbal performances by old actors as illustrations of skills preserved for a very long time despite the lack of intervening rehearsals. The same kind of anecdotal account is sometimes quoted with regard to playing pieces on musical instruments. Subjects claim to remember pieces they had memorized as children and had not played for a long time.

The systematic investigation of retention faces a number of methodological problems, and the available empirical basis is quite small when it comes to very long intervening periods (see Annett, 1979; Ericsson & Crutcher, 1988; Farr, 1987, for reviews). The goal of most studies was to explain the amount of *savings* in terms of knowledge retained after variable intervals interspersed between original acquisition and later testing. In studies of abilities consisting of discrete behaviors, such as memorizing word lists (cf. Ebbinghaus, 1964, original work published 1885), subjects were normally required to relearn a given list some time after initial acquisition. The amount of savings was expressed as the difference between the number of practice trials during original acquisition and the number of trials required to regain their original level of performance at relearning. Retention of skills involving continuous behavior, such as typing, was measured as the percentage of speed maintained. The variables investigated as possible predictors of level of retention most frequently related to the structure of knowledge or skills, the length of the retention interval, the level of performance attained during prior acquisition, and the amount and distribution of initial practice. Rehearsal or maintenance activities during the retention interval were mostly excluded as complicating factors. The general finding emerging from experimental studies with controlled learning and retention phases is that decay is proportional to the duration of disuse. From their reviews Ericsson and Crutcher (1988) and also Annett (1979) concluded that retention almost invariably followed a log-function of retention duration: The rate of deterioration is initially fast, but slows down for longer durations. Plotting knowledge or skill retained as a function of the logarithm of retention interval consequentially yields a straight line. Experimental manipulations of the meaningfulness of materials, structure of knowledge to be acquired, and training schedule for the acquisition phase change the level of retention, the exponential form of the decay function (the rate of decay); however, they do not seem to be affected by these factors. It was found in most studies that the best predictor of later retention, in the absence of maintenance practice, was the level of performance acquired during initial learning. The effect of original performance level achieved seems to be independent and also much stronger than the effect of the duration of the retention interval. Fleishman and Parker (1962), studying retention of a realistic flying task after various no-practice intervals, found correlations between .84 and .98 for level of attainment and later retention. These correlations were unaffected by the length of the intervening time without practice. Length of retention interval correlated with amount of savings at .30. The frequently reported effects of *overpractice* (continued practice after achieving correct performance) are also important in this regard. Jones (1989) was able to account for individual differences in skill retention by statistically controlling the amount of practice subjects went through after their acquisition function had levelled off. The rate of improvement early in practice had either no effect on retention or only effects mediated through overpractice or performance level after initial acquisition. While the notion of overpractice implies that there is no performance gain through additional practice, it is likely that the restructuring of skilled processes continues. Superior maintenance should then be attributed to specific mechanisms acquired during overpractice and their differential sensitivity to interference and deterioration.

Maintenance of Knowledge in Real-Life Contexts

Conditions of initial acquisition, amount of rehearsal practice, and the length of retention intervals are normally well controlled in studies on the retention of skill in laboratory tasks or knowledge of artificial materials. The maintenance of real-life knowledge and skills takes place in far less controlled contexts, and studies on this subject must rely on additional, mostly retrospective, assessments in order to statistically control for these variables.

Bahrick and his colleagues have completed several studies on long-term retention of memory contents acquired in naturalist settings. A recurrent finding in these studies was that the rate of deterioration depended on the degree of original learning. Bahrick (1983) reported that the ability of teachers to recognize the names and faces of their former students had basically deteriorated to chance level after eight years. Subjects who spent four years together at high school, however, recognized the names and faces of most of their former classmates (Bahrick, Bahrick, & Wittlinger, 1975) up to 25 years later. In his study on the retention of Spanish learned in school, Bahrick (1984) applied multiple regression techniques in order to evaluate the effects of original learning, rehearsal activities, and length of retention intervals. His sample consisted of 733 individuals. A subsample of 587 subjects had taken Spanish courses at high school up to 50 years prior to the time of testing. Results suggested an exponential decline during the first three to six years, a phase of up to 30 years of relative stability, and a further decline thereafter. A considerable portion of knowledge remained available even after 30 years of retention. The best predictor of retention was the level of original acquisition. The rate of forgetting depended on the amount of original learning (number of courses taken at high school and college). Impacts of rehearsal activities were negligible due to the fact that the majority of subjects did not report any related maintenance rehearsal at all.

In a more recent study, Bahrick and Hall (1991) investigated the maintenance of knowledge required in high school mathematics courses. In addition to completing carefully designed tests of mathematics contents for algebra and geometry classes, subjects filled out a questionnaire on the degree of original learning, relevant rehearsal activities, and time since the last course in mathematics (i. e., the retention interval). The length of the retention interval accounted for about 30 percent of the variance in the retention of algebra class contents, but for only 2 percent in the retention of geometry knowledge. The best predictor for the rate of decline turned out to be the level of knowledge attained during original acquisition. Similar to the results of the earlier study on memory for Spanish, Bahrick and Hall found only small losses for up to five decades for those subjects who had continued to take mathematics courses at college. Subjects who had performed equally well at school, but did not take college mathematics courses, dropped in performance to chance level during the same period. Scholastic Aptitude Test scores and grades were found to be predictive of test performance, but showed no relation to the rate of forgetting. Bahrick and Hall (1991) also attempted to assess the amount and intensity of rehearsal activities during the retention interval. Subjects were given a category score of zero to five depending on the frequency and presumed relevance of reported rehearsal activities. Recency of rehearsal activities was expressed as the natural logarithm of years since the last involvement in respective activities. The level of rehearsal showed significant effects on test performance, but did not interact with retention interval (i. e., did not influence the rate of forgetting). It is important to mention, however, that nearly 70 percent of participants in the study did not report any related rehearsal activities at all, and only 4 percent reported past involvement in highly relevant activities of more than six hours duration per year. Continued practice after completion of high school, like college mathematics courses, were counted as belonging to the acquisition phase. Similar to Bahrick's (1984) study on knowledge of Spanish, the overall amount of rehearsal can be assumed to be very low in this study.

Bahrick (1984; Bahrick & Hall, 1991) interpreted his results by assuming that knowledge which remains available for decades has undergone transition into a *permastore state* during original learning. The probability of information attaining permastore status is a function of original learning. While the relevance of Bahrick's findings has been widely acknowledged, his concept of permastore has become subject to criticism. Neisser (1984) points out that remembering should be viewed as reconstruction from schematic representations rather than recollection of isolated information. He suggests that the different levels in Bahrick's forgetting curves correspond to items differing in difficulty: Those which remain available for decades are most likely reconstructed from abstract schema which were not subject to forgetting through interference.

Retention of Motor Skills

Most of the skills quoted as examples of superior retention, such as riding a bicycle, swimming, and playing musical instruments, involve to a large degree motor components. Research on motor skills has for a long time continued without being acknowledged by many mainstream cognitive psychologists, and cross-references between the fields were the exception until recently. This state of affairs is regrettable and all the more surprising given the enormous impact that Fitts' (1954) work on movement control had on the development of cognitive and, especially, skill acquisition theories. The presumed higher rate of retention for motor skills compared to other types of memory has intrigued many investigators. Researchers in the field have been led to assume qualitatively different representations for motor and verbal skills in order to account for these differences.

Single-case studies on motor skills have reported remarkable savings even after long phases of disuse. Swift (1910) found that his skill of juggling with two balls could, without practice, be rapidly relearned after six years. After little more than ten days of practice, performance had matched and thereafter surpassed the original level which had taken 45 days to acquire. These results were similar to Swift's (1906) earlier findings in his study on the retention of typing skills. At relearning after two years of disuse, he started off at the level originally acquired after about 12 daily sessions. The level of performance originally acquired after 50 hours of daily sessions was achieved after only ten hours of relearning. The most famous study on long-term retention of typing skills has probably been conducted by Hill (1934, 1957; data aggregated in Annett, 1979; Ericsson & Crutcher, 1988). Hill had acquired his typing skill as a subject in Thorndike's laboratory in 1907 and tested his retention 25, and 50 years later. His original performance after 127 practice sessions was 34.5 words per minute for a fixed paragraph of 100 words and 23.8 words per minute for variable 300-word paragraphs. At the time of first relearning 25 years later, Hill's typing performance at the end of the first day matched his performance after 27 days during the original acquisition phase. Interestingly, it took him twice as many sessions to regain the original speed for the fixed 100-word text compared to the speed for the variable 300-word paragraphs. The second retention test 50 years after initial acquisition provided evidence for about 65 percent savings in relearning to type the familiar 100-word paragraph. No retention was observed for the typing speed of novel paragraphs, which might be due to eyesight problems reported by Hill, who was 80 years old at the time of testing. These findings point to a remarkable stability of motor skills which have remained unpracticed for a very long time. Ericsson and Crutcher point out that the first retention interval was not actually free of practice given that Hill had used a typewriter for his letter correspondence. Hill also reported that he had transcribed a 75-page manuscript nine years after initial training.

Probably the best available evidence on the retention of typing skills for a larger number of subjects was provided by Baddeley and Longman (1978). Four groups of postmen were trained to type alphanumeric code material using a conventional typewriter keyboard. Distribution of practice varied between groups, and all subjects were trained for at least 60 hours. Three groups received an additional 20 hours of practice. The group which had only received one hour of training per day performed best at the end of practice. Massed practice (2×2 hours per day) was significantly less efficient. Loss in typing speed was assessed after one, three, and nine months. Subjects were allowed a few minutes of warm-up and then performed two 15-minute test runs. Performance in the second run was taken as an indicator of retention. Loss in speed after nine months was approximately 30 percent. The differences between training groups had been preserved; the forgetting functions, however, were similar for all groups. Most of the loss in speed had already occurred after one month. Deterioration between three and nine months was considerably slower.

The typically higher resistance to forgetting motor skills has encouraged investigators to contrast retention for verbal and motor tasks. A major difficulty in this context is to find a common metric for practice and performance on both types of tasks. A more profound problem might be to initially define what constitutes a motor or verbal task. In his review, Annett (1979) observed that in studies comparing learning of verbal and motor tasks, evidence was found that subjects could rely on either verbal or nonverbal (visuo-spatial or kinaesthetic) encodings of the problems presented. Subjects also used verbal strategies for presumed motor tasks without explicit instruction. The problems arising for a strict distinction between verbal and motor skills are obvious from these findings.

Ericsson and Crutcher (1988) have suggested approaching the problem from a different perspective which focuses on the mechanisms underlying performance. They distinguish *procedural* skills, which require access to knowledge about the correct step at the appropriate time in a sequence of routines, from other skills. Complex procedural skills which require the retrieval of knowledge in the proper order of operations deteriorate considerably within short periods of disuse (Hurlock & Montague, 1982). Speed or proficiency as the main characteristics of skilled performance may heavily depend upon the time required to retrieve knowledge in order to select the proper response in a sequence. In the course of practice, performance on procedural tasks becomes skillful through overlearning the sequence of steps. The important factor determining speed is no longer the time it takes to retrieve the proper subroutine, but the mere execution of steps. This perspective follows theories which assume that skill acquisition does not merely involve continuous strengthening of the same associations, but proceeds through qualitatively different stages. Fitts (1964) has proposed that during an initial *cognitive stage,* subjects have to understand the task and aggregate the knowledge they need to attend to during performance; in the following *associative stage* the involved cognitive processes, especially proper retrieval and heeding of knowledge, are made more efficient; finally, at the *autonomous stage,* performance requires very little conscious processing and proceeds more or less automatically. Anderson (1982) has proposed a similar model relying on three different learning mechanisms. The different stages and mechanisms correspond to different underlying cognitive representations of knowledge and skills. According to Ericsson and Crutcher one could conceive of highly overlearned procedural tasks in the same way as motor skills. This argument is in line with Annett's claim that no motor skill is actually new, but rather a combination of already existing subskills. From this perspective, the learning of new motor skills starts at a different point in the hierarchy of acquisition stages. Novel combinations of movements are rapidly combined into an integrated sequence without further need for memory retrieval. An important consequence of this integration within a series of automated steps is the eventual resistance against forgetting.

The main implication of skill acquisition models with respect to long-term retention is that the rate of decay depends on the level of skill attained during original learning. Knowledge and skills which are incorporated in larger contexts and routines are less likely to be lost. This is consistent with general findings in research on skill retention. Ericsson and Crutcher suggest that the striking effects of overlearning (i. e., continued practice after initial mastery) on skill retention might also be interpretable in this context. The authors, and also Annett (1979), conclude that the crucial factor is actually the amount of practice during original acquisition.

Summary: The Skill Perspective

Knowledge and skills deteriorate during phases of disuse, and loss is proportional to the duration of the retention interval. The relation between the duration of disuse and the amount of savings is negative and probably log linear. Complex procedural skills are lost within the first months of retention if original acquisition involved only little practice. Real-life motor skills can remain remarkably stable for a very long time if initial learning went beyond bare mastery. Unfortunately, the evidence for long-term retention of motor skills rests mainly on single-case studies. The most important predictor of retention emerging in the studies reviewed is the level of skill acquired during initial learning. None of the studies discussed in this section, however, reported on the retention of skills which had been acquired to the level of expertise. Typing speeds obtained after original training ranged between 17 (Swift, 1906) and 35 words per minute (Hill, 1934). The average speed for business school graduates has been reported to be 56 words per minute (Gentner, 1988), which is at best a modest level of expertise in comparison to experienced typists. These differences are considerable even if one takes the advanced technology of modern typewriters into account. The original performance level attained appears to be a direct function of amounts of practice during acquisition. The limitations with respect to the level of skill investigated in the earlier studies on retention are also evident from the amounts of practice during initial acquisition in the described research: The largest amount of initial practice in studies of long-term retention was reported by Hill, who had practiced 127 sessions for an average of one hour per session when initially acquiring his typing skills. This is well below the 600 hours Gentner calculated for his moderately skilled subjects.

Retrospective assessments of the initial amount of learning and practice face considerable methodological problems when considering the retention of skills over decades. This applies even more to studies trying to assess the degree of rehearsal during the retention interval. An important methodological problem in this context is to define what constitutes practice for a given skill. Annett's (1979) argument on the composition of motor skills from existing subskills is especially relevant to skill maintenance. The striking resistance against deterioration reported for real-life skills, such as swimming or riding a bicycle, may in part be a result of transfer from related motor skills which have been exercised throughout a lifetime.

The Developmental Perspective

So far, the major topic of maintenance has been approached from the perspectives of memory structure or organization of knowledge and skills. Studies on the lifetime maintenance of real-life memory contents have accounted for retention after up to five decades by assuming different cognitive representations for overlearned knowledge (Bahrick, 1984; Bahrick & Hall, 1991). However, ontogenetic factors and aspects of memory structure are hard to disentangle when retention intervals extend over decades. One might well argue that the drop in retention after 30 years observed by Bahrick reflects general age-related changes in cognitive functioning, or cohort effects, or both. The studies described in the previous section have almost exclusively investigated retention throughout phases of little or no practice. Professional skills play a major role in an individual's daily activities and typically involve large amounts of skill-related experiences. In the following sections the focus of review will be shifted toward aspects of individual development. This shift will be initiated by a review of findings on age-related changes in job performance and professional achievement.

Job Performance and Age

The most frequently applied measures in studies on the occupational aspects of aging comprise productivity, job satisfaction, absenteeism, or performance ratings by supervisors. The picture emerging from the literature does not speak for any clear trends. According to recent reviews (Davies & Sparrow, 1985; Rhodes, 1983; Sparrow & Davies, 1988), the number of studies reporting that job performance increases with age, decreases, or remains constant is about the same. Based on their meta-analysis, Waldman and Avolio (1986) concluded that only 1 percent of interindividual differences in job performance can be attributed to chronological age. The differences among these findings and the absence of decisive findings can be attributed to three aspects: first, a lack of control regarding job-related experience and its variation with age; second, differences between or within studies with respect to the type of professional activity and its mental or physical requirements; and third, potential selection processes which work in favor of those older adults who remain on the job.

A number of studies illustrated that the effects of age on professional performance might affect less skilled individuals while highly skilled elderly professionals show a much more positive age-related performance development. LaRivière and Simonson (1965; see also Smith & Greene, 1962) reported that age-related trends in handwriting speed were minimal in adults from clerical or managerial occupations providing sufficient practice while decline in writing speed was pronounced in other professionals whose jobs involved little writing. Similarly, Murrel, Powesland, and Forsaith (1962) found elderly expert workers to perform at the same level as young experts in working an industrial mill. Marked age-related performance decline was observed in novice workers, however. One of the most impressive demonstrations of professional efficiency in older age was described by Murrell and Humphries (1978). They found that older professionals in simultaneous translation did not differ from young professionals while young novices were clearly superior to elderly novices. Given the presumably heavy processing demands involved in a simultaneous translation situation, this result is surprising.

The study conducted by Giniger, Dispenzieri, and Eisenberg (1983) was designed to control effects of experience and structure of professional activity. In their investigation of the effects of age and experience on productivity, absenteeism, accidents, and turnover in industrial garment workers the authors distinguished between jobs requiring speed and those requiring skill. Older workers were superior to younger ones in both categories which could be accounted for by the critical effect of experience rather than mere age. Sparrow and Davies (1988) distinguished between the quality of a servicing and the speed of completing a given service in their investigation of service engineers employed by a large office equipment company. The relation between age and quality of job performance took the form of an inverted U-function indicating decreased quality in young and older employees. Speed of servicing was significantly related to age, tenure, training level, and job complexity. The variance accounted for by age was very small in both measures, however. Sparrow and Davies also concluded that the effects of recent training can moderate or compensate adverse effects on job performance, like those of aging. A study by Schwab and Heneman (1977) also suggested that detrimental effects of age on job productivity can be completely compensated by training.

There are, however, occupational functions where the negative effects of age seem to be resistent to moderation through experience. Cobb (1968) and later Cobb, Nelson, and Mathews (1973) studied job performance ratings in air-traffic controllers. They found a negative correlation between performance and age which was not affected by the negligible influence of experience. One possible explanation for these findings is that air-traffic controllers constantly work at the limits of attention and effort which makes professionals more susceptible to age-related decline in relevant functions.

While most of the reported findings suggest rather limited effects of age on job performance which are compensated by professional experience and could also easily be removed by training measures, several authors have proposed a different interpretation (Davies & Sparrow, 1985; Salthouse, 1987; Welford, 1958). Two potential selection mechanisms are likely to favor efficient elderly professionals: First, those older workers who show performance decline will probably move out of the profession or be transferred to less challenging sections by the management. Second, a similar mechanism might work on highly efficient younger individuals; employees showing promise might be promoted to other domains involving more challenge. As a result of this economic rationale, negative relations between age and performance will be cancelled out. At a more general level, the reported studies fail to demonstrate, how, that is by which mechanisms, compensation through experience is achieved.

Another, near-professional, domain which is informative with respect to the relation between age, experience, and skill is driving performance. Interestingly, the likelihood to cause a traffic accident shows a similar relation to age as the U-shape function described by Sparrow and Davies (1988): Young drivers have the highest accident rate while middle-aged drivers have the lowest accident rate; the rate tends to increase again in elderly traffic participants (Charness & Bosman, 1992; Evans, 1991). Accidents involving elderly drivers are more frequently due to violations of the right of way suggesting that perceptual-cognitive processes become more critical with age (Owsley et al., 1991). The last finding is in line with multiple findings from laboratory research. When tested in more natural contexts, elderly drivers brake reaction times are no slower than those of young drivers (Olson & Sivak, 1986). One way to reconcile this finding with the decrease in reaction speed found in many laboratory settings (cf. Salthouse, 1985a, b) is to assume a positive effect of life-long experience on specific functions.

Professional Achievement, Peak Performance, and Age

Major achievements in a specific domain *(peak performances)* provide an opportunity to study the ultimate levels of performance that humans can attain. The ages at which major contributions or outstanding achievements in a field are achieved have been taken as important evidence related to developmental changes in creativity and productivity. Lehman (1953) analyzed peak performance ages for numerous disciplines in the sciences and the arts. He evaluated the significance of a contribution according to a set of criteria including the number of citations in textbooks in a specific field. The dependent variable was the age of the contributor at the time of production. Lehman found that roughly 20 percent of all high-quality contributions were made by individuals in their 20s and 80 percent of all peak performers were below the age of 50 at the time of their achievements. The age of most peak performances fell between ages 30 and 40 for almost all categories. The frequency of peak performances as a function of the contributor's age can be described by an inverted U-function. Simonton (1984a) found a similar relation between age on the one hand and productivity and creativity on the other in his studies on classical composers (1977) and authors (1975). More recently, these findings have been replicated with a larger sample of less distinguished psychologists with respect to their research productivity and quality of teaching (Horner, Murray, & Rushton, 1989; Horner, Rushton, & Vernon, 1986). The peak age for chess tournament players in Elo's (1965) analysis was about 36 years. Proficiency as a function of age showed a similar relation as in Lehman's data, with players in their 60s showing a similar proficiency to players in their 20s.

Peak performance ages in most sports differ from these findings. Olympic gold medals or world championships are won by much younger subjects in most domains (Ericsson & Crutcher, 1990; Schulz & Curnow, 1988). The ages of peak performers differ systematically between disciplines, and these differences have been shown to be remarkably stable across historical times and for different countries. Brute strength and speed events, such as short distance running, are won by younger individuals (23 years) compared to disciplines requiring endurance (long-distance running: 27 years) or high-level knowledge (golf: 31 years). Schulz and Curnow attribute the peak age differences between disciplines to biologically determined upper and lower limits of ages between which peak performance may occur. The authors also stress the importance of acquiring a huge knowledge base in skills such as golf and chess. The amount of time and experience needed to acquire the relevant knowledge might be an important factor in explaining the relatively late peak age. The size and position of these biological "windows" depends on the mixture of physical and cognitive skills characteristic for a domain. Ericsson (1990) suggested that the systematic age differences between events might be largely due to the different amounts of preparatory training necessary to excel in a specific discipline. Recent findings in sports physiology demonstrated that the physiological differences between athletes and controls are specific for each type of athletic event. Muscle fiber constitution typical of short-distance runners differs from that typical of long-distance runners. Ericsson concludes that different amounts of training are necessary to build up the different fiber types and that these differences can account for event-specific peak ages.

The available evidence suggests that extraordinary contributions tend to be made mostly by subjects at younger ages. In evaluating the implications for maintenance of high-level skills, however, some important considerations must be made. Later researchers have criticized Lehman's (1953) original work for methodological reasons, the most important of which was a sampling bias towards older ages. Dennis (1966) emphasized that Lehman's sample consisted of subjects with such different longevities that only those who had lived to a greater age would have had a chance to make major contributions later in life. When he reanalyzed Lehman's data including only those subjects who reached their 70s, Dennis found productivity to remain relatively constant. Cole (1979), in his longitudinal study of a sample of mathematicians, found productivity in terms of publications to increase to the mid 40s and to decrease only slightly in the 60s. Lehman's original claims, however, had related to the quality of contributions. Maintaining high levels of performance is, after all, different from making a peak contribution, so the two findings are difficult to relate to each other. In the context of maintaining high levels of skill it is important to acknowledge that many individuals maintain high levels of competence and creativity in the sciences throughout most of their adult lives. Ericsson and Crutcher (1990) have argued, that years of preparation are necessary prior to achieving peak performance level in the first place, and that peak performances at different ages by the same subject could not be considered independent events. They propose to study individuals who strive for their best performance over a long period of time and consider their whole lives as an attempt toward peak performance.

Systematic differences in peak performance ages across domains are not restricted to sports (Ericsson & Crutcher, 1990; Schulz & Curnow, 1988). Dennis (1966) reported that individuals in the arts and empirical sciences peaked during their 40s while professionals in the scholarly sciences (historians and philosophers) did not show any appreciable decline in later decades. While the overall shape of life-span productivity in music appears to be similar to Lehman's (1953) results, Simonton (1984b) suggested that creativity for composers differs depending on the type of music composed. His findings revealed an early peak age for great instrumental selections (25 to 29) and a late peak of productivity for contributions in light opera and musical comedy (40 to 44). The presence of these differences suggests that the knowledge and the mechanisms responsible for age-related changes in professional skill or a selective drop-out of individuals are at least partly domain specific. A central question in this context relates to the changes in activities and duties occurring with advancement in the professional hierarchy. Limitations in available time may interact with more general changes in mental or physical capacities. The quest for mechanisms responsible for age-related changes in professional expertise will be introduced by a discussion of general declines in mental capacities with age.

Age-Related Slowing in Speeded Cognitive-Motor Tasks

The most consistent finding in age-comparative experimental studies is a reduced speed of general cognitive functioning occurring with increased age (cf. Salthouse & Somberg, 1982). The extensive amount of findings has been summarized elsewhere (Kausler, 1982; Salthouse, 1985a), and only some studies relevant to the skill under investigation will be reviewed here.

A number of studies have reported negative correlations between age and speed in finger-tapping tasks (Salthouse, 1984; Welford, 1977; see also Salthouse, 1985a, for reviews). Nagasaki et al. (1989) reported a negative correlation of .66 between age and maximal tapping rate with the right middle finger. In their study, the absolute mean difference in maximum tapping rate between subjects in their 20s and subjects in their 50s was 0.9 taps per second (*M* [young] = 7.9 taps per second; *M* [elderly] = 7.0 taps per second). The average tapping rate for subjects in their 60s was 6.2. Nagasaki et al. also found a significant correlation between age and variation around the individual means when participants were asked to tap in synchronization with a regular beat. They attributed their findings to a decreased noise rate in the central movement-timing system of the aging brain. Nagasaki et al. linked this concept to the symptoms of Parkinson's disease, which has an increased rate of incidence in elderly people. Age-related declines in movement speed were also evident from the study of more complex motor behavior, such as handwriting (Birren & Botwinick, 1951), or the preparation and restructuring of complex arm movements (Stelmach, Goggin, & Amrhein, 1988). Stelmach, Amrhein, and Goggin (1988) found that elderly subjects took more time than young participants in initiating and executing bimanual movements. Complexity in this experiment was manipulated by varying the coordination difficulty of lateral and vertical bimanual movements. Subjects had to either execute symmetric (same extent amplitude) or asymmetric (different extent amplitude) bimanual reaching tasks. Complexity affects the time needed to initiate a given motor act similarly in young and elderly participants; however, execution latency was proportionally increased with complexity in elderly participants over young subjects' execution duration. Compared with the young participants, the elderly subjects showed greater asynchrony in bimanual movement initiation. Increased inability to subsequentially compensate during movement execution also resulted in greater asynchrony of response termination in elderly subjects. The authors interpret their results as evidence for specific aging deficits in bimanual coordination processes. Similar interactions of movement complexity and age were reported by Light and Spirduso (1990). Their subjects had to give speeded responses with varying hands and fingers. Elderly subjects were more impaired in their response preparation latency than young subjects when the task required rapid switching between hands and fingers used in responding to a signal.

Salthouse (1985b) compiled a number of studies which reported significant age-related declines in speed for choice-reaction time tasks and digit-symbol substitution rate. The correlations for those studies which covered an age range of between 20 to 70 years were between .40 and .60. In his discussion of these findings, Salthouse concluded that the most likely explanation for respective changes is an age-related decline in central processing capacities rather than peripheral factors.

Many theorists in the field assume reduced working memory capacity as the processing bottleneck responsible for age-related slowing. The mechanisms proposed as an explanation for this reduced capacity include a slower cycle rate for information transfer to and from working memory (Salthouse, 1985b) and decreased efficiency of inhibitory attentional processes, resulting in the greater distractibility of elderly people (Hasher & Zacks, 1988). Until recently cognitive aging researchers had engaged in an extensive quest for specific locations or mechanisms especially sensitive to age-related deterioration. The method of choice was to present tasks varying in complexity to subjects from different age-groups. A significant age by complexity interaction would then be taken as evidence for a specific age-sensitive task component. Salthouse (1978) was the first to show that many age by complexity interactions derived from respective analyses of response latencies could be accounted for by one single slowing factor relating young and elderly performance in a constant manner *(proportional slowing)*. This idea is based on the method of plotting old subjects' performance as a function of young participants' values in the same conditions (Brinley, 1965). It implies that a single constant mathematical relation exists between the response latencies, and hence the processing rate, of young and elderly subjects. Furthermore, while the absolute performance in both age-groups is a function of the nature of the task, the relation between speed for younger and elderly subjects is supposed to be determined merely by the age difference between groups. The theoretical objective of *general slowing theories* of cognitive aging (Cerella, 1990; Myerson et al., 1990) is to describe the relation between performance speed in young and elderly subjects by means of a single mathematical function applicable to basically all speeded cognitive task domains. The empirical basis for these claims are extensive meta-analyses of cross-sectional, age-comparative studies. The theoretical rationale is an age-related decline in the efficiency of central processing mechanisms. All accounts for this presumed decline are purely neurophysiological in nature. Cerella, for example, assumes a progressive loss in neuronal interconnectivity with age.

These approaches, while probably being of little theoretical appeal to many cognitive psychologists, should be taken seriously as advanced baseline models for theorizing on the processes associated with aging. In order to claim a specific age-sensitive mechanism, one needs to show that the differences in latencies associated with tasks of varying complexity are beyond what a simple proportional slowing model would account for. One way to check for this is to work with log-transformed latencies and test interactions using these more conservative criteria.

The generality of the age-related slowing models has been modified in later proposals. Based on further meta-analyses, Lima, Hale, and Myerson (1991) have shown that different slowing factors are necessary in order to model data from lexical and nonlexical task domains. More recently, Mayr and Kliegl (1993) conducted a study which illustrated how mechanisms can be differentially affected by age-related slowing without relying on a meta-analytic approach. They used figural transformation tasks which either required subjects to perform a number of successive processing steps (sequential coordination) or presumably store relevant information for further usage in later processing steps (coordinative complexity). Older participants showed overproportional slowing when different operations had to be coordinated compared to tasks where only the number of successive operations was varied. Mayr and Kliegl's data could not be accounted for by a single proportional slowing factor.

Kliegl, Mayr, and Krampe (1994) have provided further evidence to reject the generalizability of simple slowing models. They proposed a framework which permits model performance across the complete range of functioning as a relation between available processing time and performance accuracy (time-accuracy functions). Data from two extensive training studies with four different tasks revealed systematic task-specific variance in age-related performance declines. Criterion measures were derived using the *testing-the-limits method* which employs tailored testing oriented toward individual performance characteristics through the adaptation of presentation rates in successive blocks of trials.

Developmental Potential in Adult Age

Baltes (1987) suggested seven propositions characterizing a *life-span* approach to the study of development. He suggested that concepts of life-span development may neither be restricted to processes of incremental growth toward higher efficacy, nor decline when it comes to changes later in life. Baltes emphasized that intraindividual *plasticity* (within-person modifiability) remains an important factor in developmental changes throughout the complete life span. Gains and/or losses in abilities may occur at each point of ontogenetic development depending on the individual life history and life context. The original proposal was developed into a framework of continuous adaptation to the conditions of aging by Baltes and Baltes (1990).

Baltes and Baltes (1990) proposed a model of *selective optimization with compensation* focusing on the processes of adaptation to conditions of old age. A central proposition in their framework is the notion of an aging loss in the range of *plasticity*. The concept of *plasticity* emphasizes the human ability to acquire new knowledge and skill beyond maintaining past functioning levels. Reviewing results of large-scale intervention programs and extensive training studies with different age-groups, Baltes and Baltes emphasize the existence of large cognitive *reserve capacities* in elderly subjects. These capacities allow for considerable improvement through training. The authors assume that there is an age-related loss in the range of this potential *(plasticity)*—that is, the possible range of improvement is more limited in elderly subjects. Baltes and Baltes suggest that this age-related loss of reserve capacity also applies to motivational resources. This would imply that elderly subjects are likely to perform fewer strenuous actions within a given time unit compared to young subjects without exhausting their capacities. Baltes and Baltes also apply a distinction between *cognitive mechanics* and *cognitive pragmatics*. Cognitive mechanics relate to the basic speed components involved in any cognitive functioning. Mechanic component processes are presumably more directly reflected in measures of reaction time, tapping rate, or working memory capacity. Cognitive pragmatics include declarative knowledge about a task domain accumulated through experience with the skill. Mechanic processes are supposedly more susceptible to age-related losses, whereas pragmatic knowledge may even continue to grow in old age and sometimes compensate for speed decline in mechanic components.

Selection, compensation, and *optimization* constitute three mechanisms allowing accommodation to age-related changes in capacity. According to Baltes and Baltes (1990) individuals engage in processes of *selective optimization with compensation* as a general adaptive strategy throughout their lives. In the aging context, individuals have to adapt to losses in biological, mental, and also social reserves. Reduction of competing activities in order to free time and energy for a preferred activity would constitute an example of selective processes. High-level functioning of specific skill-related processes might be considered a compensation for age-related decline in basic motor speed. Baltes and Baltes illustrate joint operation of all three mechanisms with an example that fits the context of the research presented here. Referring to a TV interview with the pianist Arthur Rubinstein, in which he describes how he deals with the weaknesses of aging in his piano playing, the authors summarize:

> First, he reduces his repertoire and plays a smaller number of pieces *(selection);* second, he practices these more often *(optimization);* and third, he slows down his speed of playing prior to fast movements, thereby producing a contrast which enhances the impression of speed involving fast movements *(compensation)* (Baltes & Baltes, 1990, p. 26).

Kliegl, Smith, and Baltes (1989, 1990) provided evidence for reduced plasticity in elderly subjects. They investigated improvement in performance through extensive training in a mnemonic technique facilitating serial recall of word lists, the method of loci. Two groups of subjects received up to 20 training sessions in serial word recall using the mnemonic technique. Young participants were in their early 20s and the age range for the elderly group was between 65 and 80. The results showed that the elderly participants were clearly able to dramatically improve their performance. However, minimal differences between age-groups at pretest were magnified through training. Kliegl et al. interpret their results as evidence for an age-related decrease in plasticity, that is, the possible range of improvement in cognitive functioning by means of practice. The authors attribute their findings to neurophysiological limitations of the aging brain. The magnification of age differences remained stable when subjects from the two studies received another 18 sessions of training (Baltes & Kliegl, 1992). The distribution of performances between young and elderly subjects showed minimal overlap. Only one subject in each age-group was within the performance range of the other group.

Disuse Accounts of Age-Related Performance Declines

A prominent critique in aging research is that most studies underestimate cognitive capacities in elderly people. Kirasic and Allen (1985) argue that the poorer performance of older adults can be attributed to a disadvantage in recent experience *(disuse)* which is especially pronounced by elderly subjects' lack of familiarity with psychometric and laboratory tasks. An innovative study designed by Kirasic (described in Kirasic & Allen, 1985) required subjects to plan and execute the most efficient route possible in picking up items from a shopping list in a supermarket. The task-setting was either the subjects' usual supermarket or a novelty store which was explained prior to testing.

Familiarity did not affect the performance of young participants; however, elderly subjects were more accurate and efficient in their familiar setting.

The disuse approach has two important implications: First, it suggests that elderly subjects, given sufficient amount of training, would ultimately attain a performance similar to that of young subjects. Training which was efficient in removing the lack of familiarity, and which was administered to young and elderly subjects should indeed decrease initial performance differences. The second implication relates to individuals with extensive task-related experience due to their occupations: Performance declines in these individuals should be less pronounced compared to less experienced subjects of the same age. The results of the study by Baltes and Kliegl (1992) reported in the previous section are relevant to the first issue. Both young and elderly groups of subjects in that study showed improvements in recall performance after the initial training of 20 sessions; however, the differences between groups were larger after training than prior to training. Baltes and Kliegl consider their results at odds with disuse accounts. The authors point to the robustness of their findings despite extensive practice and the fact that the acquisition curves asymptote in the late stages of practice.

The demonstration that age differences in the ability to acquire a new skill may be irreversible despite considerable amounts of training does not, however, rule out the disuse explanation completely. Differences between young and elderly subjects prior to training may have been altogether too large to be removed within 38 sessions. In a recent study by Lindenberger, Kliegl, and Baltes (1992), individuals with presumably high levels of task-related professional experience were compared to age-matched controls. Elderly professional graphic designers were trained in the same mnemonic technique (the method of loci) used in the experiments by Kliegl, Smith, and Baltes (1989, 1990) and Baltes and Kliegl (1992) described earlier. Elderly expert subjects attained a higher level of recall performance compared to controls matched for age and verbal intelligence. They were still outperformed by a group of young nonexpert controls, however. There was no advantage for the elderly expert group in a far transfer task involving serial recall of digits. Young professional graphic designers and young controls did not differ in memory performance. Lindenberger et al. concluded that the joint effects of talent and experience in experts in a real-life skill may attenuate, though not compensate for age-related decline in a laboratory task. While the literature suggests that the creation of interactive images related to the word pairs presented in the memory task used by Lindenberger et al. is indeed an effective and critical factor for the method-of-loci technique, it is less obvious whether this ability is relevant to the skill of graphic design as such. One could argue that the similarities lie at a more global level with less relevance to the task than suggested by the authors. The study illustrates that the degree of attenuation of age-related declines depends largely on the amount of transfer between skill and laboratory task.

Expertise research has always emphasized the domain specificity of knowledge and procedures relevant for the skill. Starting with the early research on chess expertise (Chase & Simon, 1973), it has been demonstrated for various domains that expert subjects rely on strategies and mechanisms which are specific to their field of excellence and show little transfer to tasks outside the skill. An illustrative example for the sensitivity to transfer characteristic of skilled mechanisms was provided by Ericsson and Polson (1988). They studied memory skill in a waiter who could take up to 20 dinner orders without making notes. They found that their subject's memory skill transferred to the memorization of different materials with the same category structure as dinner orders. However, performance declined markedly when the transfer materials did not have a corresponding structure.

Lifelong experience in a certain profession does not necessarily transfer to an experimental task. Complex natural skills involve a number of different components and mechanisms. Most studies of expertise are therefore based on a task analysis aiming at breaking down the complex skill into several components. Performance is then assessed by a number of different experimental tasks. One of the major conclusions from the review of the literature on long-term retention was that different types of knowledge and skills might be retained to different degrees depending on the level of initial acquisition. Few experimental studies have directly looked at the interaction of aging and skill with respect to different component functions. Their findings are the topic of the next section.

Age-Related Changes in Skill Components

Charness (1981a, b) studied chess experts varying in age and proficiency. Subjects in his sample were selected such that age and official chess ranking were uncorrelated. Think-aloud protocols generated during the evaluation of displayed chess positions showed that chess expertise was correlated with extensiveness and depth of search through the problem space. Elderly players searched less extensively, but equally deep. The quality of moves eventually selected varied only as a function of skill, not of age. These results indicate that elderly players engage in a highly systematic and efficient search with respect to problems relevant to their skill. Charness' findings are in contrast to numerous studies demonstrating that search efficiency decreases with age. One possible interpretation of Charness' findings is that elderly chess experts can compensate for normal age-related decline (e. g., a slower rate of memory retrieval) by more effective search mechanisms and movement generation processes.

In a similar study on bridge players differing in age and skill level, Charness (1983) found that skill in playing bridge was associated with faster reading of a symbolic bridge card display, faster bidding, and greater accuracy of bidding. The time required to analyze a bridge problem as well as the time taken for giving the subsequent opening bid increased with age. Multiple regression analyses indicated that all skill advantages for speed of problem evaluation were virtually eliminated by the age of 60. Accuracy of bidding, the relevant variable in a game situation, however, was only related to skill level.

The strategy of sampling subjects toward a zero correlation of age and skill level was also applied by Salthouse (1984) in his study on typists. Salthouse administered several tasks which he considered to be related to basic component processes of typing skill, namely, the digit-symbol substitution test, finger tapping, and a choice-reaction time task. Stepwise regression analyses revealed significant negative relations between age and transcription speed for these measures. At the same time, however, measures were also positively correlated with typing skill. Salthouse also assessed the amount that typists looked ahead of the letter currently being typed, the so called *eye-hand span.*

The eye-hand span is positively correlated with typing skill (Butsch, 1932). Salthouse found that the size of the eye-hand span was not only positively correlated with transcription speed, but was also positively correlated with age. The latter effect remained significant even after skill was partialled out of the regression equation. These results implied that basic cognitive-motor functions deteriorated with age while complex cognitive mechanisms, as reflected in the eye-hand span, remained largely intact or even increased in efficiency with age in this sample. The latter interpretation suggests a compensation for age-related decline in elderly typists through skilled mechanisms at a higher, more specific cognitive level. Salthouse was very careful about this interpretation, however; his findings point to one of the most intriguing issues with respect to the interplay of age and skill factors.

The influence of professional experience with spatial visualization problems on task performance in subjects varying in age was recently investigated by Salthouse et al., 1990). Participants with presumably high levels of task-related experience were active or recently retired architects. Performance on several experimental tasks and psychometric markers measuring spatial abilities decreased with age. However, in a comparison with unselected adults, elderly architects outperformed an age-matched control group. Using regression analytic techniques on data from a larger sample of architects and unselected subjects varying in age across five decades, Salthouse et al. found that age trends were very similar in both groups. The regression slope modeling the age-related decline in the architect group was even steeper, suggesting a relatively higher loss rate in the experienced group. The authors contrast two different explanations for their general findings: The first perspective, *differential preservation,* attributes the performance advantage of the older architects to their accumulated experience with spatial visualization. This view would assume that extensive experience in their profession helped to maintain relevant abilities. The *preserved differentiation* view, on the other hand, implies an interpretation in terms of continued differences which presumably already existed between individuals at a young age. According to this view, superior spatial abilities may have influenced occupational choice, but individuals highly capable at a young age would also suffer from age-related performance decline, possibly even to a relatively larger degree. The reported results from regression analyses are interpreted as evidence for the preserved differentiation model by the authors. The main implication of this interpretation is that age-related declines are largely independent of experiential factors like differential amounts of preserving activities.

More recently, Bosman (1993) tried to more directly approach the issue of compensatory mechanisms related to skilled transcription typing in elderly subjects. She used simplified typing tasks which required participants to execute one or two keystrokes in reaction to a letter display. Choice reaction time and finger-tapping rate served as measures for the efficiency of basic cognitive-motor processes. Her results suggested that low-skill elderly typists exhibited a deficit both in translation and execution components of motor performance. In high-skill older typists only translation processes showed decreased efficiency with age. Based on additional findings from an experiment manipulating the preview available to participants while typing, Bosman argued that older typists compensate for age-related slowing by beginning keystroke preparation earlier.

Summary: The Developmental Perspective

The review of age-comparative studies revealed an intricate picture. While the majority of important contributions to science and the arts tend to be made by younger individuals, elderly professionals can certainly maintain an impressive level of skill and productivity. Perceptual, cognitive, and motor functions generally tend to decline with age in normal, unskilled subjects if the task requires speeded responses. Several authors assume that learnability decreases with age or that the ultimate level of possible improvement is more limited in the elderly. Intensive practice is efficient in raising the performance level in elderly subjects to the original level of young participants. However, intensive training has been shown to increase rather than diminish differences between age-groups. Other theorists claim that practice is indeed an effective means to compensate for elderly subjects' lack of task-related recent experience. Elderly skilled subjects perform better than age-matched controls in tasks which are related to their domain of expertise. However, they may even be outperformed by young unskilled control subjects if the task is not central to the skill. Charness' findings (1981a, b, 1983) have illustrated that the speed but not the quality of reasoning processes in experts show some age-related decline. These findings are different from the reported phenomena of "normal aging." Salthouse's (1984) findings about age-related performance declines in basic component processes and the extended eye-hand span in older typists are subject to multiple interpretations. One possible conclusion from these findings is that older typists compensate for their loss of speed in basic processes by looking further ahead when transcribing. The most conservative conclusion is that measures of basic motor speed, reaction time, and perceptual-motor speed show developmental trajectories different from those of skill-relevant cognitive processes. The apparent similarities between choice-reaction time and aspects of digit-symbol substitution test, on the one hand, and typewriting, on the other, may not disguise the fact that both simple tasks may have little relevance to the complex skill rather than reflecting its functional components: Fluent performance cannot be accounted for by a series of local decisions and responses which are (ideally) the prevailing processes in a choice-reaction time task (Lashley, 1951; Shaffer, 1982). Research on typewriting, as will be discussed in later sections, has revealed large evidence for advance coordination and parallel processing at different levels. The digit-symbol substitution test certainly requires rapid eye-hand coordination; however, neither the symbolic input (numbers or digits, respectively) nor the response type (handwriting, in the case of paper and pencil tests) are compatible with typing. Finger-tapping speed, on the other hand, clearly reflects a peripheral component of typing. The largest differences between expert and novice typists were found for movements alternating between different fingers rather than for repetitive strokes at the same key. The latter differences were in actual fact the smallest (Gentner, 1988).

One way to account for a decline in the performance of elderly experts in simple tasks is to assume that higher efficiency for respective functions had existed as a prerequisite prior to skill acquisition. Its remnants are thus preserved throughout most of the life-span; however, the originally higher levels of functioning undergo the same age-related decline (Salthouse et al., 1990). The *preserved differentiation* view is not definite with respect to the causes of the large differences in functioning between young experts and young unselected subjects; however, it negates the role of experiential factors with respect to maintaining respective functions throughout later phases of life.

Two methodological approaches have provided empirical evidence which gave rise to critique of the disuse concept: So far, training studies with both young and elderly subjects have shown that age differences cannot easily be removed by extensive practice. The other approach, based on comparisons between young and elderly experts and respective controls, has not yet provided a clear-cut picture, though. There are some indications for similar age-related changes in skill-relevant functions in elderly experts. For methodological reasons discussed in an earlier section, none of the studies undertaken in the context of the second approach has assessed the actual amounts of training which subjects had invested in the acquisition and maintenance of their skills. Several studies have attempted to measure experience in terms of number of years on the job. These measures were not predictive of performance in experimental tasks. The difference between *experience* and *training* is central to research presented here and will be discussed in more detail in one of the following sections.

The demonstration that elderly expert subjects perform better than age-matched controls on a given task is a good indication that the ability assessed is related to the skill. It does not necessarily imply, however, that it is central or was even practiced throughout the life course. The latter perspective is captured in the notion of limited *transfer* from the skill to more general abilities. Expertise research has been largely concerned with the demonstration of specific mechanisms and procedures accounting for the superior performance of skilled subjects. The relevant processes are assumed to be highly context sensitive and only efficient to the degree of relatedness to the skill. The capacities reflected in psychometric markers are most likely very global in nature, while skilled mechanisms are likely to increase in specificity with skill level. The latter notion is captured by Anderson's (1982) concept of *compilation* which assumes that highly overlearned routines are entrenched in specific procedures which are not effective in operating on tasks outside of the skill. Psychometric research has offered the distinction between *crystallized* and *fluid* intelligence (Cattell, 1972; Horn, 1982) in order to capture differences in age-related changes of performance on different tests. This distinction has a lot of descriptive appeal; however, there is considerable disagreement among theorists and studies with respect to the specific tests measuring either one of the two factors. Rybash, Hoyer, and Roodin (1986) phrased the term *encapsulated knowledge* in order to refer to knowledge highly associated with certain competences which remain largely stable across age.

Exceptional Levels of Performance

The review so far has illustrated that individual dispositions moderating performance throughout the life course play an important role in accounting for age-related changes in skilled and unskilled performance. While not necessarily attributed to genetic differences between individuals, these dispositions are generally believed to remain stable over time. As an example, one might imagine an individual whose high spatial visualization abilities encourage his choice of career as an architect. These same abilities subsequently undergo age-related decline to the same degree as or even more than in normal subjects. The reasons for this decline are mainly physiological in nature. Following biological models of aging, individual differences in the rate of decline are widely attributed to individual genetic predispositions. Two problems emerge in this context: First, changes which have a substratum or correlate in physiological processes tend to be taken as genetically determined. Second, the acceptance of models which consider experiential factors to be negligible compared to the role of genetic differences are based on the rejection of the disuse hypothesis rather than on direct evidence. This rejection can be challenged on important grounds as was discussed in the previous section.

Another field which has been widely cited as evidence for the role of inherent individual dispositions in human achievement is the acquisition of exceptional levels of performance. While the effectiveness of practice for improvement in real-life skills remains undebated, considerable disagreement remains regarding the relative importance of practice in attaining extraordinary levels of performance in real-life skills. Extreme levels of performance are widely believed to reflect inherited talent for a domain or genetically-based general dispositions. Talent concepts will be discussed in the next section with a focus on musical abilities.

Talent and General Dispositions

The notion of specific innate abilities is especially prominent in the domains of the fine arts and music. The occurrences of child prodigies in those domains have nourished similar speculations in scientific literature.

> ... musical ability is a separate and innate neurological capacity requiring comparatively little external stimulation in order to emerge. In this sense, musical ability may be much like the physical ability to walk, or the ability to master the syntax of language.... The difference is that the capacity to walk or to speak is possessed by the average human: only the exceptional human possesses the capacity to make music (Winner, 1982, p. 238).

The notion of talent refers to success in the acquisition of skills in a certain domain. Talented individuals are assumed to reveal their interests and dispositions early and to acquire relevant skills more quickly and with far less effort than less talented individuals. Consequentially, hard work or extensive practice are often regarded as a compensation for lack of talent. Conceptions of talent or giftedness motivated the development of tests which should allow early selection of promising individuals for special promotion in a given domain. Tests designed to assess musical talent have focused on perception and discrimination of tones. Studies with accomplished musicians showed moderate correlations (violinists) or zero correlations (clarinet or trombone) with skill for the respective subscales (cf. Sloboda, 1985, for a review). These results suggest that the abilities measured by tests of musical talent differ in their relevance for specific instruments. This is exactly what one would expect, assuming that the mechanisms underlying performance in these tests had been acquired in the course of learning how to play a specific instrument. Pitch discrimination and tonal perception may not be good candidates for measures of innate talents as such. One of the most striking examples of superior sensory judgments, absolute pitch, has for a long time been associated with innate musical talent. By now it is widely accepted that absolute pitch constitutes a skill of categorical judgment rather than perceptual discrimination, which can be acquired by normal individuals given the proper amount of training and motivation (Sloboda, 1985). Probably more problematic than the weak relation between abilities measured by tests of musical talent and professional accomplishment is the lack of predictive power with respect to success of training in a given domain. Tyler (1965) concludes that efforts to predict adult expert performance from latent ability scores were largely unsuccessful. In the context of his evaluation of available tests on musical talent, Sloboda arrives at the conclusion that it would be "foolish, and possibly unfair, to make major educational decisions on test scores alone" (1985, p. 238).

The idea that "talent runs in the family," often illustrated with reference to the famous sons of J. S. Bach, has encouraged researchers to investigate the family trees of outstanding musicians (cf. Scheinfeld, 1939). More recent studies have illustrated that individuals who are outstanding musical performers are more likely to come from families with interest and positive attitude toward music and rarely from families of professional musicians (Sloboda & Howe, 1991; Sosniak, 1985). The notion of inborn musical abilities is also disputed in the context of research in behavioral genetics. A recent study by Coon and Carey (1989) found similarly high correlations of musical abilities for both identical and dizygotic twins, illustrating the large impact of environmental factors on the development of musical skills. Most interestingly, the impact of environmental factors turned out to be stronger in the group with higher involvement in music than in the less accomplished group. Counter to many common beliefs, Coon and Carey suggest that musical ability might be a domain in which heredity is less important than in general cognitive functioning.

Revesz (1954) perceived talent as an inherited disposition enabling an individual to produce achievements far above the average level in a specific domain. Revesz points out, however, that talent, as well as general aptitude for music, needs to be developed through practice. In this context, practice is considered a necessary, but not sufficient, prerequisite for attaining high levels of skill. A century ago, Francis Galton (1892) proposed a concept of talent which was directed at more general personality dispositions rather than at specific abilities. The features of a talented person depicted by Galton are: a high activity level stimulated by large resources of mental energy, the ability to focus this energy in pursuing selected goals, independent judgment and thinking, the ability to organize work towards maximum use of opportunities, and an emotional dedication to a specific domain (cited from Manturzewska, 1986). Contemporary concepts of talent have taken a more pragmatic perspective integrating general dispositions, specific abilities, and external factors. Manturzewska defines talent as a dynamic constellation of interacting characteristics, consisting of five independent sets of factors: specific musical skills, general intelligence, personality traits, biographic and environmental factors, and practical skills acquired in the course of instrumental training and individual experience. This approach has apparent integrative power but little explanatory appeal, given that few factors remain which are not included in the talent concept in the first place.

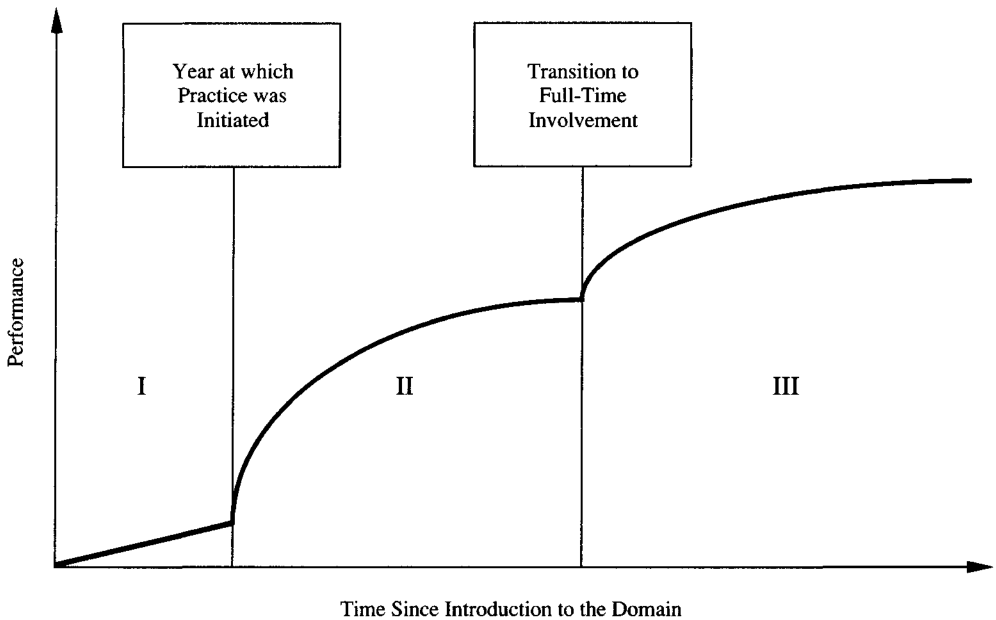
Keele and Hawkins (1982) approached the question of broad abilities underlying high levels of motor skills from an information processing perspective. Construct validity for three main factors, namely, general time-sharing ability, attentional flexibility, and speed of reciprocal activity was determined in multiple experiments. Only the third ability, measured as rate of repetitive tapping in different muscle groups, showed high correlations across tasks. Keele and Hawkins quote evidence for high correlations between tapping speed and skills like typing or handwriting. They propose a general central timing mechanism as a disposition determining performance in high-level motor skills.

In summary, the talent notion reflects a widely held belief in everyday and scientific thinking. While modern talent concepts even include acquired skill, it seems fair to say that talent implicitly refers to stable interindividual differences which moderate acquisition of skills through practice. These differences should not by themselves be acquired unless the talent notion is rendered completely trivial. Extraordinary abilities in mental calculators and idiot savants have been shown to rely on specific mechanisms which were acquired under extreme conditions, providing motivation and time for long-term practice in a number of case studies (Ericsson & Faivre, 1988; Howe, 1990). Immense amounts of early stimulation also appear to account for an idiot savant's extraordinary skill in playing the piano, as studied by Sloboda, Hermelin, and O'Connor (1985). The notion of general dispositions appears to rest on the rejection of the skill acquisition position more than on empirical support considering the acquisition of high performance levels. One important reason for this may be that the amounts of effort and practice involved in acquiring high levels of skill are underestimated and especially difficult to assess. More recently, the acquisition of exceptional skills in real life has been approached from a perspective which focuses on the role of practice and motivation. This approach and related studies will be described in the following sections.

Acquisition of High-Level Skills in Real Life

Ericsson, Krampe, and Tesch-Römer, (1993; Ericsson, Tesch-Römer, & Krampe, 1990) have proposed a theoretical framework on the acquisition of expert performance in real life. This framework attempts to build upon findings from laboratory research on skill acquisition and extend the expertise approach toward life-span development. The central proposition employed for these purposes is that exceptional levels of performance can be viewed as the result of an extended process of skill acquisition. High-level skill represents the extreme outcome of long-term adaptation to the constraints of a specific domain. The most important constraint is the need for extensive practice. The notion of practice used by Ericsson and his colleagues, however, is intentionally distinguished from experience as it may occur in the working context or as it may occur merely in the use of a skill, such as walking in everyday life: Practice is defined as a *deliberate, goal-directed, and effortful activity.* Practice, thus defined, demands careful analysis of one's own performance and continuous fine-tuning in the acquisition of new procedures through massive repetition. Playing music for fun or engaging in sports at a recreational level do not involve instruction and practice techniques designed to optimize improvement for specific skills to the same degree as goal-directed training, which is typical of professional coaching. The major goal of recreation is enjoyment rather than progress in the skill. Practice activities designed to improve performance, according to the definition, are not inherently enjoyable. The term *deliberate* was chosen to indicate that improvement of performance, rather than enjoyment or accommodation to external social standards (e.g., in a working context), is the goal motivating individual efforts. The presumed effortful nature of monitoring one's performance and the differences in goal structure account for the fact that engagement in practice activities is of rather limited duration in recreational sports and music. The same line of argument applies to the occupational use of a skill: Long-standing professionals in a domain tend to perform according to employment standards and are often able to improve given further deliberate practice or motivating rewards. According to the above definition the most important distinction between practice and other forms of skill-related behavior relates to the goals motivating the investment of time and effort. Recreational or professional use of skills does not automatically lead to advanced performance because it is not primarily motivated by the goal of improving relevant abilities. This motivation and direction, however, are the prerequisite for the continuous evaluation of current performance and search for advanced techniques. Exceptional performance in real-life expertise relies upon processing mechanisms and knowledge which take years or even decades to acquire.

Figure 1
Three Stages in the Acquisition of Real-Life Skills



Note. Schematic description of the model proposed by Ericsson, Krampe, and Tesch-Römer (1993).

Long-term commitment to a domain is necessary for this acquisition process. Stable motivation is especially important in the face of misfortune or failure when persistence needs to be maintained.

Following cognitive models of skill acquisition (cf. Anderson, 1982), Ericsson, Krampe, and Tesch-Römer (1993) assume that the level of skill attained is a monotonic function of practice at each stage of development toward adult expertise, as depicted in Figure 1. The model comprises a sequence of three stages and was adopted with slight modifications from Bloom (1985). During the first stage, the individual is introduced to the skill domain. Involvement and activities are assumed to be playful and motivated by curiosity or encouraged by adults. Many individuals already quit their involvement in the domain at this stage. Stage II is marked by the start of systematic practice under the auspices of coaches or teachers. Encouragement and design of practice activities is still under the control of supportive adults in this phase. The amount of practice activities is assumed to increase gradually throughout this stage. Careful allocation of time and energy is required to optimize the outcomes of practice. One important aspect of this allocation is the possible restriction of leisure time in favour of skill-related activities. The end of stage II is marked by the begin of professionalization and full-time involvement in a domain. Master teachers may continue to play an important role in guiding practice, but the design of practice activities and the budgeting of time and energy resources is mainly under the control of the individual. This third stage in the development of expertise is characterized by a stable state in terms of time and energy organized toward optimizing the outcome of practice activities.

A Study on Young Elite Violinists

In a recent investigation developed from this framework, Ericsson, Krampe and Tesch-Römer (1993) studied individuals who had practiced playing the violin for more than ten years. The study is described in more detail because of its importance for the research presented here. Subjects consisted of three groups of students at a musical academy differing in their level of skill in playing the violin. The *best* students were nominated by their music professors as having exceptional potential as violinists. Two comparison groups of violin students matched for sex and age to the first group were recruited from the same academy. One of these groups consisted of *good* violinists in the same department.[1] The other comparison group consisted of violin students from the department for the training of *music teachers,* which had lower admission criteria. Group selection was validated by analyzing the number of successful entries in violin competitions. According to the framework described earlier, all subjects were at the end of phase II and were already involved full-time in their domain of expertise.

A taxonomy of 22 activities was used in order to allow fine-grained distinctions with respect to musical activities (12 categories) and everyday activities (10 categories).

[1] The assessment criteria for *best* students communicated to the music professors were "potential to become an international-level soloist or to play in an orchestra with an international reputation (A-orchestra);" *good* students were explicitly assessed by their professors as not conforming to these criteria.

Musical activities included practice alone as distinguished from playing for fun, taking lessons, public performances, and the like.[2] The categories relating to musical activities were constructed from extensive interviews with expert musicians. Note that the distinction between *practice alone* and *playing for fun alone* refers to activities which would probably appear very similar to an outside observer; however, in terms of intensity, motivation, and relevance for improvement, a number of important implications are implied here. The categories relating to everyday activities were taken from earlier research on time budgeting. Subjects were asked to rate each of the 22 activities using three different scales: relevance for improving performance on the violin, effort involved in the activity, and inherent enjoyment associated with a given activity. *Practicing alone* with the instrument received the highest rating in terms of improving violin performance from 27 out of 30 subjects. Practice alone was further judged to require significantly more effort compared to the average of all activities. Contrary to activities like listening to music, however, practice was not considered to provide above average inherent enjoyment. The subjects' perception of activities appeared to be in line with the general framework. More specifically, these findings indicated that the concept of practice proposed by the framework was very similar to the subjects' notions.

In order to assess current involvement in music-related and other activities, subjects kept a detailed diary for each day during a whole week. Daily activities had to be listed on a form sheet dividing the day into 96 15-minute intervals. Activities were then categorized by subjects according to the taxonomy of 22 activities. Analyses of aggregated data revealed that the best students and the good students did not differ with respect to current amounts of practice ($M = 24.3$ hrs.). The average of both groups, however, was reliably different from that of the trainee music teachers ($M = 9.3$ hrs.). The pattern of practice in the two more accomplished groups revealed that most practice took place during the morning and in the late afternoon. The amount and the pattern of practice was stable across all days of the week. No corresponding pattern was found in the third group. The *best* group was also shown to have significantly less leisure time compared to the *good* group. Interestingly, students in the two more accomplished groups were found to sleep reliably more than those in the third group. This difference was due to short afternoon naps frequently taken by these subjects.

During an extended biographic interview, subjects also estimated their past amount of practice activities for each year of their lives. The retrospective estimates were used to compute accumulated amounts of practice for each subject until the age of 18, the year of entry to the academy. The best group had practiced more in earlier years, especially around the age of 15 (puberty) compared to the good group. Both groups were reliably different from the trainee music teachers. It is worth noting that these differences were not due to different starting ages, which were similar for the three groups.

[2] The procedures for the assessment of current and past involvement in skill-related activities described here were identical to the research described in this dissertation. The taxonomy and an example diary form sheet from this study are included in Appendix A.

The results from the study described above provided empirical support for the general model. Subjects in the two more accomplished groups had arranged their daily lives toward a stable level, thereby maximizing the outcome of their practice activities. The best subjects had decreased their leisure time, probably in favour of other musical activities beyond practice, as was shown in subsequent analyses. The higher amount of sleep in the more skilled groups can be interpreted as recuperation from effortful practice. The findings on accumulated past practice illustrate a central aspect of the model. Past amounts of practice determine performance at any given time in development. While past amounts of practice are the critical factor in predicting adult levels of performance, it is important that the theoretical scope of the framework is not restricted to predicting performance merely as a function of accumulated amounts of training. Sufficient time and energy for practice, as well as proper instruction, are largely determined by social support. In later phases of development allocation of master teachers and training grants is normally determined on the basis of comparisons among individuals of the same age. Most music academies have a maximum age for admission to advanced soloist classes, and competitions for young musicians are held according to age-groups. The claim put forward by Ericsson, Krampe, and Tesch-Römer (1993) is that the amount of practice accumulated at a given age determines the critical performance level relevant for access to the limited resources provided by society to support full-time involvement in a competitive domain. An important implication of this assumption is that the starting age may indeed be a relevant factor in predicting the later attained level of skill under certain circumstances: An early start in a domain can provide an advantage which cannot be compensated for by an individual of the same age who started later (assuming that gradual increases in practice are the same for both). Evidence from a number of different domains, such as tennis, chess, swimming, and music, reviewed by Ericsson, Tesch-Römer, and Krampe (1990) demonstrates the relation between starting age and the ultimately attained level of skill. The integration of social support and starting age as relevant factors in the skill acquisition framework provides an alternative explanation for two major pieces of evidence frequently cited as support for the talent position—namely, that talent runs in families and manifests itself very early in gifted individuals. As was mentioned earlier, at least two studies (Sloboda & Howe, 1991; Sosniak, 1985) have shown that highly skilled musicians are more likely to come from families that are interested in music and that provide the support and encouragement needed than from families of active or high-level musicians. These observations fit well with the proposed skill acquisition framework.

The notion of extended skill acquisition as a process of long-term adaptation to domain specific constraints has proven to be a promising approach to the study of exceptional performance. The most important aspect of this development is the adaptation to the mental and physical demands of intensive practice, the most relevant activity for advancement under the control of the individual. Starting from the introduction to a domain, individuals gradually increase the amount of time and energy invested in skill-related activities. The question arises as to what happens in the later phases of adulthood after attaining the expert-level stage. The role of practice and other skill-related activities in later phases of skill development is the topic of the following section.

Skill Maintenance: The Role of Practice

Most studies of skill retention tried to measure performance decrements after various phases of disuse. Subjects who reported rehearsal during the delay period were normally discarded. Measures of intervening rehearsal are problematic in many respects, the most important of which is the definition of activities assumed to help maintain a given skill. Salthouse's (1984) study on typists of different ages described earlier also included measures of past and current amounts of experience. The measures used were accumulated typing experience (months of relevant employment with more than ten hours of typing per week) and recent amounts of experience (average hours of typing per week during the last six months). Both measures were positively correlated, although not always significantly in both of his samples, with transcription speed. Amounts of recent experience and age were uncorrelated, which is interesting, given that subjects were sampled toward a zero correlation of age and transcription speed. One could argue that this sampling bias is effective in terms of selecting elderly subjects who remain highly active in their profession. In the light of our discussion of differences between goal-directed practice and job-related experience, the modest correlations between skill-related activities and skill are plausible. They do not reject the idea of effectiveness of practice in terms of maintaining a skill as such. In their study on architects of various ages, Salthouse et al. (1990) had participants estimate the recent amount of time they spent on task-related activities in their everyday lives. Interestingly, there was a significant negative correlation between age and time in the group of architects. This points to the possibility that the focus of engagement for elderly architects may have changed with age, leaving less time for those activities best suited for the maintenance of the skills reflected in the experimental tasks.

The dominance of physiological accounts for performance changes in cognitive aging research makes a comparison with findings from sports medicine and physiology especially interesting. A number of physiological variables, such as maximum rate of heart pulse, constitution of muscle fibers, and strength, have been shown to have a higher level of functioning in master athletes than in normal individuals. These differences were for a long time believed to reflect genetic predispositions. More recent evidence (for a review see Ericsson, 1990), however, indicates that these physiological changes are the result of extensive training. Furthermore, differences between accomplished sportsmen and control subjects are restricted to those physiological functions relevant to the athletes' specific discipline. During long phases of disuse, as after severe injuries, the efficiency of these functions has been observed to decline dramatically, subsequently requiring considerable time to be reestablished. Ericsson concluded that the observed differences in physiological functioning reflect a long-term adaptation to continuously increasing amounts of training during years of preparatory exercise. Decreasing the amount or intensity of practice also changes the physiological performance constraints. According to Ericsson, these findings complement the results on systematic differences in peak ages between disciplines in sports discussed earlier. The relevant physiological functions characteristic of master athletes differ between specific events. Differences in ages of maximum achievement are thus likely to reflect the different amounts of training necessary for these functions to develop toward optimum efficiency. Both findings illustrate that the notion of extended skill acquisition is completely in line with physiological accounts for performance differences. The major difference regarding talent conceptions is that the physiological characteristics of distinguished performers are assumed to be acquired.

A comparison of cross-sectional and longitudinal data provides further insights into the complex interactions between aging and practice. A comparison of winning times for competitions according to age-groups shows that best performances in different disciplines tend to decline linearly with age until the sixth decade and more rapidly thereafter. This finding is similar to age-comparative studies on physiological functioning in athletes and untrained subjects. Analysis of longitudinal changes in track events (Stones & Kozma, 1982), on the other hand, have revealed a decline which is only half as steep as in comparable cross-sectional studies. Similar findings were reported from swimming competitions by Letzelter, Jungermann, and Freitag (1986). Mean differences in three age-groups (total range 35 to 44 years) were significant; however, the performance of those individuals who had participated in all respective competitions over a 13-year period did not show reliable decrements. Letzelter et al. interpreted the findings of their cross-sectional comparisons as a result of changes in frequency and intensity of training rather than as an indication of biological changes. Longitudinal studies provide a most valuable source in evaluating age-related performance changes. The major problem of cross-sectional comparisons is that they are subject to cohort effects or secular trends, like changes in the educational system or opportunity for guided instruction. The results of cohort-sequential studies suggest that between 25–56 percent of the performance differences in intellectual functioning between young and old adults might be due to secular trends (Schaie, 1988). A comparison of Olympic records and performances at contemporary competitions according to age-groups reveals that today's master athletes between the ages of 50 and 60 perform at levels which would have sufficed to win Olympic medals at the turn of the century. Ericsson (1990) attributed this finding to differences in type and intensity of training as the primary causes. As a conclusion, Ericsson suggested that peak performance age does not reflect age-specific biological constraints as such, but rather the optimization of preparation with respect to multiple age-related constraints. Declines in peak performance with age should be considered in the light of pure aging effects on physiological function, decreases in the intensity and amount of training, and possible interaction effects.

Especially interesting in the context of skill maintenance is the work by Hagberg and his collaborators (described in Ericsson, 1990). This group made detailed physiological assessments of eight master long-distance runners, whose ages averaged 56 years. Comparison groups were healthy, age-matched subjects with no active participation in sports and two groups of young runners in their 20s. One young group was matched to the old master athletes on the basis of race times, training mileage, and running pace during training. The other young group had a running performance relative to their age group, which was comparable to the old master athletes. They were, so to speak, young master athletes. This latter young comparison group was found to have faster race times than the old masters. They also spent considerably more time on training. Physiological measures revealed that old master runners had about twice the aerobic power compared to age-matched controls. Their values were reliably lower, however, than those from the training-matched young group ($M = 9\%$), and considerably below the measures of the young competitive runners ($M = 19\%$). Hagberg and his colleagues suggest that these differences are moderated by training level. They also point out that aerobic power is to some degree determined by maximal heart rate. According to the authors, decrease in maximal pulse rate occurring with age, however, appears to be an inevitable consequence of aging in the light of present findings. The main implication of these results is that the decline in physiological functioning found in normal adults is not typical for elderly master athletes. Age-related decline of many, but not all, physiological functions can be minimized through maintained practice.

A study designed to scrutinize the changes in skill-related activities occurring during middle age was recently conducted by Heizmann, Krampe, and Ericsson (1993). Subjects were ten male violinists (M [age] = 50.5 years) recruited from two Berlin orchestras with international reputation. Past and current amounts of practice and other skill-related activities were assessed through the same procedures used for the study on young violinists described earlier. Earlier development in terms of practice until the age of 18 was remarkably similar to the elite group of young subjects in the previous study. Amount of practice accumulated until age 18 was basically identical for the two groups. Starting from the age of 26, however, Heizmann et al. found a constant decline in the weekly amounts of practice. The amount of time spent on actual solo violin practice had decreased to seven hours compared to the most accomplished young subjects' average of 24 hours. The total amount of time that middle-aged subjects were involved in music-related activities, however, was not reliably different from the young elite subjects. These results suggest a central shift in the focus of activities. An important question in this context remains whether the shift of focus in the activities of middle-aged subjects reflects motivational changes in life goal perspectives and how it relates to the level of performance.

Skilled-Movement Coordination

Overview

The usual research strategy applied to the study of expertise is to analyze a complex skill into a number of subcomponents, to develop experimental tasks likely to reflect the relevant cognitive functions, and to try to scrutinize those skilled processes which distinguish expert and novice behavior. This strategy has also proved useful in the study of expertise and aging. The evidence reviewed in the first half of the chapter on theory has illustrated that different task components may not be equally affected by age-related changes. The main purpose of the following sections is to review the existing literature on playing the piano from the perspective of a complex cognitive-motor skill and to derive a suitable analysis into components. This analysis is guided by two motives: First, the components should reflect superior functioning in expert pianists, but they should also be relevant to behavior outside the skill of playing the piano. Second, the task components derived should relate to cognitive-motor functions which have been shown to deteriorate with age in unskilled subjects. The latter aspect provides a critical perspective on the interaction of skill and aging processes.

The ultimate goal of musical performance may be defined as the expression of ideas and emotions by means of intentional variations in timing, duration, and loudness of generated tones. At the level of observable performance, playing the piano mainly consists of complex movements involving all fingers of both hands (there are, of course, important aspects in the coordination of the feet on the two or three pedals of the grand piano which will not be considered here). Timing in the coordination of complex finger movements will be the focus of the following review of previous research. Theorists in the field (Shaffer, 1982) propose that timing in terms of adaptation to performance constraints is the crucial feature underlying a whole range of cognitive-motor tasks of varying degrees of complexity. While constraints in simple tasks like finger tapping may be mainly determined by biomechanical factors, performance in typewriting has to be adapted to multiple external constraints, such as keyboard layout and the text to be typed. Playing the piano constitutes a special case of skilled movement timing, in the sense that variations in timing and force are not only adapted to performance constraints provided by the instrument and the abstract score, but they also demand deliberate control on the part of the performer who tries to express his ideas in the music he is playing.

The review of the literature will be structured along the performance constraints for hand and finger movements of increasing complexity. The initial description of previous studies on single and multiple finger-tapping tasks will serve to illustrate that simple movements are subject to important constraints in unskilled subjects. Motor programs and schema as basic concepts in movement research will be briefly introduced. The subsequent review of findings on the coordination of two-handed movements sets the stage for a discussion of more complex skills. Following the analogy to playing the piano suggested by Shaffer (1982), the findings from research on expert typists will be reviewed. The two domains will be compared and the relevance and limitations of the analogy is discussed. Previous research on skilled piano playing is summarized toward the end of the literature review.

Performance Constraints in Simple Motor Tasks

Movements and actions occur in time. Even simple motor behaviors normally involve more than a single movement of one muscle group. Multiple movements need to be coordinated with respect to their occurrence in time *(movement timing)*. Some obvious performance constraints in rapid execution of hand or finger movements result from biomechanical factors, such as handedness or finger dexterity. One of the earlier attempts to scrutinize the effects of handedness in unskilled motor tasks was undertaken by Provins (1956). The participants' task was to reproduce a particular pressure using the index fingers of preferred and nonpreferred hands respectively. No hand differences were found with respect to accuracy. In a second experiment, participants were asked to produce maximum speed in repetitive tapping with the index fingers of one hand regardless of the accuracy of the pressure applied. Provins found significant differences in the speed of tapping between the preferred hand and the nonpreferred hand at all three force values necessary to produce a tap. Consistency of cycle length between taps was markedly higher in the preferred hand. The latter finding, however, has to be interpreted with caution, considering that means and standard deviations generally tend to be correlated for latencies. Provins was also able to show that asymmetries in performance between the left and right hands could be reduced by practice. The amount of practice administered was, however, fairly limited in this experiment. Todor and Smiley-Oyen (1987) demonstrated that different finger-tapping rates for preferred and nonpreferred hands coincided with more efficient force modulation in the dominant hand. Left-finger movements were characterized by greater average downward force and higher variance in terms of force applied compared to right-finger movements (all subjects were right-handed). The mean time that the key was held in the lowest position provided a measure of the time necessary for a reversion of movement direction. This duration was significantly shorter in the dominant hand. The implication of these findings is that the effects of handedness are most pronounced if rapid serial production of movements is required by the task. Decrease of variability in the sense of effective force modulation coincides with higher speed of movement production.

Povel and Collard (1982) provided impressive evidence for the impact of memory representations on motor performance in a repetitive tapping task. Movement sequences were presented as digit strings, each number indicating one of four different fingers to be used. Tasks varied with respect to the assumed underlying coding representation of stroke sequences, but were matched in terms of motor demands. Povel and Collard's findings supported the contention that cognitive representations formed through a hierarchical grouping of digit units determined the transition times between subsequent strokes. Geoffrey and Norman (1982) found similar effects varying the grouping implied by stimulus presentation in a five-finger tapping task.

Correlations between rates of repetitive tapping and proficiency in more complex skills have been reported in a number of studies. Book (1924) found that tapping rates of world champions and ex-world champions in typewriting contests were on average 25–33 percent higher compared to age-matched reference groups. Salthouse (1984) reported a significant correlation of finger-tapping speed for left, right, and alternate index fingers with rate of transcription in typists. Telford and Spangler (1935) found higher rates of finger tapping in pianists compared to control groups. In their study, complexity was manipulated by requiring subjects to tap the same key repeatedly with different fingers in a specified order. Skill differences were, however, not affected by complexity.

The study of timing mechanisms in tapping synchronized to an external beat was pioneered by Wing and Kristofferson (1973). They developed the *continuation paradigm* which requires subjects to produce a series of taps after initial synchronization with a computer beat. The basic underlying assumption of their model is a central timekeeper, an internal clock with a certain variance which triggers responses at a random motor delay reflecting peripheral factors. Vorberg and Hambuch (1978) extended the original proposal in their investigation of rhythmic structure in tapping tasks. Through their analyses of variance and covariance patterns, they were able to provide support for a model of concatenative timing, the timing of successive intervals within a rhythmic group being under the control of independent timekeepers. More recently, Keele et al. (1985) showed that pianists' accuracy of timing intertap intervals as well as their maximum tapping rate was higher than for controls. While these results held for tapping with the right forefinger, there were small or no differences between groups when subjects were required to tap with their heels. Keele et al. nonetheless maintained their model of a central timekeeper; however, their results point to the issue of near and far transfer in piano-related tasks.

Coordination of Two-Handed Movements

Experimental studies of bimanual movements have been mainly concerned with aspects of *hand independence.* A well-documented phenomenon in this context is that movements initiated by a certain muscle group tend to trigger movements in mirror-image limbs. Neuropsychology has tried to account for this effect by pointing to the large number of neural interconnections between the lateral brain areas which control the respective muscle groups. The basic assumption was that neuronal activation spreads between lateral hemispheres, producing *motor overflow* (Kinsbourne & Hicks, 1978). These models assume that the interconnections in the newborn infant favor this spread. The tight coupling of mirror image limbs *(entrainment)* is indeed evident from children's early movements. Overcoming the effects of the entrainment plays an important role in children's development of motor abilities, and the limitations to hand independence are still evident in adult movements. Acquiring expertise in bimanual coordination skills can be described as a matter of overcoming performance constraints imposed by entrainment or, positively stated, acquiring a large degree of hand independence (Swinnen & Walter, 1988) in the sense of interlimb decoupling (Swinnen et al., 1993).

Kelso, Southard, and Goodman (1979) found evidence for tight coordinative coupling between both hands in simultaneous movements. Their aiming task required participants to move hands to targets varying in size and distance from the home position. Subjects simultaneously initiated and terminated movements in both hands to targets of widely disparate difficulty, although not explicitly instructed to do so. Combining difficult movements (small, remote targets) in one hand with simpler movements (large, close targets) in the other led to a decrease in overall speed, which could be accounted for by the single-hand speed for the difficult trajectory *(temporal invariance).* The authors interpreted their findings as evidence for a centrally programmed duration parameter allowing for the control of the different muscle groups as if they were one unit. Kelso et al. contend, however, that their subjects were unskilled with respect to the task. They suggest that highly skilled performance might be viewed as a release from the temporal invariance imposed by a coordinative coupling of hands.

Klapp (1979) examined processing limitations in bimanual performance when generating different rhythms with the two hands. His subjects had to perform periodic tapping tasks in synchronization with a light stimulus. The left hand was always tapping a steady beat, while the right hand tapped "melodic" rhythms. The right-hand rhythm divided the frequency of the left hand (harmonically related) or did not coincide with the left-hand pulses (nonharmonically related) at all. Klapp found that the accuracy of performance in this task was degraded, compared to completely synchronized left-right tapping, when the temporal periods of responses were not harmonically related. He interpreted his results as evidence for a single processing base for the timing control of both hands. Klapp suggests that a pianist playing polyrhythms (e.g., "three against four") in musical performance must integrate both rhythms into a single time frame, which may then be used for a central monitoring of strokes. More recently, Jagacinski et al. (1988) provided further evidence for integrated structures in polyrhythmic performance.

Ibbotson and Morton (1981) used similar tasks, but systematically varied the limb combinations applied between hands and feet. Participants were required to produce a steady beat with one limb and a rhythmic variation with the other. Ibbotson and Morton found that the task was quite easy for almost all of their subjects when the steady beat was produced by the left hand and the rhythm by the right hand. For most subjects in their first experiment, the task was impossible the other way around. All rhythms were quite simple and could be done by all subjects with either hand alone. The difficulty arose from the combination of hands and rhythms. Ibbotson and Morton termed this phenomenon *rhythm dominance effect.* When comparing trained musicians and unskilled subjects, the rhythm dominance effect was basically absent in the skilled group. This was partly due to a ceiling effect in the musicians' performance. Detailed analyses revealed that the pattern of results was basically not different for reported sinistrals (subjects who showed a left-hand preference). The authors conclude from their findings that precise temporal control of fine-motor actions, rather than differential dexterity of the limbs is the crucial factor determining performance asymmetries. Ibbotson and Morton refer to neurophysiological evidence, indicating that temporal motor control might be located in the same hemisphere as the speech center. The speech center is located in the left hemisphere even in most sinistrals.

One of the problems evident in most studies of polyrhythmic performance is that even skilled subjects have great problems to do the task at all (e.g. Deutsch, 1983). A recent study by Summers et al. (1993) showed that subjects adopt a hierarchical form of integrated motor organization in which movements of the slower hand (e.g. the three in a three against four rhythm) were subordinate to movements of the faster hand. Vorberg and Hambuch (1984) have tried to extend their earlier model of concatenative timing to bimanual performance. Their evidence supports the notion of a central timekeeper monitoring performance in both hands. None of their tasks required polyrhythmic performance. The authors point out that most studies on rhythmic timing suffer from a lack of systematic variation of tempo, which might affect the structure of the timing mechanisms coming to bear on subjects' performance. More recently, Krampe, Kliegl, and Mayr (1993) have studied accuracy of timing in expert and amateur pianists performing polyrhythmic and isochronuous bimanual tasks at a large range of different tempi. Their findings suggest that beyond an optimal tempo the percentage of deviation from perfect timing increases (see also Wing, 1980). Expert pianists revealed superior timing for fast tempi, reflecting higher adaptation to peripheral-motoric constraints. Experts reach their optimal (i.e., most accurate) timing at faster rates than amateurs do, especially when timing requirements are more complex (polyrhythms). At the slower tempi, sophisticated strategies like special counting or accentuation methods were applied (mostly by experts) to cope with the cognitive difficulty of timing long interval durations. The overall relation between speed and timing accuracy follows a U-shaped function.

Complex Motor Skills

The evidence reviewed so far has illustrated a number of severe processing limitations in the performance of unskilled subjects. The results from studies on multiple finger-tapping tasks have demonstrated that timing in the execution of multiple movements is not merely determined by peripheral constraints, but depends on memory encodings formed on the basis of stimulus presentation formats (Rosenbaum, Kenny, & Derr, 1983). Povel and Collard (1982) could demonstrate that their subjects had memorized groupings of digits which denoted the fingers to be used in their serial tapping task. Interstroke intervals in performance could be predicted on the basis of the encoding pattern. The fact that those interstroke intervals coinciding with presumed group boundaries were consistently longer, independent of motor requirements, implies that serial activation of coding patterns determined the performance speed. The performance speed in bimanual tasks appears to be a function of the ultimate speed of the hand doing the more difficult task, due to the fact that control is normally integrated into a joint processing frame for the concurrent movements. Frequently, bimanual coordination is not only determined by single-hand constraints, but also reveals constraints emerging from the asymmetric mutual interference of the hands. These processing constraints become most important when temporal or kinematic independence of the hands is required by the task.

The acquisition of complex motor skills requires adaptation to those constraints, and limitations evident in the performance of unskilled subjects need to be overcome through skilled mechanisms. The higher rate of tapping found in earlier studies on typists and pianists suggests that this adaptation might include "peripheral" factors. Musical training seems to be efficient in overcoming some of the limitations on bimanual performance. Release from mutual interference (entrainment) between the left and right hands, or, positively stated, hand independence, is an important feature of any motor skill requiring bimanual movements. Studies on skilled mechanisms in typists and pianists are the topic of the following sections.

Motor Programs and Schema

Mental representations controlling movements are referred to as *motor programs* (Shaffer, 1976) or *schema* (Rosenbaum, 1984; Rumelhart & Norman, 1982; Schmidt, 1975) in the literature on this subject. The human ability to form, use, and refine these structures is called *motor programming.* Motor programs are not conceived as a list of subsequent movements, but rather consist of a more or less elaborated representation of parameters (force, direction, speed) for the different movement components. These representations can be integrated into more complex schema. The degree of integration and flexibility is assumed to vary as a function of proficiency in the task. More specifically, the concept of motor programming refers to the idea that movements in sequential behavior are mentally organized in advance of their execution (Lashley, 1951; McKay, 1982; Shaffer, 1978). Cognitive representations of movements and their specific parameters are assumed to form the processing base for an important phenomenon, namely, *anticipation.* In any form of rapid, complex action, anticipation of the next movement to be executed increases behavioral flexibility beyond the limits of mere reaction to momentary performance demands. The concept of motor programming has been widely applied in describing cognitive processes in simple motor tasks, as well as more complex skills like speech production, typewriting, and playing the piano (Shaffer, 1976). One convenient assumption, often made in theorizing on motor programming, is that the program controlling motor output is the same, whether it originates in a mental representation or is derived from stimulus input, as in transcription typing. Conscious accessibility of motor schema or programs is assumed to be limited.

Researchers in the field of cognitive-motor processes often distinguish between mechanical and cognitive performance constraints (Gentner, 1988; Salthouse, 1984). Mechanical constraints in executing, for example, a series of typing keystrokes comprise biomechanical factors (handedness, finger dexterity) and physical task constraints (keyboard layout, repetition or alternation of fingers and hands in specified movement sequences). Cognitive constraints refer to a subject's ability to encode movement sequences, form mental representations, and efficiently use these in controlling execution. Skill differences in complex motor abilities, like typewriting, have been explained as a matter of optimizing cognitive functioning to a degree that performance speed is mainly limited by mechanical constraints (Gentner, 1988).

A central characteristic of skilled motor programming (like basically all types of skill) is the adaptation to specific task constraints. At a more general level, this adaptation refers to the availability of a large tacit base of knowledge on the task space, which reduces the requirement for time- and resource-intensive decision processes during performance. Knowledge-guided evaluation allows the skilled player to predict the trajectory of a high-speed projectile in ball games, leaving considerably more time to initiate the proper reaction. The existence of available motor programs for skill-specific problems in the first sense of adaptation accounts for a decrease in the variability of different performances of the same task in experts. At a more detailed level, movement parameters can be fine-tuned to peripheral constraints even in the course of movement execution. The flexibility in terms of "on-line" adaptation predicts that variation across different performances is functional in skilled subjects. The effectiveness of both types of adaptation to performance constraints is evident in Shaffer's work (1981) on pianists. Skilled pianists can produce highly consistent repeated interpretations of the same piece, when asked to (decrease of performance variability). On the other hand, Shaffer found that his subjects could rapidly compensate for errors while maintaining the overall pattern of movement timing in the course of performance. Similar findings have been provided for typewriting (Gentner, 1987) and expert table tennis (Bootsma & van Wieringen, 1990).

Cognitive-motor performance in unskilled subjects, on the other hand, is characterized by serial decision and execution processes determining the speed of performance. Measures tapping into respective processes, such as speed in choice-reaction time tasks, have been used to predict success in learning how to type (cf. Cleaver & O'Connor, 1982). The nature of described skill mechanisms implies, however, that the speed of performance in high-level cognitive-motor skills, like typing or playing the piano, cannot be reduced to a series of single responses (Lashley, 1951; McKay, 1982; Shaffer, 1976). These skills do not rely on serial decision and reaction processes, although the observable behavior in simple tasks might share similarities with complex performances.

Expertise in Typewriting

The most striking difference between expert and novice typists is speed. At the end of business school, average students are able to type at a speed of 56 words per minute (less than five strokes per second). Experienced professional typists have been reported to maintain a typing speed of more than 100 words per minute (Gentner, 1988; Shaffer, 1978), which amounts to an average of more than nine strokes per second. These performances are even surpassed by competitors in typing championships, performing at a speed of 200 words per minute (Rumelhart & Norman, 1982).

When transcribing texts, skilled typists look ahead of the letter they are typing at a given moment. The number of letters read ahead is referred to as the eye-hand span. Shaffer (1978) manipulated the amount of text his typist was allowed to look at in advance, by presenting the text in a computer display window. The next character appeared in the window whenever a stroke was executed. Shaffer demonstrated that the amount of preview available affected performance dramatically: Typing speed dropped from 118 words per minute (eight or more characters preview) to 27 words per minute if only one character was visible at a time. He took his finding as evidence for *advance coordination of movements* prior to execution. Faster typists tend to have larger eye-hand spans than less skilled subjects (Salthouse, 1984). Studies manipulating the semantic structure of text in transcription typing (Gentner, 1988; Salthouse, 1984; Shaffer, 1976) provided evidence that perceptual encoding mainly takes place below the word level. Reversing a text letter by letter affected typing speed, whereas scrambling words in a text had little, if any, impact on experts' performance. Grudin and Larochelle (reported in Gentner, 1988) analyzed interstroke intervals with respect to the frequency of digraph occurrence in written English. They found a significant, but small, positive correlation between frequency and interstroke latencies. These findings illustrate that preview is essential for fluent typing performance. At the same time, the relevance of perceptual encoding for the ultimate speed of typing is rather limited. The effects of advance preparation emerge at the level of the transition between subsequent pairs of letters. Rumelhart and Norman (1982) modelled expert typist performance using a computer simulation. Their model is based on parallel activation and selection of distributed motor schema. The implementation does not use any sophisticated perceptual encoding device; however, it simulates many of the basic features of skilled typewriting, especially the effects of the context surrounding a given finger transition.

Overlap of subsequent movements in time is a general characteristic of fluent skilled motor performance. In transcription typing, the text determines the sequence of keystrokes, and thus the respective fingers to be used, given that most typists apply a standard method which assigns each key to a particular finger. The possibilities of overlapping movements between subsequent fingers in time can thus be manipulated by controlling the sequence of letters to be transcribed. Analyses of high-speed video films (Gentner, 1981, 1988; Gentner, Grudin, & Conway, 1980) illustrated how skilled typists' movements of different fingers overlap in time. Expert typists tend to start their movements toward the next key to be pressed much earlier than novices, often while previous strokes are still in the phase of execution. Movements toward keys are often initiated in a different order to that in which the strokes are eventually executed. The benefit of movement overlap is obvious. The advantage is greatest for subsequent strokes executed with fingers of different hands. These transitions have been found to be the fastest in skilled typists (Rumelhart & Norman, 1982; Shaffer, 1978). Salthouse (1984) reported a significant correlation between typing skill and movement overlap. His index was the ratio of one-finger to two-hand digraphs. Shaffer (1976) found that typing speed increased in his expert typist when words in a text were constructed solely from two-hand digraphs, allowing for optimal movement overlap through alternation between the hands.

Gentner (1988) has thoroughly studied movement overlap by comparing interkeystroke intervals for different pairs of letters (digraphs). Analyzing expert and novice transcription typing performance, he was able to account for skill differences in terms of differential speed-up for distinct digraph classes: Gentner found that his fastest expert typed digraphs executed with different hands about 12 times as fast as his slowest novice. Doubles (repeated typing of the same key) only differed by a speed factor of three. The relative speed-up for digraphs typed with different fingers of the same hand amounted to a factor of ten. The interstroke latencies for these latter digraphs reflect the degree of finger-independence within the same hand. Gentner found that this measure of finger independence was a very good predictor of overall typing speed in his expert group (typing rate above 60 words per minute). Gentner's findings indicate that expert typists optimize their performance with respect to movement overlap constraints inherent to the task (letter context). Doubles do not allow for any overlap of movements, given that they are executed with the same finger (as in a repetitive tapping task). Two-hand digraphs provide maximal opportunity for overlap, which is similar to an alternate finger-tapping task. The amount of training involved in the acquisition of skilled coordinative mechanisms was illustrated in an interesting study by Salthouse (1986) which was described earlier. His subjects were trained for 20 hours in a typing-like keying task and improvement as a function of "digraph" classes was assessed. Despite considerable improvements in overall speed, the pattern of interstroke intervals did not change in the course of training. Repetitive strokes of the same key (the slowest in expert typists) were still the fastest, while alternate strokes with different hands (the fastest in expert typists) were the slowest.

Munhall and Ostry (1983) presented intriguing data on the limitations of bimanual coordination in moderately skilled typists. The subjects' task was to rapidly type words presented one at a time on a computer screen. Stimulus materials were constructed, such that transitions for digraphs typed with alternate fingers in opposite hands could be investigated. Mirror image movements (same finger in opposite hands and mirror location on the keyboard) were reliably slower compared to other movements alternating between opposite hands. A reanalysis of typing errors revealed that more than a third of all between-hand errors reported in confusion matrices from two older studies could be attributed to mirror image movements. Munhall and Ostry interpret their findings in terms of natural intermanual relationships which endure in a complex skill. While the reported evidence is in line with the notion of entrainment described earlier, it is important to point out that Munhall and Ostry's subjects were only modestly skilled (average typing speed in screening tests was 48 words per minute). The concept of entrainment discussed earlier suggests that mirror image movements have a tendency to trigger each other in the course of rapid execution. High accuracy requires inhibition between elicitation of subsequent strokes for this type of transition. The advantage for mirror image movements in synchronized performance turns out to be a problem when serial execution is required.

A recurrent finding in research into typing skills is the relation between skill level and *variability of performance* (Salthouse, 1984; Gentner, 1988). Salthouse had his subjects type the same sentence ten times and found a significant negative correlation between skill in terms of overall typing speed and variability between repeated instances of the same keystrokes (intrakey variability). The same finding was true for interkey variability in terms of comparing latencies for different keystrokes. Gentner reports similar findings, but points out that the absolute decrease in variability as a function of skill level is not surprising, given the dramatic increase in overall typing speed. He computed relative variability by dividing the half-width of respective latency distributions by the median. Gentner found that relative repetition variability was also clearly lower for the experts.

Skilled Piano Performance

Probably the first to study the ability of pianists to encode briefly presented displays of musical notation was Bean (1938). He presented cards with short sequences from musical scores in a mechanic tachistoscope mounted on top of a piano. Presentation rate was probably in the range of 200 milliseconds. Bean asked his subjects to "leave about half a second to a second time after the stimulus to place his hands for the notes and then play them promptly without debating mentally whether he was right or wrong" (p. 25). Subjects were asked to play at a moderate tempo and to make a guess if they had not identified clearly the exposed pattern. "Recording" of errors was done by Bean himself relying on his absolute pitch perception. Interestingly, Bean reports that frequent errors were due to a misplacement of a whole sequence in pitch while the overall contour was maintained. Bean trained several subjects for 30 hours in this experiment and found remarkable increases in accuracy. Subjects' introspective evidence in the course of training progressed from "seeing only two notes," through "getting a vague impression of the contour," to "recognizing the whole pattern as a unit." Sloboda (1976, 1978) studied pattern recognition in musicians and inexperienced subjects, varying the exposure time with technically more advanced methods. Subjects had to reproduce notes on a blank stave immediately after presentation. Recall advantage for musicians occurred after presentation times of above 100 milliseconds and increased with longer exposure durations. Halpern and Bower (1982) studied retention of visually presented melodies in musicians and untrained subjects who were able to read music. They also varied stimulus materials by presenting selected good melodies, bad melodies, and random note arrangements. Recall was higher for the group of musicians and also differential with respect to the difficulty of the stimulus material. However, musicians were still reliably better in recalling random sequences than nonmusicians. This finding is different from Chase and Simon's work (1973) on chess, which showed no recall advantage for experts for random positions. It illustrates that it is very difficult to generate note sequences which are really meaningless in a musical sense.

Research on perceptual encoding has illustrated the availability of a large number of encoding patterns in musicians. One may assume that these patterns reflect the structure underlying music and that this underlying structure is also important in performance. However, the direct relevance of these encodings for performance was not demonstrated in this context. The development of technically advanced recording devices allowed for a more direct study of musical performance in pianists. Several studies have demonstrated the superior abilities of pianists to vary timing and pressure of keystrokes in a systematic fashion. The basic rationale underlying the experimental study of musical performance in pianists is that variations in timing and pressure of keystrokes serve the expression and communication of musical ideas and are, therefore, *intentional* (Shaffer, 1981). The term is not used in a philosophical sense in this context. It rather implies that cognitive representations underlying performance are abstract *(musical ideas)* and subject to purposeful variation on the part of the performer. Intentional variation does not imply the conscious control at the level of each single keystroke, but refers to flexibility at the level of communicating different musical ideas. The notion of *intentional* variations is especially used in contrast to *noise* variations, due to performers' limitations in technical realization (e.g., muscle control). One idea behind this distinction is that a performer cannot perform expressively without having mastered the technical difficulties of a piece to a certain degree. A prerequisite of musical performance would thus be flawless performance in a steady tempo. This strict distinction, of course, is only partly applicable in practicing a piece. It served, however, as a heuristic in developing a fruitful research strategy. The basic procedure is to have musicians give repeated performances of the same piece. Instructions stress that participants should be as consistent as possible in terms of interpretation across performances. Subsequent analyses of covariation across repeated performances allow separation of two sources of variation: *intentional* and *noise.* Consistency across repetitions does not provide a measure of the aesthetic value of a given interpretation. Nevertheless, it does reflect a performer's ability to realize his ideas in a systematic and purposeful manner.

Povel (1977) compared recorded performances of different harpsichord players performing the same piece of music (the Prelude No. 1 from J. S. Bach's "Wohltemperiertes Clavier"). He showed that the pattern of timing for identical notes within bars varied throughout the piece. Group boundaries are marked by relatively long durations illustrating the fact that deviations from prescribed durations are not arbitrary or just proportional to the overall tempo, but reflect the interpreter's intentions. Michon (1974) and Clarke (1982) studied timing in pianists' performances of Erik Satie's "Vexations." Both studies revealed that tempo and dynamic changes in force applied to keystrokes are by no means independent, but vary or covary according to the structural characteristics of the musical interpretation.

McKenzie, Nelson-Schultz, and Wills (1983) analyzed repeated performances of the same piece played by high and intermediate level skilled pianists. Participants were asked to give five performances, trying to be as consistent as possible across repetitions. Instructions stressed maximal tempo while at the same time maintaining accuracy and consistency. Advanced musicians played faster, made fewer errors, and were more consistent across trials. Palmer (1989) found that deviations from metrical performance in pianists' interpretations of musical pieces were systematic across performances and could be attributed to three predefined expressive timing methods. When subjects were asked to give "unmusical" performances, in the sense of restraining from expressive features, deviations were significantly reduced. This latter finding gives strong support to the notion that variability is under the intentional control of the performer.

The best evidence of the outstanding capabilities of skilled pianists in generating precise timing patterns in musical performance has been provided by Shaffer (1981). He used a grand piano which was technically modified for his experiments in order to allow computer recordings of keystrokes. In his thorough analyses he showed that his pianists were able to systematically vary movement timing independently for the two hands. Concert pianists deliberately depart and return from regular timing for either hand, in order to express musical ideas. This ability challenges the concept of a single timing mechanism responsible for the control of both hands. Interestingly, Shaffer's subjects were able to compensate for rarely occurring flaws by reducing force for wrong notes and reestablishing the proper timing context in the course of execution. This flexibility points to the possibility of adjusting parameters in available motor programs to the immediate performance context.

Sloboda (1983) developed a direct method for studying the abilities of pianists to vary timing and loudness according to a given musical interpretation. He designed short sequences which were identical in terms of pitch and duration values assigned by the score (identical notes), but differed with respect to the location of the measure bars. In musical terms this means that the expressive features implied by the score, like accentuation on the first beat, differ between versions. Sloboda had skilled pianists give several performances of each version using Shaffer's piano and recording devices. Analyzing the time between the onset of subsequent strokes, the duration of respective notes, and the loudness in terms of key pressure applied, Sloboda found strong evidence that pianists systematically varied performance depending on the interpretation prescribed by the score. Sloboda also asked trained listeners to categorize tape recordings from this experiment, according to which score version was underlying a given performance. He found that the accuracy of identifying the underlying score was correlated with the playing experience of the respective performer. Although this latter finding was based on a limited number of subjects, it points to the relation between experience and skill in communicating musical ideas to a listener.

Typewriting and Playing the Piano: A Comparison

Much of the theorizing on piano skills has employed concepts from research into typewriting. The analogy between the two skills has proved useful and will be relied upon to some degree in the study described in the second part of this thesis. Application of this research strategy requires the description of important similarities and differences in order to explicate underlying rationales for modeling and task construction. Five aspects are central to the empirical investigation described later: biomechanical constraints, speed in complex movements, coordination of bimanual movements, changes in performance variability, and the role of practice in the acquisition of skilled mechanisms. The relevance of these aspects in both skills is discussed below. A comparison of findings with respect to the role of transcription and memorization abilities is included in order to illustrate important differences between the two skills.

Biomechanical constraints. There is evidence for a significant relation between finger-tapping speed and skill in transcription typing as well as in playing the piano (Book, 1924; Salthouse, 1984; Telford & Spangler, 1935). Mental control structures are effective to the degree that they are adapted to relevant biomechanical constraints (e.g., the coupling of middle and fourth finger, handedness). Finger-tapping rate is a good measure of the reflection of biomechanical constraints in both skills. A crucial question remains whether the efficiency of peripheral functions sets upper limitations to performance in complex skills or is itself subject to change in the course of skill acquisition.

Speed and timing of movements. The speed of generating keystrokes in skilled piano performance is just as impressive as in typewriting. Production rates sometimes reach levels of 30 strokes per second in skilled pianists (Rumelhart & Norman, 1982). It is important to point out, however, that speed of performance is not the ultimate criterion, if at all, of musical performance. The major goal of musical performance can be described as the expression of emotions, moods, and ideas. Speed, which is certainly the best measure for skill in transcription typing, is one important aspect in playing the piano, serving the overall goal of communicating with an audience. Timing of keystrokes in playing the piano is further characterized by another important facet of music: rhythm. Musical performance requires maintenance of a steady overall tempo and purposeful deviation from steadiness rather than just rapid generation of subsequent strokes. Playing the piano also differs from typewriting with respect to the role of force applied in pressing the keys: Force modulation is central in realizing dynamic changes of loudness in order to express musical ideas. No attention has been given to force modulation in research in typing skills so far, but it is certainly not an explicit task demand. While speed of movement production may not be the ultimate criterion of musical skill, it is highly valued in professional performers. Taking into account the additional constraints of steadiness, the speed of complex movements may be considered an important feature of skill in playing the piano.

Bimanual coordination. Higher speed in transcription typing was attributed to increased hand and finger independence (Gentner, 1988). The finding that interstroke intervals for letter pairs typed with opposite hands are the fastest in experts but the slowest in novice typists, points to the central role of bimanual coordination in typing. The study by Munhall and Ostry (1983) suggests that the constraints on bimanual coordination found in unskilled subjects persist in moderately skilled typists. The bimanual coordination abilities in pianists reported by Shaffer (1981) indicate that skilled pianists may have overcome the constraints typical for unskilled subjects. As opposed to typewriting, however, bimanual performance in piano playing rarely serves the generation of one linear series of movements. The left hand normally accompanies melodies played in the right hand with rhythmic figures. This means that synchronization of concurrent strokes is probably more important than rapid alternation between hands. Bimanual coordination may be considered central for playing the piano and constitutes a promising measure of skill, when the characteristics of musical performance are taken into account.

Performance variability. This aspect, while basically characteristic of any skilled behavior, relates to close similarities between the two skills. Overall typing speed correlates with smaller variability in the repeated typing of the same letter transitions as well as for the comparison of different letter transitions (Gentner, 1988; Salthouse, 1984). Little is known about the variations of force in typing. Skilled pianists can reproduce a given interpretation at will, if asked to do so. Timing and force variations in playing the piano clearly serve additional purposes, namely, the expression of moods and ideas. Variation of these parameters in musical performance is under the control of the pianist (Palmer, 1989; Shaffer, 1981; Sloboda, 1983). Reduced performance variability in the sense of optimal adaptation to stable task constraints is clearly highly relevant to both skills; the ability to intentionally control variability in performance is probably even more relevant in playing the piano.

Practice. Twenty hours of intense practice in laboratory settings do not suffice to acquire mechanisms central to skilled typing performance (Salthouse, 1986). Becoming a skilled typist takes considerable time (Gentner, 1988), and even subjects working at a professional level still have ample room for improvement after additional practice (Dvorak et al., 1936). Unfortunately, little is known about the amounts of practice in champions of typing contests. Gentner's estimate of 600 hours for becoming a moderately skilled typist is small compared to the estimates for violinists provided by Ericsson, Krampe, and Tesch-Römer (1993). Data gathered by Sosniak (1985) suggest that the intensity of practice in concert pianists during younger years is in the same range as for the best subjects in the study by Ericsson et al. Even the least accomplished group of violinists in this study had practiced for an average of 3,500 hours prior to starting professional training as a music teacher. One may conclude that both typing and playing the piano require at least several hundred hours of training to reach the level of bare mastery. However, the amounts of practice involved in attaining high levels of proficiency certainly differ by orders of magnitude from this conservative estimate. In addition to working on musical pieces, professional musicians practice scales or études, focusing on certain difficulties in order to keep movements fluent and rapid. Analyses of video recordings of practice sessions (Gruson, 1988) indicate that experienced pianists more often work on specific details in the context of a certain piece, while amateurs repeat the whole piece in an attempt to "get through" their difficulties. Methods related to the detailed practice of special letter combinations are relevant to typists' instructional techniques, but their application is normally restricted to training prior to professionalization. Professional musicians, on the other hand, normally continue to apply these practice methods throughout their careers. In general, typists tend to use their skill extensively on the job, but they do not necessarily practice their skill with respect to improvement. This may, however, be different for people participating in typewriting competitions. In sum, both skills seem to rely on mechanisms which require large amounts of practice to acquire. The concepts and methods of practice differ between skills, however, and little is known about the role of practice in attaining high levels of performance in typing.

Transcription and preview. Studies manipulating the amount of preview have provided considerable evidence that the size of the eye-hand span increases with the acquisition of typing skills. While similar research has found indications for "looking ahead" in pianists playing from a score (Sloboda, 1978), the relevance of respective findings seems limited. In typewriting, the text to be transcribed is normally new to the typist. The nearest equivalent to transcription typing in playing the piano would be sight-reading (playing from a score), or "prima vista" performance (sight-reading an unknown piece). The prima vista performance of difficult pieces is considered to be an outstanding skill even among professional musicians. Normally, musicians practice a piece for a considerable time before they perform it publicly. The role of symbolic external representations differs widely between the two skills. Text in transcription typing and musical score in playing the piano both indicate the relevant keys to be used in the respective order of striking. Modern typing methods exactly prescribe a fingering for particular letter transitions. Except for minor idiosyncratic differences, the fingers used in performance can be derived from the text for this reason. The standard 88-key piano keyboard requires lateral movements for efficient use, movements which are not part of typewriting skills. There are standard methods of fingering technique in playing the piano. Which finger strikes a particular key, however, varies between pieces and performers. Finding the most convenient series of movements is an important part of practicing a musical piece. Most editions of sheet music have digits annotated to those notes where the optimal order of fingers is difficult or not obvious. Annotated digits in piano scores ranging from one to five refer to the particular fingers on each hand. Playing from memory is mandatory for solo performers in concert, but not for chamber musicians or for orchestra musicians, who normally rely on the score. Memorization is not considered to be a necessary by-product of mere repetition by most musicians. Professionals use a variety of different methods and strategies to memorize pieces, like repeated playing at a very slow tempo or mental practice. Playing from memory is much more risky than playing from a score. Prior to a public performance, a piece is often overpracticed in order to guarantee reliability of memory traces. There is no obvious equivalent to memorization in typewriting.

In sum, the comparison of features in both skills points to important differences and similarities which can serve as guidelines for the empirical study of piano-playing skills. Similar to typewriting, hand and finger independence are crucial in playing the piano, with speed of performance being highly valued in both skills. The coordination of bimanual movements is central for playing the piano. The synchronization of concurrent movements in both hands probably has a higher ecological validity for playing the piano than the alternation between the hands, which is important in typing. The ability to play at a regular tempo qualifies the value of speed in playing the piano. Purposeful variation and its systematic control in repeated performances constitutes the highest level of musical skill. There are important differences with respect to the symbolic representations (letters vs. notes), the role of transcription skills, and memorization between the two skills. Memorization is clearly more relevant to playing the piano than to typewriting while transcription of unknown material is the exception in playing the piano. Large amounts of practice are important in order to acquire skilled mechanisms in both domains. The exact nature of the relationship between practice and performance is still awaiting thorough investigation in both domains. This is especially true with respect to the role of additional practice after formal training has ended.

Toward a Processing Model of Skilled Piano Performance

Processing models of typewriting differ considerably with respect to the exact nature of cognitive representations assumed to control performance. Hierarchical representations, allowing for parallel processing at different computational levels, have been applied to these phenomena, as well as to distributed parallel processing models. All of these models, however, try to incorporate the idea of different processing mechanisms working in parallel, in order to capture the phenomena of speed, flexibility, and movement overlap in time. The same models have been applied, or are in principle applicable, to skilled piano performance within the discussed limitations of the analogy.

Shaffer (1976) proposed the perception of timing abilities in serial movement production as a *continuum of invention,* stretching from mere adaptation to peripheral constraints to the deliberate and creative use of expressive features typical for playing the piano. He attributed the characteristics of skilled performance to hierarchical, schematic representations. These representations include movement parameters which can be adapted to performance requirements at different levels in parallel. The flow of information between different processing levels is maintained through buffers of limited capacities. One processing bottleneck in the model where limitations are evident is at the level of translating perceptual input into motor commands by means of selecting and adapting available motor programs. Shaffer (1978) also pointed to similarities between expressive timing variation in music and the ability of typists to adapt the timing of single keystrokes to the surrounding letter context. He claimed that any form of fluent, rapid movement production requires *rhythmic* performance, and is, in a sense, expressive. In his extension of the model, Shaffer (1982) tried to integrate his findings on skilled typewriting with his studies on pianists. Skilled piano playing adds new aspects and task demands to performance, which may not be found in unskilled movements at all, or be less central in typewriting. Most salient in this regard are rhythm and the creative use of timing variations in expressive performance. He contends that the ability of a pianist to intentionally vary and reproduce timing patterns in expressive performance relies on highly abstract representations *(musical ideas)* which must be effective in some form of top-down processing. The most fascinating aspect of his model is the assumption that independent variation of timing for the two hands is based on the generation of internal reference time frames *(pulse)* in the course of movement production. This concept is quite different from older models, which assumed that a single internal clock controls the execution of motor commands. These models accounted for variations in movement timing by assuming that peripheral constraints interact with the internal clock pulse, thereby producing noise and irregularities.

Rumelhart and Norman (1982) proposed a highly elegant model of typewriting, which is based solely on peripheral processing mechanisms. Their model is based on the parallel activation and selection of distributed motor schema. The processing base for the activation patterns is a network of distributed motor schema which are connected by links. The model metaphor is intentionally leaned toward neural network concepts. A perceptual input (a string of letters) initiates the simultaneous activation of several schema. A keystroke is executed if activation for a particular schema exceeds a threshold value. In the course of execution, the scheme deactivates itself. All activated schemas compete for execution at any point in time. Variations in interstroke latencies are explained as a result of the respective activation state in the whole network, rather than being attributed to hierarchical processing. The likelihood for a given scheme to exceed the execution threshold is a function of the current activation state and the strength of inhibitory connections with competing schemas. This basic conception provided the model with considerable computational power in terms of successful simulation of interstroke intervals and typing errors in a computer implementation.

Gentner (1988) accounted for the differential speed-up in letter transitions during skill acquisition in typewriting by referring to Rumelhart and Norman's model (1982). Learning in the distributed network was conceived as adding new inhibitory and excitatory links between schema or changing the weights of connections between schema in the course of practice. This approach is especially promising in terms of modeling bimanual coordination in piano performance. One could assume that the original state of a neural network controlling two-hand movements reflects a tight coordinative coupling of movement schema (entrainment). Increased hand independence will then emerge as a result of new inhibitory and excitatory structures. The picture is different for finger coordination within the same hand. Decreased interstroke latencies point to a reduced inhibition between respective schema. At the same time, reduced inhibition would increase the a priori likelihood of sequential errors occurring.

The brief description of existing processing models may illustrate that performance characteristics in both skills are beyond the explanatory scope of respective accounts for performance in unskilled subjects. Skill models have approached expert performance by assuming specific underlying representations. The abilities attributed to pianists, however, remain a challenge with respect to the further development of models for skilled behavior. At this point it is hard to see how the intentional variation of force and timing characteristic of musical performance could be incorporated into parallel distributed processing accounts. On the other hand, these models clearly provide a more elegant account for the high speed and flexibility observed in the fluent performance of typists. Further discussion of processing models for typewriting and playing the piano, however, is beyond the scope of the research presented here.

Statement of the Problem

Four goals were outlined in the introduction and pursued throughout the theory section: First, the theoretical concepts characteristic of the skill perspective and the developmental approach were discussed. Differences in basic theoretical concepts as well as considerable overlap in research interest emerged from the review of the literature. Second, it was documented from the review of earlier research that complex skills can be decomposed into a number of components which show different trajectories of developmental change. Age-related changes in performance on cognitive-motor tasks depend on the relevance of particular functions for the complex skill—that is, the transfer from the skill with respect to the specific component challenged by the experimental measures. The review of the literature further illustrated that the level of maintenance depends largely on the degree of learning during acquisition. Effects of training during retention have been little investigated; the skills under study were mostly acquired to a low level and little effort was invested in their subsequent maintenance. Third, a model of the acquisition of real-life skills focusing on the role of a lifelong adaptation to the demands of training was proposed. The framework was shown to be suitable for the investigation of skill development in real-life domains. The potential of the model to integrate developmental aspects in the expertise framework was illustrated by two recent studies. Fourth, a review of the existing literature on complex cognitive-motor skills provided theoretical grounds for a decomposition of the skill of playing the piano into subcomponents. The analysis of the skill and its components illustrated that the domain under investigation was suitable in order to address the research questions outlined in the introduction.

When accounting for high levels of skilled performance, developmental and cognitive research employ different concepts. The study of skill maintenance aimed at in this research clearly constitutes a field of overlap between the two paradigms. The cognitive approach in general (and even more so the expertise approach) is characterized by reference to acquired processing mechanisms. Expert performance relies on specific mechanisms which allow the limitations found in unskilled subjects' performance to be circumvented. The acquisition of a skill is described as a development of these mechanisms in the course of practice. Performance in experimental tasks is explained as a function of level of acquisition and transfer. The transfer notion captures the relatedness of the experimental task to the expertise. With increasing expertise the skill is assumed to become more self-contained—that is, the underlying mechanisms become more stable and less sensitive to interference and decay. At the same time, it is assumed that the transfer to tasks outside of the skill becomes more restricted. Maintenance of skills is a function of the stability of acquired mechanisms. If no further training is invested into maintaining relevant abilities, skills deteriorate with a rate which largely depends on the initial level of acquisition. Along the lines of the above arguments, one can assume that the maintenance of different cognitive-motor functions in the context of a complex skill depends on the level of initial acquisition, training intensity during later phases, and the degree of transfer between the skill and specific functions.

The general finding in numerous age-comparative studies was that processing constraints increase with age in a large number of different task domains. There is considerable evidence for age-related decline in both physiological and cognitive functions. The magnitude and generalizability of these effects has encouraged theorists to assume a general age-related decline in central processing capacities, which is largely independent of experience and the specific mechanisms presumably underlying various tasks. Investigations of expertise and aging are thus faced with a paradox or, to say the least, an intricate interaction of constraints: On the one hand, there is good evidence for increasing limitations in general processing resources with age; on the other hand, skilled mechanisms have been shown to be effective in overcoming processing limitations typical for unskilled performance.

The model proposed by Ericsson, Krampe, and Tesch-Römer (1993) provides a starting point for integrating developmental perspectives into the skill acquisition framework. The proposed method of assessing the level of past and current practice has proved useful in predicting interindividual differences at extreme levels of skill in young adults. Central to the model is the distinction between deliberate, goal-directed practice and experience with the domain. In this regard the proposed model differs from most accounts which argue against the disuse hypothesis with reference to the higher experience of elderly experts' with the task domain. Ericsson, Krampe, and Tesch-Römer have argued that exceptional performers can be characterized by their lifelong adaptation to the demands of training in specific skills. The level of performance is consequentially considered as a function of past and current practice intensity at each stage of development. Ericsson (1990) has argued that age-related changes in skilled performance reflect changes in practice intensity, probably irreversible effects of aging, and the interaction of both factors. Research with athletes has pointed to moderations of age-related performance decrements through maintenance practice. Little is known, however, about the amount of training high-level performers invest in the maintenance of their skills. Studies of long-term retention have illustrated that for most abilities it is very difficult to determine which activities are effective in improving performance and assessing the relevant training in a task over the life span.

Playing the piano is a complex, real-life skill with an inherent notion of practice that allows skill-related activities to be distinguished with respect to their effectiveness for improvement. A pianist's skill rests on a number of cognitive-motor functions which have been shown to be subject to severe processing limitations in normal individuals. Isolation of these functions makes the skill an ideal candidate for the study of expertise. Three major aspects of skilled performance emerged from the review of the literature on complex motor skills and playing the piano: the speed of single finger movements as a measure of the efficiency of peripheral motor functions, speed and accuracy in the performance of complex bimanual movements, and the ability to intentionally control force and timing parameters in expressive performance.

The general problem investigated in this research can now be summarized into three major aspects. The first aspect relates to the individuals' involvement in skill-related activities. Most important in this regard is the intensity of solo practice at the piano and differences between experts and amateur pianists along with changes in level of practice across the life span. This aspect not only involves the amount of time invested in practice at the piano, but also possible concurring developments, such as changing social and professional commitments, time for recuperation, and the like. The definition of *deliberate practice* as proposed by Ericsson, Krampe, and Tesch-Römer (1993) can serve as a conceptual means to distinguish those activities which are presumably relevant for the improvement and maintenance of specific skills from mere experience with a domain.

The second aspect relates to differences between experts and amateurs in performing tasks specifically designed to reflect skilled cognitive-motor processes in playing the piano. The basic assumption derived from the skill acquisition approach is that proficiency in skill-relevant tasks reflects mechanisms acquired in the course of training. It needs to be shown that expert pianists are superior in those tasks which are presumed to reflect skilled processes. A central test for the isolation of skilled mechanisms in experimental tasks is the efficiency of a complexity manipulation. Along the line of the main argument about overcoming processing limitations through skilled mechanisms, experts were assumed to be less impaired in their performance than subjects at a lower level of skill when the complexity of a skill-relevant task increases. Following the general methodological approach, this set of tasks needed to be complemented by a second set of control tasks reflecting cognitive-motor processes which are presumably not skill-specific. Experts should not differ from less skilled subjects in cognitive-motor tasks which are less relevant to the skill. There is no reason to assume that expert pianists should be more trained in a task which is not relevant to their skill if transfer is skill-specific.

The third aspect relates to differences between age-groups and the role of practice in that regard. Age-related decline in unspecific markers of cognitive-motor intelligence has been extensively documented in previous research. The tasks measuring general cognitive-motor performance not related to the skill serve a double purpose: First, they are control tasks with respect to the isolation of skill-specific mechanisms; and second, they should be sensitive to the age-related decline in general processing speed reported in the literature. No differences between skill levels should emerge within age-groups. The situation was different for skill-related tasks. The major proposition put forth in this thesis was that the level of performance in skill-related tasks is a function of prior amount of practice. This proposition is relevant for the acquisition as well as the maintenance of skills in later adulthood. It was expected that elderly experts had invested large amounts of training in order to raise their skills to a certain level and later on maintain them. Following the theoretical discussion of skill maintenance and long-term retention of knowledge, little if any decline in performance is to be expected for the elderly experts. Indeed, their performance level should still be above that of less trained young subjects if the tasks are relevant with respect to the skill.

Together with experimental measures of performance in skill-related and far transfer tasks, measures of the amount of deliberate practice during different phases of development can serve to distinguish between four theoretically plausible alternatives regarding skilled performance in elderly experts. (1) High levels of skilled performance at all ages are a function of general cognitive-motor dispositions. In that case, performance in far transfer tasks should show similar effects of age and skill level as performance in skill-related tasks. A skill effect in these tasks would speak to the assumption of general cognitive-motor talents determining pianists' proficiencies; a lack of dissociation between far transfer tasks and skill-relevant tasks with respect to age-graded changes follows from the preserved differences view (Salthouse et al., 1990). Except for this first proposition, all other alternatives assume a strong relation between practice intensity and performance and thus predict that age effects for experts are much stronger in far transfer tasks than in skill-related tasks.[3] (2) High levels of skilled performance are acquired at young ages and maintained with relatively little effort in later adulthood. This assumption would be corroborated by a strong correlation between practice during skill acquisition phases in younger years which is not affected by the amount of training invested in skill maintenance later on. It follows from an extension of findings in earlier studies on the retention of knowledge and skills (Annett, 1979; Bahrick, 1984; Bahrick & Hall, 1991). (3) Elderly experts selectively maintain relevant skills through deliberate practice. A correlation between the amount of practice invested later in adulthood and performance would support this hypothesis. This hypothesis is based on the extension of the Ericsson, Krampe, and Tesch-Römer (1993) model on the acquisition of expert performance toward the maintenance of expertise. (4) Elderly experts compensate for age-related decline through mechanisms specifically acquired for this purpose (Bosman, 1993; Charness, 1981a, b; Salthouse, 1984). This hypothesis is not exclusive with respect to hypothesis 3. The two accounts could be distinguished by comparing age-effects in experts between simpler tasks challenging peripheral motor efficiency and complex tasks permitting reliance on sophisticated processing mechanisms.

Decline in performance compared to their young counterparts was expected in elderly, less skilled subjects. Skill acquisition would not have exceeded a certain level during initial acquisition in this group of subjects. The selection criteria for the amateur group imply a lower level of practice in these subjects. Acquired mechanisms are thus likely to have deteriorated to some degree. Along the same line of argument, amateur subjects were not assumed to possess mechanisms to overcome general processing constraints; the reduction in overall capacity with age was thus more likely to impair elderly, less skilled subjects.

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[3] A more specific version of this account is the *preserved differences* hypothesis proposed by Salthouse et al. (1990). These authors claim that superior performance in elderly experts is the result of even higher levels of skill which have deteriorated with age. The account is also based on higher, general cognitive motor abilities which are assumed to have determined professional choice in young subjects.

Empirical Investigation

Overview of the Study

This study aimed at scrutinizing adult development in a real-life skill: namely, playing the piano. The theoretical goal was to extend the model of acquisition of real-life skills through deliberate practice proposed by Ericsson, Krampe, and Tesch-Römer (1993) to skill maintenance in later adulthood and to compare the predictive power of this framework to models of general, age-related performance decline. The main hypothesis in this study was that performance differences between experts and amateurs of different age-groups in skill-related tasks could be predicted from the measures of deliberate practice at different phases of development.

Four groups of subjects participated in the presented study: elderly professional pianists, elderly amateur pianists, young professional pianists, and young amateurs. The procedures developed by Ericsson, Krampe, and Tesch-Römer (1993) were used to obtain measures of past and current amounts of practice. The recent development of electronic keyboards has made it possible to computerize experiments involving a piano and obtain precise recordings of accuracy, timing, and force applied for single keystrokes. This equipment was used in order to guarantee a high level of experimental control, while making the task situation as ecologically valid as possible with respect to the apparatus. The experimental tasks used in this study were developed on the basis of a decomposition of the skill into different subabilities. Control measures for general cognitive-motor ability were the digit-symbol substitution test and a standard two-choice reaction time task. Three aspects of skilled performance were investigated: speed of repetitive finger tapping as a measure of efficiency of peripheral motor functions, speed and accuracy of finger movements in tasks requiring coordination between opposite hands, and the ability to intentionally vary movement parameters in musical performance. The tasks are briefly outlined below (for more detailed description see the procedure section).

Three tapping tasks were used to reflect the efficiency of peripheral motor processes: namely, repetitive tapping with right-, left-, and alternate forefingers. At the simplest level, repetitive tapping of the same finger, there was no possibility of overlapping movements in time. Alternate tapping was considered to be the simplest form of bimanual coordination.

The more complex experimental tasks developed to reflect coordination abilities required performance of movement sequences of nine strokes each. Instructions enforced accuracy, steady beat, and speed. The experimental tasks may be considered simplified versions of the exercises described in the Hanon exercise book for piano students. A three-level experimental complexity manipulation was introduced: playing a given sequence with either of the two hands alone, sequences consisting of mirror-image movements in opposite hands, and playing different movement sequences in opposite hands as the most complex condition. Two different experiments were conducted using these tasks: namely, playing from a task display (transcription) and playing from memory.

The ability to control the variation in timing and force applied to keystrokes during expressive musical performance was assessed by comparing repeated interpretations of the same musical piece. Subjects were asked to give three performances of a familiar piece (J. S. Bach's Prelude No. 1 in C-Major from the "Wohltemperiertes Clavier," Vol. 1) and try to reproduce their chosen interpretation as closely as possible. Statistical analyses of computer recordings from these performances were used to determine consistency across repetitions. Tape recordings were also judged by experienced musicians in order to validate the distinction between expert and amateur pianists.

Research Predictions

Predictions 1 to 12 listed below referred to the analysis of group differences for practice variables, performance in general markers of cognitive-motor speed, and performance in skill-relevant tasks. Predictions 13 and 14 referred to the regression analyses of selected variables from the speeded skill-relevant tasks, using the measures of past and current practice intensity as predictors in addition to the design variables.

Practice Intensity: Current and Past Amounts of Skill-Related Activities

The proposed model predicted a strong correlation between skill level and current practice intensity. The framework proposed by Ericsson, Krampe, and Tesch-Römer (1993) claims that expert performers accommodate to the changing requirements of their domain at each stage of development. The diary method allowed solo practice at the piano to be distinguished from other skill-related activities. Naturally, the amount of skill-related activities should also be higher in experts than in amateurs. While the total amount of time spent on skill-related activities was expected to remain constant or even increase with age in experts, the amount of solo piano practice was predicted to be considerably reduced in elderly experts compared to their younger counterparts due to increased professional requirements following the end of formal training. The amount of practice invested by elderly experts into maintaining their skills was nonetheless expected to be reliably above the amateur level (age by skill interaction for current practice intensity).

Little information was available on which to base a prediction regarding differences in the current level of practice for the amateurs. Based on the proposed framework it was plausible to expect only minor differences in the current level of practice between the young and elderly amateur groups. All amateur subjects were also involved in their professions or their professional training which placed natural limits on the amount of practice. It was also assumed that subjects in these groups might not dramatically change practice intensity or involvement in musical activities as such beyond their level attained. Past amounts of practice were predicted to correlate with age. A less trivial prediction was that past amounts of practice should be higher in expert pianists regardless of age.

Prediction 1a: Main effect of skill level on current practice intensity.
Prediction 1b: Age by skill level interaction on current practice intensity.
Prediction 1c: Main effect of age on past amounts of practice.
Prediction 1d: Main effect of skill level on past amounts of practice.
Prediction 1e: Main effect of skill level on amount of current skill-relevant activities.

General Markers of Cognitive-Motor Speed

The digit-symbol substitution rate as a correlate of general intelligence and a measure of cognitive-motor speed constitutes a case of very far transfer with respect to skill in playing the piano. Choice-reaction time reflects speed in serial perception, discrimination, and response selection. Serial processing is typical for unskilled performance and is replaced by parallel processing and sophisticated encoding in experts. Digit-symbol substitution rate and two-choice reaction time are sensitive markers of age-related slowing. According to the model, cognitive mechanisms which are not relevant to the skill were not assumed to be practiced more by experts than by amateurs. Consequentially, age-related decline in these measures was predicted to be similar in both skill-groups.

Prediction 2a: Main effect of age in digit-symbol substitution test.
Prediction 2b: Main effect of age in two-choice reaction time task.

Performance in Skill-Related Tasks

Four experiments were designed to measure aspects of skilled performance. The experiments required repetitive tapping of single and alternate fingers, complex movements requiring bimanual coordination, complex movements requiring bimanual coordination after prior memorization of movement sequences, and consistent interpretation of a short musical piece (musical performance task). The main dependent variable in the first three experiments was speed measured as mean onset latency between successive strokes (interstroke interval). The memorization experiment required subjects to memorize a given movement sequence prior to testing for speed and accuracy. The number of trials necessary to attain a prescribed criterion provides a measure of efficiency of memorization processes. Dependent variables for the musical performance task were the intercorrelations between timing and force applied to single keystrokes in repeated performances of the same piece.

Difficulty of bimanual coordination was realized as a complexity factor within subjects in the simple tapping tasks and both complex movement coordination experiments. In the case of the finger tapping experiment, alternate tapping versus single forefinger tapping constituted the complexity manipulation. Note that while coordination requirements increased for alternate tapping, movements between alternate fingers can overlap in time and thus performance speed was predicted to generally increase in this condition despite higher complexity.

The two movement coordination experiments involved all fingers, and movements in opposite hands had to be coordinated for synchronized bimanual performance. Three levels of complexity were realized in both experiments: single-hand performance, mirror-image movements in opposite hands, and different movements in opposite hands. The location of effects of increasing task complexity in these experiments was specified in two orthogonal contrasts: Based on previous research it was assumed that bimanual coordination has to counter interference between motor programs for opposite hands. Bimanual performance (the average of the two complex conditions) was thus predicted to be slower than single-hand performance (contrast 1). Interference can be reduced if both hands execute the same movements (mirror-image condition); however, it is pronounced if different movements between opposite hands must be coordinated. Different movements in opposite hands were thus predicted to be slower than mirror-image movements in the two hands (contrast 2).

Prediction 3: Main effects of coordination complexity for all groups.

A core of four predictions was identical for those skill-relevant tasks which required speeded performance. Pianists' skills in coordinating movements was predicted to be reflected by interactions between skill level and the complexity factor in the tapping as well as the two complex movement coordination experiments. In addition to reflecting skill in playing the piano, finger tapping and complex movement coordination tasks challenged the speed of cognitive-motor functions and were thus assumed to be sensitive to age-related declines. It was predicted that the mechanisms supporting the coordination of complex movements had deteriorated to some degree in elderly amateurs compared to their younger counterparts. Effects of age were thus expected to be pronounced in the more complex conditions (age by complexity interaction). It was also assumed that elderly experts maintained a high level of functioning for those processes relevant to their skill. Slowing was predicted to be minimal or nonexistent in elderly skilled subjects. This interaction between age and skill factors was predicted to be pronounced in the performance of more complex tasks (three-way interaction age by skill by complexity). Across all tasks it was predicted that elderly expert pianists will outperform younger amateurs in the presence of significant differences between age-groups. This prediction implied a generalizable main effect of skill level. Note that the differences between age-groups are predicted to be qualified by higher order interactions. The main effect of age is therefore not listed below. The predicted order of group means for tests of reliability of higher order interactions was: elderly amateurs, young amateurs, elderly experts, young experts.

Prediction 4: Three-way interaction skill level by age-group by complexity.
Prediction 5: Interaction skill level by complexity.
Prediction 6: Interaction age-group by complexity.
Prediction 7: Main effect of skill level.

(Elderly experts perform reliably better than young amateurs in the presence of significant effects of age.)

Prior to performing at their maximum speed, subjects had to memorize each movement sequence in the context of a learning-to-criterion procedure in the second version of the complex movement coordination experiments (memorization). The task was to play the proper sequence of strokes at a convenient tempo until three successively correct performances were attained. In order to memorize a given sequence it had to be coded as a movement pattern or in terms of harmonic relations between successive tones. Speed was not a task requirement in this procedure (no age effects predicted). It was predicted that the complexity manipulation affected the number of trials needed for rehearsal. Expert pianists can rely on a large number of patterns allowing rapid encoding of new sequences into meaningful units. A main effect of skill and a skill by complexity interaction was thus predicted for this measure.

Prediction 8: Main effect of complexity on the number of trials to criterion.
Prediction 9: Main effect of skill level on the number of trials to criterion.
Prediction 10: Interaction of skill level and complexity on the number of trials to criterion.

The dependent variables in the musical performance task reflected consistency of variation with respect to timing and force of single keystrokes. Subjects were free to choose their own tempo and their specific interpretation of the piece. Speed was not a task requirement in this experiment. The presumed underlying ability referred to the effective use of timing and force variations in translating musical ideas into movements. These processes were assumed to rely heavily on experience rather than on processing speed. The selected piece did not constitute a level of difficulty which would have set severe technical constraints on individual interpretations. It was predicted that expert pianists are more consistent in applying expressive variations than amateurs. Fluent musical performance is rarely completely free of errors, even in skilled subjects. It was predicted that the number of errors would be higher in amateurs than in expert pianists.

Prediction 11: Main effect of skill level on consistency of force and timing variations in musical performance task.
Prediction 12: Main effect of skill level on number of errors in musical performance task.

The Role of Practice Intensity in Accounting for Interindividual Performance Differences

The main proposition put forth in the presented research was that proficiency in a skill reflects past and current levels of training at each point in development. In the context of this study this proposition implied that differences in performance on skill-related tasks between skill levels and age-groups reflected differences in past and current levels of training. Performance in skill-related tasks was further analyzed with respect to the effects of past and current amounts of deliberate practice. Note that the tapping tasks and the two experiments testing the speeded coordination of complex movements had been designed to be maximally sensitive to interindividual differences in this regard. It was predicted that practice intensity would account for additional variance beyond the design variables age, skill level, and their interaction. This was especially expected for the more complex tasks given their higher sensitivity to age and skill differences in proficiency. The strongest prediction which could be derived from the model was that interindividual differences in performance could be accounted for by past and current levels of practice without reference to the design variables.

Prediction 13: Past practice intensity accounts for additional variance in performance beyond group factors and their interaction.

Prediction 14: Interindividual differences in performance can be accounted for by past and current practice intensity without reference to the design variables.

Method

Subjects

Fifty-three subjects differing in age and skill level with respect to playing the piano participated in the experiments, providing four cells in a two by two age by expertise design. One elderly expert and one young amateur had specialized in light and jazz music, while two young subjects and one elderly amateur were unable to perform the musical interpretation task. These subjects were not included in the sample, leaving a total of 48 subjects for analyses.[4] The mean age for the young subjects was 24.7 years (*range:* 20 to 32 years). Mean age for the elderly participants was 60.3 (*range:* 52 to 68) years. Subjects were equated for mean age within skill levels. The two skill levels were realized as a professional-amateur distinction. Young expert pianists ($N = 12$; 5 women, 7 men) were students at the Hochschule der Künste (HdK) in Berlin. All of them were members of an advanced soloist class ("Meisterklasse") working toward the "Konzertreifeprüfung" and had already started to perform in public concerts. Elderly experts ($N = 12$; 4 women, 8 men) were professional pianists who had graduated from a music academy in earlier years and had considerable experience as public performers and teachers. Most of the elderly experts had performed on TV or radio productions, or had produced records. Expert subjects were recruited through contacts with the HdK and other professional musicians. Amateurs were recruited through advertisements in a local newspaper and at the Free University campus in Berlin. Young amateurs ($N = 12$; 4 women, 8 men) were students in various academic and nonacademic training programs. Elderly amateurs ($N = 12$; 7 women, 5 men) were subjects from various professions. The two amateur groups were similar in terms of years of

[4] None of the effects reported in the results section was affected by including the two subjects with complete data sets into analysis. Subjects having their focus on jazz music were excluded from the presented study in order to have a higher homogeneity with respect to the sample's training background.

academic training, with a higher mean for the elderly subjects (M = 4.8 years) compared to the young group (M = 3.2 years). Expert groups were similar in terms of formal training at a music academy (M = 5.4 years). No differences between the four groups emerged with respect to self-rated health conditions. All subjects reported to be in an at least average state of health. Two participants (both young expert pianists) were reported left-handers; four subjects (two young amateurs, one elderly expert, one elderly amateur) reported to have been left-handed as a child.

Biographical Background of Participants

Thirteen subjects (27%) reported coming from families with at least one professional musician. Five of these participants were young amateurs, three were young experts, and five were elderly experts. The majority of participants in the study (52%) came from families where music was played at an amateur level. Expert pianists had started practice at a much earlier age (M = 6.75 years; SD = 2.75) than amateurs (M = 9.33 years; SD = 3.82), $F(1,44) = 7.38$; $MSe = 80.1$; $p < .01$. Age-groups were similar in this respect, however. The start of systematic practice coincided with the beginning of guided instruction for all subjects except for one elderly amateur and one elderly expert, who started practicing two years before they received their first systematic instruction. The mean ages when participants received their first instruction were 9.42 years (SD = 3.83) for the amateurs, which was again reliably older than for the experts (M = 6.83 years; SD = 3.03), $F(1,44) = 6.84$; $MSe = 80.1$; $p < .05$. Young amateurs had had 9.9 years (SD = 4.9) of formal instruction at the piano compared to only 6.0 years (SD = 3.0) for elderly amateurs. Naturally, young experts (M = 19.1 years; SD = 3.2) and elderly experts (M = 15.3 years; SD = 4.0) reported more years of formal instruction. Differences between skill-groups, $F(1,44) = 69.3$; $MSe = 1{,}035$; $p < .001$, and also age-groups, $F(1,44) = 11.9$; $MSe = 11.95$; $p < .01$, were reliable, indicating that elderly experts tended to get into the job earlier. Most subjects in the elderly groups would also have suffered during the post-war period with probably fewer opportunities for instruction. All of the young experts and none of the elderly experts received formal instruction at the time of investigation. Six young amateurs, but only one elderly amateur, received instruction at the time of testing. The time that had passed since the last formal lesson for the other subjects was 4.25 years (*range:* 1.5 to 8 years) for young amateurs and 35 years (*range:* 17 to 57 years) for elderly amateurs and elderly experts (*range:* 31 to 42 years). On average, experts had had 4.5 different instructors (SD = 1.8), while amateurs had studied with only 2.8 teachers (SD = 1.3), $F(1,44) = 14.6$; $MSe = 36.8$; $p < .001$.

All but one young expert had participated in public piano competitions as had eight elderly experts and two young amateurs. While it was difficult to evaluate the quality of the contests, it is interesting to note that young experts reported their first participation at the age of 11.3 years (SD = 3.4) compared to 21.9 years (SD = 5.9) for the elderly expert group. This difference was reliable: $F(1,17) = 24.5$; $MSe = 520.6$; $p < .001$. Informal interviews indicated that certain types of competitions promoting young musicians were founded not more than three decades ago. Elderly experts' recollections also focussed on international competitions, which took place later in life; almost all of the first competitions mentioned by young experts occurred at the local level.

Elderly expert pianists decided on their professions at the age of 12.5 years on average (SD = 5.1) compared to 16.2 years (SD = 3.4) for young experts. Elderly amateurs made their professional choice at the age of 17.2 years (SD = 5.4) which was also earlier than young amateurs (M = 18.7 years; SD = 2.3). The differences between skill-groups, $F(1,42) = 8.15$; $MSe = 142.6$; $p < .01$, and age-groups, $F(1,42) = 4.28$; $MSe = 74.8$; $p < .05$, were reliable. These data indicated that high-level pianists decided on their careers earlier than normal subjects. The age-effect is probably due to secular trends similar to the differences in years of training. Ten young amateurs and seven elderly amateurs reported playing at least one additional instrument (including singing in a choir) compared to seven elderly experts and only two young experts. The average number of additional instruments was higher in the amateur group (M = 1.25; SD = 1.07) than in the expert group (M = .67; SD = 1.01), $F(1,44) = 5.62$; $MSe = 5.57$; $p < .05$. This finding illustrates professional pianists' focus on their main instrument.

Validation of Expertise

External evaluation of expertise was done by ratings of tape recorded musical performances. Three successive interpretations of J. S. Bach's Prelude No. 1 in C-major from the "Wohltemperiertes Clavier" (see procedure section for further details) were recorded with a high-speed stereo tape machine (Uher 4200 REPORT) at a speed of 19 cm/sec. in the course of the musical performance task. Recordings were passed through a Sony five-band graphic equalizer in order to improve technical quality. The second performance was taken from each subject and recordings were copied on four different tapes in a randomized order. Three expert raters used the same tapes and rated recordings in the same order on seven different scales ranging from zero to ten. The seven scales are included in Appendix B. All three raters were professional musicians and had experience in evaluating live as well as recorded musical performances. Rater A (male, age 32) was a professional pianist with research interest in the psychology of music, who had also served on many examination boards as a performance teacher. Rater B (male, age 29) was also a professional musician who had worked in the studio production of music. Rater C (female, age 42) was a professional pianist and recorder player with extensive teaching experience.

Scores on the seven scales from all three raters were averaged and z-transformed to control for different anchor points between raters. While the interrater reliability was quite high (*Cronbach's alpha* = .871), detailed inspection revealed that the three raters systematically agreed only in their reliably higher evaluation of both expert groups as compared to the elderly amateurs. To preserve a conservative comparison along the lines of predicted effects, a repeated measures ANOVA was conducted on the three z-transformed averages with two orthogonal contrasts comparing elderly experts with young amateurs and young experts with elderly amateurs. Elderly experts received a higher average rating (M = .361; SD = .653) than young amateurs (M = –.179; SD = .828), $F(1,44) = 4.12$; $MSe = 5.26$; $p < .05$. Young experts (M = .771; SD = .422) were rated better than elderly amateurs ($M = -.953$; $SD = .638$), $F(1,44) = 41.95$; $MSe = 53.45$; $p < .001$. There were no interactions between group and rater in this analysis. While this analysis allows for a conservative approach to the skill-level distinction, it precludes a systematic comparison of age-groups. Inspection of means and standard errors indicates that the two expert groups did not differ reliably; however, there were clear negative age-trends in the amateur group. The lack of agreement among raters regarding specific group comparisons suggests a careful interpretation of these data. However, the distinction between experts and amateurs can be considered valid from this analysis.

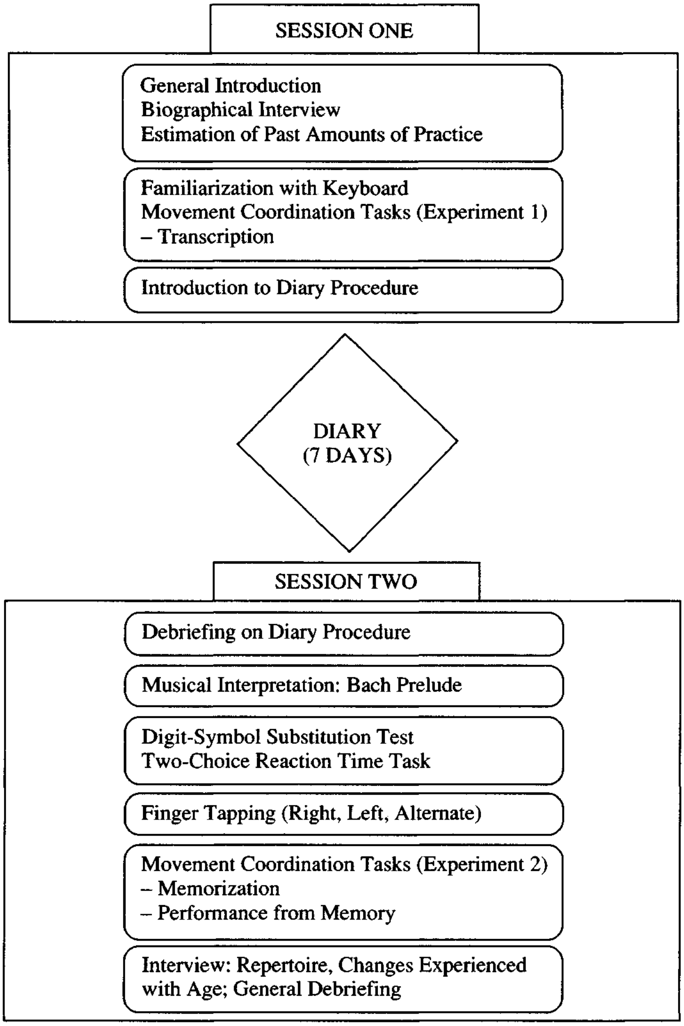
Apparatus

The piano used for the experiments was a Yamaha CB-300 weighted keyboard piano with a full range of 88 keys. The keyboard is velocity sensitive and designed to match normal pianos in terms of sound and touch. The output of the keyboard was fed into a MacIntosh II computer through a MIDI interface. Read-out of data and time measurement was carried out by a PASCAL program. Accuracy of measurement was 4 ms (limited by the interface's transfer rate). The apparatus registered which keys were struck and released and when, and the onset velocity—that is, the force applied to single keystrokes. The keyboard apparatus was used for all experimental tasks except for digit-symbol substitution, which was administered as a paper-and-pencil test. Subjects were seated at the piano on a piano stool adjusted for comfortable height and reaching distance. The 13-inch computer screen for the display of task and feedback information was located directly behind the piano at comfortable viewing distance.

Procedure

Subjects participated in two sessions with seven to twelve days between. Sessions lasted two hours on average, including a break. Duration of experimental tasks rarely exceeded one hour per session. Subjects were paid for their participation. The general procedure consisted of two standardized interviews, experimental tasks, and a diary. The first session started out with a biographical interview, followed by the first administration of movement coordination tasks in the *transcription* version *(Experiment 1)*. The diary procedure was introduced at the end of session one, and subjects were asked to keep the diary for seven days between sessions. The musical performance task in session two consisted of playing three consistent interpretations of a prelude by Bach. Afterwards, the digit-symbol substitution test, a two-choice-reaction time task, and single- and alternate-finger tapping tasks were administered. The second movement coordination experiment *(memorization* version, *Experiment 2)* completed the experimental data collection. Participants evaluated all six experimental tasks with respect to their perceived relevance for reflecting skills in playing the piano. Session two ended with a standardized interview and the general debriefing. The different procedures are described in more detail below. An illustration of the order of tasks and their allocation to the two sessions is shown in Figure 2.

Figure 2
Schedule of Sessions and Tasks



Interview Procedures and Ratings

The biographical interview in session one was initiated by subjects giving a free five-to fifteen-minute report of life events they considered relevant for their musical development. The interviewer then used standardized questions to complete a tabular description of the life-course of each subject on a form sheet. Subjects estimated their average weekly amount of practice for each year of their lives using these biographic events as cues. Appendix A includes a translated version of the interview scheme and one example form sheet with extracted life events and practice estimates. Following the second movement coordination experiment in session two, subjects rated each of the six experimental tasks with regard to their relevance for skill in playing the piano. Subjects were asked to consider which abilities they felt were challenged by a given task and then judge how relevant these abilities were with respect to playing the piano. Tasks were evaluated in the order of occurrence during the two experimental sessions using scales ranging from zero to ten. The standardized interview administered toward the end of session two included estimates of active performance repertoire and standardized questions regarding practice goals and changes experienced with aging. The interview scheme is also included in Appendix A.

Diary

The diary procedure was introduced by presenting a taxonomy of ten musical and twelve everyday activities along with examples. After clarifying labels and examples, the experimenter asked the participant to recall what he had done on the previous day. Subjects filled out a form sheet dividing the 24-hour day into 96 15-minute intervals and marked duration and nature of activities in the appropriate time slots. Participants then classified each activity using the taxonomy according to the 22 categories. Subjects who played more than one instrument categorized activities separately for the piano and other instruments. Between sessions, subjects filled out these form sheets during a full seven-day week and mailed a copy of the completed form to the investigator on the following day. Before returning for the second session, subjects, working from copies of their diaries, encoded each activity according to the taxonomy. Subjects were allowed to use more than one category in cases of parallel activities, but they were asked to mark the more important activity if possible. Appendix A includes the taxonomy, instructions, and one example diary form sheet.

Digit-Symbol Substitution Test

The digit-symbol substitution test (DS) is a subtest of the Wechsler Adult Intelligence Scale (WAIS). The task consists of filling in boxes with symbols according to a one- to nine-digit-symbol mapping illustrated on top of a form sheet. Participants were instructed to focus on accuracy and fill out as many boxes as possible within 90 seconds. The experimenter monitored the start and the termination of the task with a stop watch.

Two-Choice Reaction Time Task

Participants' task in this experiment was to respond to a single stimulus letter displayed on the terminal screen in front of them by pressing either one of two assigned keys on the piano keyboard. Four different letters were used as stimuli, namely "R," "r" and "L," "l." The proper reaction to "R" or "r" was to press an assigned key with the right forefinger. "L" and "l" required left forefinger responses. Each type of stimulus accounted for 25 percent of trials. Instructions encouraged participants to react as fast as possible while keeping errors to a minimum. Stimuli occurred one at a time in randomized order and remained on the screen until the participant's response. The stimulus letter was then replaced by an asterisk in order to maintain the subject's visual fixation between trials. After a one-second intertrial interval the asterisk was immediately replaced by the next stimulus. Subjects went through 120 trials; the first 20 trials were considered as warm-up.

Finger-Tapping Tasks

Three different tapping tasks were administered: tapping with the left and the right index fingers and alternate tapping using both index fingers. The instructions encouraged participants to tap as fast as possible for 15 seconds following an auditory start signal. Trials were terminated by an auditory stop signal. Subjects were instructed to keep all their fingers in a stable position above the keyboard and minimize concurrent movements involving wrist and elbow joints. The experimenter emphasized that proper hand position was crucial and controlled subjects' hand positions during trials.

Complex Movement Coordination Tasks

These tasks involved all five fingers of each hand. The main experimental manipulation concerned three levels of complexity in terms of hypothesized movement coordination demands: *single-hand* performance, *mirror-image movements* with opposite hands, and *different movements* in both hands.[5] Each trial within a given task condition consisted of the execution of a series of nine strokes in either hand for the *single-hand* condition, and nine strokes in each hand for the bimanual conditions. There were two different movement coordination experiments: Experiment 1, the *transcription* version, allowed subjects to look at the task display specifying the movement sequence during execution. Experiment 2, the *memorization* version, was designed to extend the results from the first experiment by adding a memory component. Task requirements in Experiment 2 were identical to Experiment 1, but subjects were required to perform from memory after previous rehearsal.

Two different finger movement sequences were used in each version to construct four different *single-hand* tasks, namely, two right-hand and two left-hand tasks. Combinations of identical sequences provided two tasks in the *mirror-image* condition. The two possible combinations of different stroke sequences constituted the tasks for the *different-movements* condition. The specified combinations did not require lateral changes in hand position on the piano keyboard given that only five adjacent white keys were used for each hand, each particular key being assigned to a certain finger. All participants performed tasks in a fixed order of increasing difficulty, namely *single-hand, mirror-image,* and *different movements.* Repeated assessment of *single-hand* performance was inserted after each of the two-hand tasks. The order of hands in the *single-hand* condition was counterbalanced across subjects. The order of movement sequences was identical within tasks for all subjects. Appendix B includes a

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[5] A mirror-image movement involved the same finger in opposite hands. Trajectories are also identical for both hands and aim at mirror-image spatial locations on the keyboard, given that each finger was assigned to a fixed key. Different movements in both hands involved different fingers of opposite hands which had to strike at different keyboard positions. Note that this complexity manipulation referred to the actual finger movements executed as far as the concordance between hands was involved, not the harmonic relation between melodies generated (in this regard, both two-hand conditions involved playing different melodies in the two hands).

complete description of task materials and instructions together with further details on the feedback format.

Experiment 1 (Transcription). A given task was always performed in three blocks of trials, the sequence to be performed remaining the same for all three blocks. Each task was introduced by presenting a sheet with the sequence for the hand(s) to be used. Movement sequences were presented as strings of numbers indicating the particular fingers to be used (e. g., one for thumb, five for small finger). This notation was derived from supplementary illustrations of fingering in standard piano scores. The experimenter described the overall task to subjects by drawing on similarities to études designed to practice various finger combinations (e. g., Hanon). Instructions encouraged subjects to push speed to their personal limits, while playing flawlessly and maintaining a steady tempo. Subjects played through each specified sequence at least three times before the computer recording of strokes started. The experimenter controlled whether subjects had indeed chosen the proper sequence and combination of strokes. At the onset of each trial the specified movement sequence appeared on the computer screen together with an auditory signal, prompting the subject to perform the sequence. The first and the third blocks consisted of six trials each, the second block consisted of twelve trials. The sequence remained on the screen during performance, and error feedback was given after each trial. In addition to error feedback, subjects received graphic feedback on average tempo and steadiness of tempo after each trial in the second block. An illustration of the feedback format and its description are given in Appendix B.

Experiment 2 (Memorization). The basic set-up for the memorization experiment in session two was identical to the transcription tasks. The four-movement sequences from which the the different tasks were constructed were the same as those in Experiment 1, but in the reversed order of finger strokes (see Appendix B for a detailed description of task materials). The additional manipulation in this experiment required subjects to play from memory. At the beginning of the experiment, subjects were told that they would eventually have to play from memory and that they should use the first block of trials for memorization. The procedure distinguishing Experiment 2 from Experiment 1 was inserted as the second block of trials: Participants' task was to perform a given sequence until they had produced three flawless successive trials *(learning to criterion).* Starting from the second block, the specified sequence was only presented if subjects made an error in the previous trial. Subjects were then allowed to inspect the sequence as long as they wanted, but the display disappeared once they had started playing. When the memorization criterion was reached, the task proceeded with two more blocks of twelve, and six trials in the same manner as was described for Experiment 1. Subjects were again instructed to push speed while being accurate and play at a steady tempo.

Musical Performance Task

The piece used in this task was the Prelude No. 1 in C-major from the "Wohltemperiertes Clavier," Vol. 1 by J. S. Bach. Subjects' task was to work out an appropriate musical interpretation, which they then played three times, while trying to be as consistent as possible across performances in their interpretation. Participants were allowed to play through the piece during a warm-up phase and practice it for up to 15 minutes. All performances were played from score. In addition to the computer recordings using the described devices, performances were tape recorded for later evaluation. All subjects were familiar with the piece in question; most of them had played it before or even practiced it. Those subjects who had previously not played the piece were capable of doing so after a short practice, with the exception of those three subjects excluded from the sample for this reason.

Results Section

Overview

The results section is organized in four major topics related to (1) deliberate practice and other activities, (2) general cognitive-motor abilities, (3) group differences in performance in skill-related tasks, and (4) the accountability of task performance through deliberate practice. The amount of skill-related activities in the four groups is examined first by the analysis of current practice intensity as derived from the diary data. The validity of subjects' retrospective estimates of their amounts of practice is determined by a comparison with measures derived from the diaries. The development of practice intensity across the life span is then compared between the four groups using subjects' retrospective estimates of their past amounts of practice. A more detailed analysis of subjects' daily activities is provided in order to address changes in the focus of skill-related activities with age. It was hypothesized that, regardless of age, expert pianists show a reliably higher engagement in musical activities. This should be especially true with respect to solo practice at the piano. However, elderly experts were expected to have decreased their active practice at the piano due to other professional commitments and activities.

Analyses of performance in general markers of cognitive-motor speed (digit-symbol substitution test and two-choice reaction-time task) are subsequently described. It was predicted that pianists do not differ from less skilled subjects in these measures. Elderly subjects, however, were predicted to show a marked decline in speed of performance in both tasks.

Performance in skill-relevant tasks was analyzed using two different approaches. First, measures were analyzed using a four-group ANOVA (analysis of variance) design. In the second part of the results section, hierarchical linear regression techniques are used to scrutinize the contribution of design variables and practice variables to the variance in speeded skill-related tasks. ANOVA analyses were done for an age (2) by skill (2) orthogonal design. Effects significant at an alpha level of $< .05$ will be interpreted. Predicted performance in skill-related tasks implied the following ranking of groups: young experts, elderly experts, young amateurs, and elderly amateurs. The strong prediction with respect to the magnitude of skill effects was that elderly experts should outperform young amateurs in all skill-related tasks even in the presence of age effects. Consequentially, three post-hoc tests were used to compare "neighbouring" groups: (1) young experts versus elderly experts, (2) elderly experts versus young amateurs, and (3) young amateurs versus elderly amateurs. Note that all other comparisons between groups were implied by significant differences for these comparisons. Post-hoc comparisons were performed as t-tests, with two-tailed alpha probability levels adjusted using Bonferoni's method. Differences reaching significance with a probability of error less than .016 were thus considered to be reliable.

It was predicted that experts should perform better on all skill-related tasks than amateurs. The main effect of skill level was predicted to interact with complexity. Effects of age were hypothesized to emerge in speeded tasks and to be pronounced in the more complex conditions. Elderly expert pianists were predicted to have selectively maintained those mechanisms relevant to performance in skill-related tasks. The effect of age was thus predicted to be qualified by an interaction with skill level and complexity. A brief analysis of subjects' ratings for each experimental task regarding their relevance for the skill under study is included after the comparisons between groups. An overview table of all effects resulting from group comparisons is included on page 117.

The regression analyses in the last part of the results section permit to separate the different impact of age, skill, and practice effects on performance in skill-related tasks. Three different models are proposed contrasting the contribution of age, skill, and practice variables to interindividual differences in performance. It was predicted that practice intensity can account for interindividual differences within groups, that is, beyond mean effects of age and skill and their interaction. Furthermore, it was hypothesized that a model based on practice variables alone would account for performance differences between groups. A summary of the regression analyses is provided on page 135.

Involvement in Skill-Related Activities

Current Practice Intensity

Current practice intensity was derived from the amount of time coded by subjects as practice alone during the diary week. Mean hours practiced alone during the diary week are shown in Figure 3. The ANOVA revealed a significant age-by-skill interaction, $F(1,44) = 20.16$; $MSe = 693$; $p < .001$. Young experts practiced for 26.71 hours ($SD = 8.66$) during the diary week, which was reliably more than the 10.83 hours ($SD = 7.56$) practiced on average by the elderly expert group, $t(22) = 3.74$; $p < .002$. The mean for elderly experts was reliably different from the 1.87 hours ($SD = 1.95$) found for young amateurs, $t(22) = 4.04$; $p < .002$), giving way to a general main effect of skill level, $F(1,44) = 103$; $MSe = 3{,}562$; $p < .001$. The mean for elderly amateurs ($M = 1.21$ hrs.; $SD = 1.31$) did not differ reliably from the young amateur group.[6]

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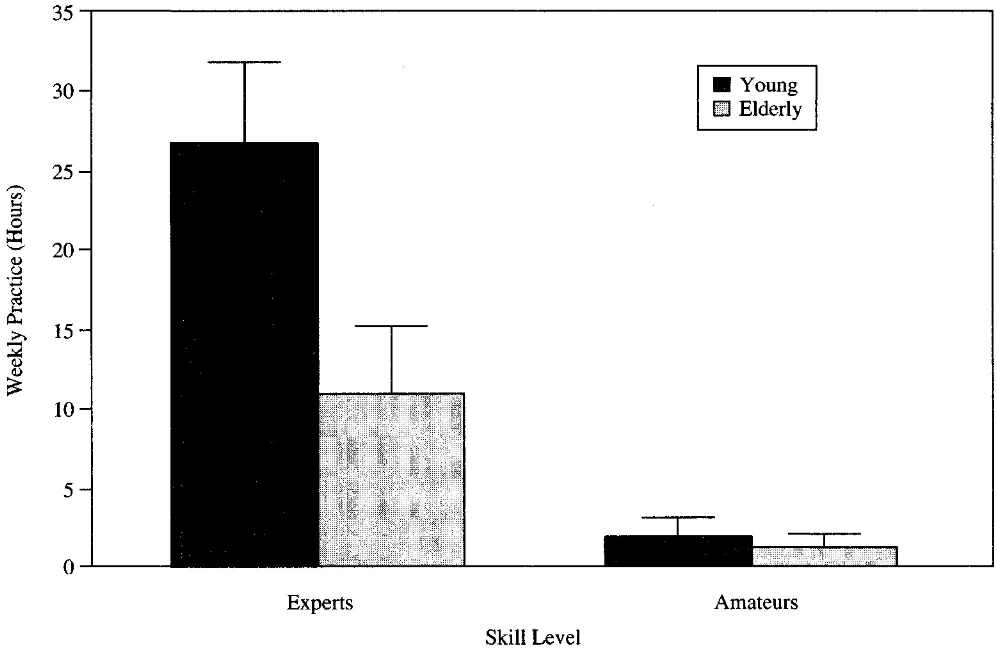
[6] Given the violation of homogeneity of variances in this analysis, a control analysis was done based on log-transformed values. The actual measure used was raw value + 1 in order to take values of 0 into account and prevent the log function from assuming negative values. Analyses of log values lead to the same effects: age × skill, $F(1,44) = 5.20$; $MSe = .435$; $p < .05$; skill, $F(1,44) = 106$; $MSe = 8.88$; $p < .001$. The two post-hoc comparisons between young experts ($M = 1.42$; $SD = .162$) and elderly experts ($M = .949$; $SD = .401$) and young amateurs ($M = .368$; $SD = .294$) and elderly experts were reliable, $t(22) > 4$; $p < .001$. The mean of young amateurs did not differ reliably from that of elderly amateurs ($M = .280$; $SD = .244$).

Figure 3
Amount of Solo Practice During Diary Week



Note. Means and standard deviations for four groups in hours.

These results confirmed the predictions with respect to current practice intensity: The amount of practice was much higher in expert pianists than in amateurs (Prediction 1a). However, elderly experts' current amount of practice was reliably reduced to only 40 percent of the time practiced by young professional pianists, while still being reliably above the practice level of amateurs (Prediction 1b).

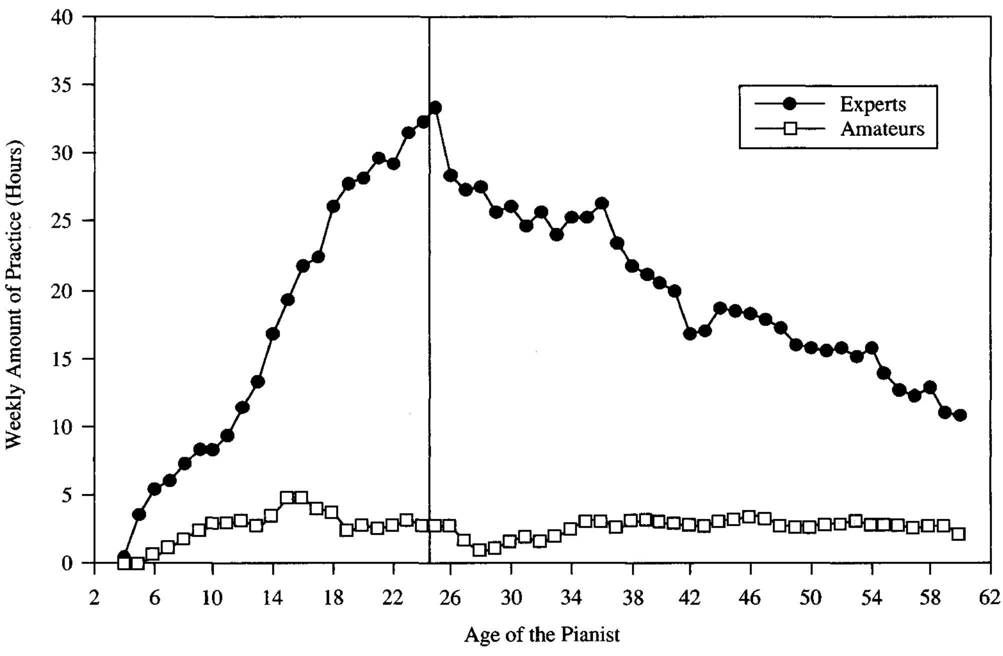
Past Amounts of Practice

Diary assessments were compared to the weekly practice reported for the last year in the retrospective estimate procedure in order to test how accurately subjects could estimate their amounts of training. The two measures of current weekly amounts of practice were highly correlated, $r(46) = .88$; $p < .001$. Subjects generally tended to overestimate their effective amounts of practice. The mean amounts of weekly practice estimated for the current year by the four groups were: young experts ($M = 33.4$ hrs.; $SD = 6.19$), elderly experts ($M = 13.6$ hrs.; $SD = 9.18$), young amateurs ($M = 2.63$ hrs.; $SD = 2.13$), and elderly amateurs ($M = 2.91$ hrs.; $SD = 2.97$). A repeated measures ANOVA including the type of assessment as within-subjects factor was performed. Type of assessment yielded a significant effect, $F(1,44) = 10.4$; $MSe = 212.9$; $p < .01$, but it did not interact with any of the group factors. These results indicate that while subjects tended to overestimate their actual amounts of practice, there was no indication of an age- or skill-differential bias. Analysis yielded a significant age-by-skill interaction, $F(1,44) = 38.8$; $MSe = 1{,}861$; $p < .001$, and a main effect of skill level, $F(1,44) = 180.4$; $MSe = 8{,}649$; $p < .001$. Mean differences between young and elderly experts, $t(22) = 6.53$; $p < .001$, and also between elderly experts and young amateurs were reliable, $t(22) = 4.15$; $p < .001$. The two amateur groups did not differ with respect to the average of both estimates.

Weekly amounts of practice were extracted from subjects' biographical estimates and calculated for each year of life. Estimates were compared within skill-groups for ages 5, 10, 15, and 20 (the age of the youngest subject). While expert pianists differed significantly from amateurs in all measures except for age 5, there were no significant differences between young and elderly participants within skill levels. Mean estimates as a function of subjects' ages are shown in Figure 4 for the two skill-groups.

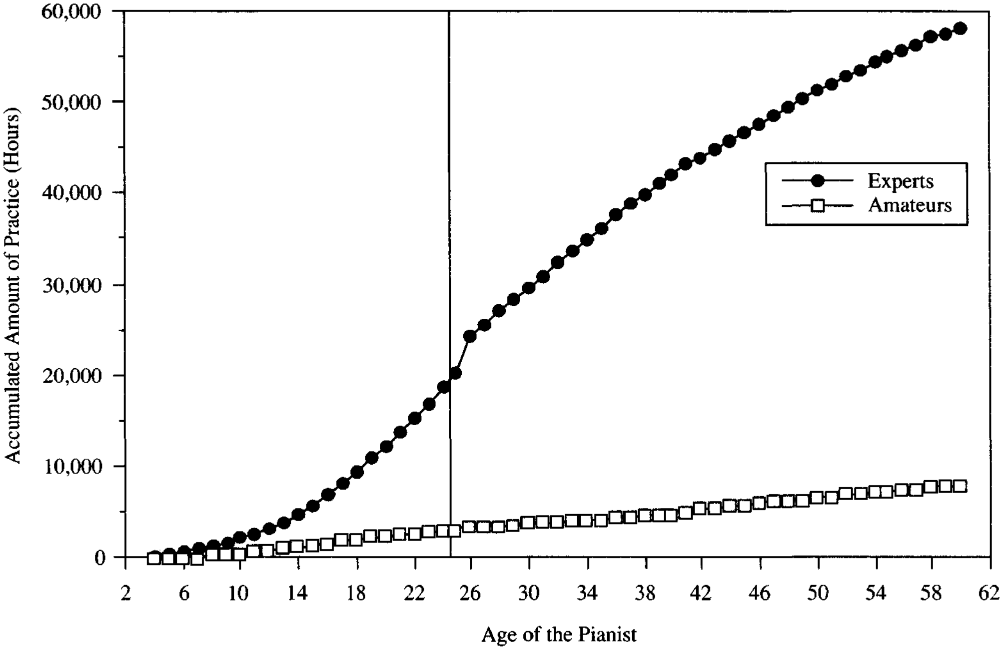
In order to illustrate the long-term effects of practice, weekly estimates were summed up across years. Accumulated amounts of practice as a function of age and skill level are shown in Figure 5. The accumulated estimates showed the same similarity between respective age-groups within skill levels until the age of 20, and thus the

Figure 4
Weekly Amount of Practice as a Function of Age



Note. Data in the left panel are averaged for young and elderly subjects within skill levels. Minimum age in young subjects was 20, minimum age in elderly subjects was 52. Data aggregated above minimum ages include at least 50 percent of all subjects within each group.

Figure 5
Accumulated Practice as a Function of Age



Note. Data in the left panel are averaged for young and elderly subjects within skill levels. Minimum age in young subjects was 20, minimum age in elderly subjects was 52. Data aggregated above minimum ages include at least 50 percent of all subjects within each group.

data were aggregated for illustration in the same manner as described for the weekly amounts of practice.

Analysis of estimated accumulated hours yielded a significant age-by-skill interaction, $F(1,44) = 29.7$; $MSe = 3{,}557{,}300$; $p < .001$.[7] The accumulated amount of practice for the elderly expert pianist group totalled an average of 57,739 hours ($SD = 20{,}159$), which was reliably different from the 17,927 hours ($SD = 6{,}615$) accumulated by young expert pianists, $t(22) = 6.5$; $p < .001$. The order of magnitude in terms of the amount of time which must be invested in order to become an expert pianist is illustrated by comparing young expert pianists to the elderly amateur group, who had accumulated 7,908 hours ($SD = 5{,}171$) on average. By the mean age of 24, professional pianists had already accumulated more than twice the amount of practice as had amateur pianists by the mean age of 60! This difference between young experts and elderly amateurs was reliable, $t(22) = 4.13$; $p < .001$. The mean for the young amateur group was 2,531 hours

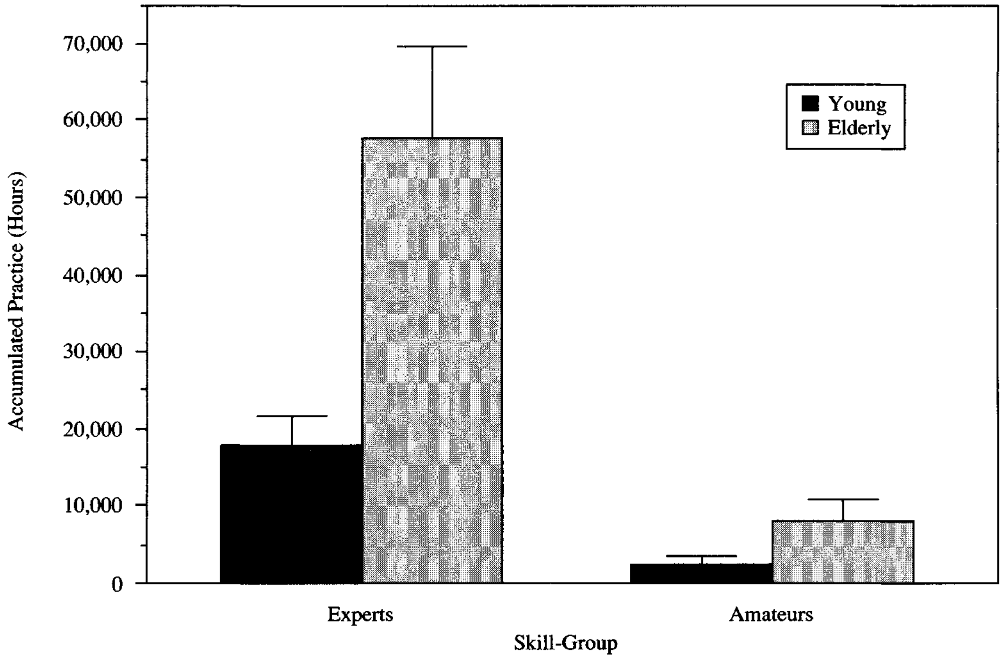
[7] Mean squared errors for analyses of accumulated practice are given as multiples of 1,000. This was not true for the analyses of log-accumulated amounts of practice.

($SD = 1{,}642$), which was reliably less than the amount of practice accumulated by the elderly amateur group, $t(22) = 3.43$; $p < .005$.

The pattern of results in post-hoc comparisons supports the generalizability of the main effect of skill level, $F(1{,}44) = 106$; $MSe = 12{,}763{,}591$; $p < .001$. The main effect of age, $F(1{,}44) = 51.0$; $MSe = 6{,}126{,}371$; $p < .001$, must be interpreted with regard to differences in skill level: Elderly subjects *within* each skill level had accumulated larger amounts of practice. Mean accumulated practice for the four groups is shown in Figure 6.

As an additional step, accumulated amounts of practice were log-transformed and resubmitted to ANOVA analysis. One important reason for this measure was to make the variances for the different groups more homogeneous and thus concur with the statistical assumptions underlying analysis of variance designs. The theoretical rationale behind using log-transformed data was that the acquisition of skill has been demonstrated to follow a *power law* (Anderson, 1982). The ANOVA on log-accumulated amounts of practice yielded main effects of age-group, $F(1{,}44) = 36.3$; $MSe = 2.83$; $p < .001$, and a main effect for skill level, $F(1{,}44) = 135$; $MSe = 10.58$; $p < .001$. The age by skill interaction was no longer significant. Post-hoc t-tests on log-transformed measures revealed the same picture as before: Measures were reliably different between elderly ($M = 4.74$; $SD = .159$) and young experts ($M = 4.23$;

Figure 6
Total Amount of Practice Accumulated in the Four Groups



Note. Error bars indicate 95 percent confidence interval.

$SD = .153$), $t(22) = 7.97$; $p < .001$. The difference between young experts and elderly amateurs was reliable, $t(22) = 3.63$; $p < .002$, as was the difference between young ($M = 3.31$; $SD = .314$) and elderly amateurs ($M = 3.77$; $SD = .405$), $t(22) = 3.13$; $p < .01$. It can be concluded that the effects of skill level and age, with respect to the amount of practice accumulated, were stable. These findings were clearly in line with the predictions (Predictions 1c and 1d).

Time Allocation during the Diary Week

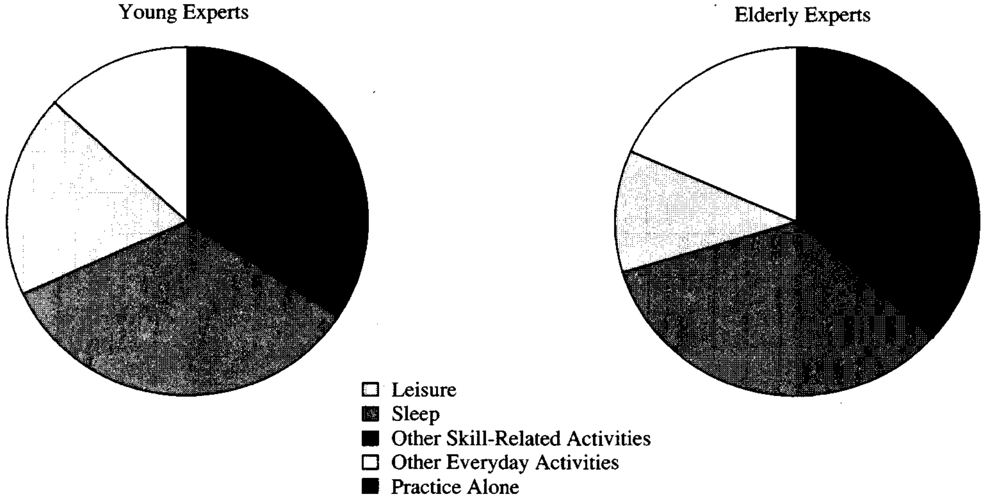
In order to further scrutinize possible reasons for the large decrease in solo practice in the elderly expert group, the other activities in the diary were further analyzed.[8] The 22 categories used by subjects when encoding their own diaries were collapsed to illustrate the general picture for the following analysis. Tables C1 and C2 in Appendix C give the means for single categories. The 12 categories of musical activities were summed up to a measure of the total amount of music-related activities. Leisure time and sleep were kept as pure categories. Figure 7 shows the allocation of time to the different categories for the expert pianists. Practice alone is shaded black beside other musical activities. A third of the total time during a week is used for music-related activities in the two pianist groups. According to these data, professional pianists spent an average of 58.5 hours ($SD = 16.1$) a week on activities related to their profession, which by far exceeded a normal 40-hour working week. The average amount of time spent on music-related activities by the amateur group was 7.4 hours ($SD = 6.5$). This difference was significant, $F(1,44) = 201$; $MSe = 31{,}288$; $p < .001$, as was predicted (Prediction 1e). No other effects emerged on this measure.

The pie charts in Figure 7 illustrate important differences between age-groups with respect to time allocation in expert pianists: Young expert pianists spent almost half (47%) of all skill-related activities on practice alone at the piano. The picture was quite different for the elderly expert group: The total amount of time spent on skill-related activities—namely, 60.2 hours a week on average—even surpassed that of the younger experts ($M = 56.8$ hrs.) by a slight margin. These results illustrate that the elderly musicians' involvement with music had not decreased, but rather that their focus of activities had shifted; solo practice at the piano (only 18% of all music-related activities) had decreased, mostly in favor of teaching, which amounted to 35 percent of the professional time in elderly experts ($M = 21.23$ hrs.; $SD = 12.69$) but only 6.5 percent in young experts ($M = 3.66$ hrs.; $SD = 4.52$), $t(1,22) = 4.52$; $p < .001$.

Further analyses were carried out on the amount of leisure activities occurring during the diary week. Figure 8 shows the distribution of time across the different activities for the amateur group. Analyses revealed a significant age-by-skill interaction, $F(1,44) = 5.44$; $MSe = 639.8$; $p < .05$. Young expert pianists had considerably more leisure time ($M = 31.1$ hrs.; $SD = 8.59$) than elderly experts ($M = 18.9$ hrs.; $SD = 10.3$). This difference was reliable, $t(22) = 3.16$; $p < .005$. The amount of leisure

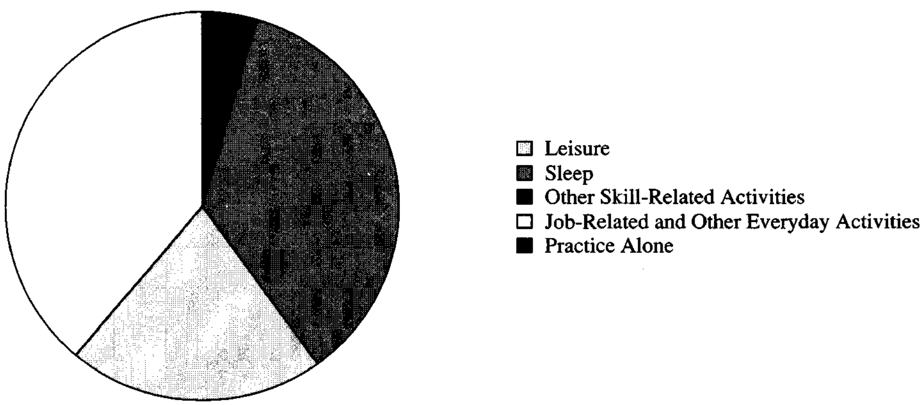
[8] Participation in the first session of the study was often the first diary day, given that especially expert subjects had a tight schedule. This time accounted for practically all of the missing diary data. On average, two hours (1% of the total time) could not be accounted for in the diary recordings. There were no differences between groups with respect to missing data.

Figure 7
Time Allocation in Expert Pianists during Diary Week



Note. The allocation of total time available (168 hours) is shown for young expert pianists in the left-hand chart and elderly expert pianists in the right-hand chart. Skill-related activities are dark-shaded. Other activities are light-shaded.

Figure 8
Time Allocation in Amateur Pianists during Diary Week



Note. Data are averaged between young and elderly subjects. Skill-related activities are dark-shaded. Other activities are light-shaded.

time was similar in the other three groups ($M = 33.9$ hrs.; $SD = 10.9$). Presumably, elderly experts reduce their leisure time in favor of working on their skills in addition to the immense professional requirements.

Closer inspection of everyday activities which were not skill-related revealed one major difference between age-groups: namely, in the category "health and body care." Elderly subjects spent more time ($M = 18.0$ hrs.; $SD = 5.26$) on related activities than young participants ($M = 13.5$ hrs.; $SD = 3.72$), $F(1,44) = 11.7$; $MSe = 246.4$; $p < .002$; no other effects or interactions were significant. The finding that health and body care tend to be more time consuming in elderly subjects regardless of skill level is highly plausible. No group differences emerged regarding the amount of sleep during diary week.

Summary: Involvement in Skill-Related Activities

In sum, the analysis of the diary data revealed clear evidence that expert pianists spent more time on skill-related activities compared to amateur subjects. This is also true with respect to the amount of solo practice at the piano, which may be considered the most relevant activity in terms of improving or maintaining performance skills following results of earlier studies (Ericsson, Krampe, & Tesch-Römer, 1993). The detailed structure of daily activities, however, revealed important differences between young and elderly expert pianists. While the total amount of time spent on skill-related activities was similar in both age-groups, elderly experts spent less than half the amount of time on solo practice at the piano compared to younger experts. The continued high involvement in professional activities on the part of elderly experts was underlined by a significant decrease in leisure time compared to their younger counterparts. Young expert pianists spent more than half of their time allotted for music-related activities practicing the piano, while having only slightly less leisure time compared to amateur subjects. The data point to a shift in focus of professional activities in elderly experts. Most of their music-related activities involve teaching.

The idea of a change in the focus of activities was supported by an analysis of retrospective estimates for past amounts of practice. Elderly experts showed a similar trajectory as young experts for the earlier years of their career, with weekly and accumulated amounts of practice until the age of 20 being highly similar for the two groups. The amount of practice necessary to become an expert pianist, on the other hand, was illustrated by the comparison of skill-groups. Starting from a very early age expert pianists invested reliably more time for improving their skills than amateurs and continuously increased their amounts of practice. Practice intensity peaked for elderly experts in their late twenties and continued to decline thereafter. At a much lower level of commitment, average practice levels in amateurs appeared to be relatively stable over time, partly due to a lack of systematic variation across individuals.

General Markers of Cognitive-Motor Speed

Digit-Symbol Substitution

The number of errors in the digit-symbol substitution test was very low ($M = .13$; $SD = .39$) and did not differ between groups. Only four subjects made even a single error in this task. Substitution scores and number of errors were uncorrelated, $r(46) = -.01$; $p > .45$, indicating that speed-accuracy trade-offs were quite unlikely. Scores were reliably higher for young subjects ($M = 69.0$; $SD = 9.62$) than for the elderly group of participants ($M = 50.8$; $SD = 10.9$). The effect of age-group, $F(1,44) = 36.6$; $MSe = 3{,}979$; $p < .001$, was reliable. No higher order interactions were significant. Means and standard deviations for single groups are provided in Appendix C.

Two-Choice Reaction Time

The overall rate of errors was reasonably low ($M = 3.5\%$; $SD = 2.95$) with no differences between groups emerging. The number of errors in this task and the mean response times were correlated, $r(46) = -.38$; $p < .01$, pointing to a speed-accuracy trade-off.[9] Young subjects' response times ($M = 422$ ms; $SD = 44.3$) were faster compared to the elderly group ($M = 518$ ms; SD $= 68.4$). The difference between age-groups was significant, $F(1,44) = 32.1$; $MSe = 109{,}793$; $p < .001$. No higher order interactions turned out to be significant. Means and standard deviations for single groups are given in Appendix C.

Summary: General Markers of Cognitive-Motor Speed

In sum, the outcomes were basically identical in both tasks and exactly as predicted (Predictions 2a and 2b). There was clear evidence for age-related slowing in unspecific, serial cognitive-motor processing. No reliable differences between skill levels were found, however.[10] The digit-symbol substitution test may be considered a highly age-sensitive marker of cognitive-motor speed. Age-related decline in digit-symbol substitution performance similar to the data presented here were reported in earlier studies (cf., Salthouse, 1978, 1985a). Note also that the correlation between DS-substitution rate and the overall IQ score derived from the Wechsler test is among the highest for all subtests. Stimulus (digits) and response (handwritten symbols) formats, however, are essentially different from any performance context relevant to playing the piano. Pianists have to rapidly encode note patterns when playing from score; moreover, they mostly play music which they have seen before or even memorized prior to performance. Mental representations of the stimulus material are translated into motor programs controlling the execution of complex finger movements. These motor programs have been shown to involve more than a single note and a single movement at a time. Performance of single keystrokes in playing the piano is probably highly affected by surrounding contexts pointing to underlying complex representations. Parallel processing at different levels can account for aspects of fluent performance in real-life motor skills. One-by-one processing and serial execution is typical of unskilled digit-symbol task performance.

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[9] An additional ANOVA was performed with the number of errors as a covariate. The pattern of statistically reliable findings did not change.

[10] Additional post-hoc comparisons were performed given the theoretical significance of skill-differences in these general measures of cognitive-motor speed: All four single-group comparisons with respect to age-differences were significant for DS as well as CRT ($t > 3.5$; $p < .002$). No difference between groups of the same age but different skill levels approached significance ($t < 1.1$; $p > .25$).

The response format for the choice-reaction time task is similar to playing the piano, especially given that keys from the piano keyboards were used for the responses. The stimulus-response mapping is different for playing the piano and the choice-reaction time experiment, however. Left- and right-hand responses were indicated by letters "l, L" and "r, R" respectively in the reaction-time experiment. In musical notation for piano scores, notes for the left and right hands are presented in two different notational systems with the left-hand notes forming the lower part of the stave in each line. Probably more important, a choice-reaction time task requires a local decision on a single response and successive responses cannot be integrated into mental representations in advance. Several theorists (Lashley, 1951; McKay, 1982; Shaffer, 1982) have argued that this advance integration into complex schema is essential for fluent performance, and thus speed in choice reaction time tasks cannot account for performance in the complex skill. The findings reported above support this notion.

Assuming that general factors of intelligence or cognitive-motor speed were responsible for performance in skill-specific tasks, one would expect superior performance on both measures—the digit-symbol substitution test and the choice-reaction time task—for expert pianists compared to amateurs. The absence of reliable skill effects in both age-groups in the presence of large differences in skill-relevant tasks does not support the idea of general factors with predictive power for skilled performance. In terms of transfer, the outcome of both experiments does not suggest that skill in playing the piano has any impact on task performance. The reliable differences between age-groups in both tasks suggest that elderly expert pianists are subject to the same age-related performance decline in unspecific markers of cognitive-motor speed which was found in unskilled subjects. The conclusion drawn from these findings is that the processes reflected in both tasks are of little, if any, relevance for playing the piano. Both tasks, however, reflect age-sensitive processes of general cognitive-motor performance.

Group Differences in Performance in Skill-Related Tasks

Interstroke latencies in all skill-related tasks were log-transformed at the level of single transitions prior to aggregating data for further analyses. There were two reasons for this approach, each of which was already mentioned earlier: (1) The log-transformation increased the homogeneity of variances; (2) recent discussions of general slowing theories in cognitive aging literature suggested log-transformation of latencies to safeguard age-by-complexity interactions against accounts based on a single age-related slowing factor. Unspecific age-related slowing implies that variances increase by a constant factor when complexity increases. Using log-transformed latencies provides a conservative test of age-by-complexity interactions in this regard.

Finger-Tapping Speed

Mean log-interstroke intervals from the three tasks were submitted to a repeated measures ANOVA with finger(s) performing the task as a within-factor. Means for raw and log-interstroke latencies are given in Appendix C. Two planned orthogonal comparisons were specified as within-subjects orthogonal contrasts: *right hand* versus *left hand,* and *single* (average left and right) versus *alternate* tapping.[11] Log-transformed latencies for the three different tasks are shown in Figure 9.

Subjects were reliably faster with their right finger than with their left index finger (contrast 1: $F(1,44) = 43.7$; $MSe = .02$; $p < .001$). The second specified contrast, single versus alternate tapping, was also highly significant, $F(1,44) = 767$; $MSe = 1.48$; $p < .001$, indicating that tapping with alternate fingers was reliably faster than with single fingers. The second contrast showed a significant interaction with skill level, $F(1,44) = 15.1$; $MSe = .03$; $p < .001$. Differences between experts and amateurs in all three tasks were reliable, $t(46) > 6.3$; $p < .001$, giving way to a reliable main effect of skill level, $F(1,44) = 62.2$; $MSe = .28$; $p < .001$. There was no indication of age effects or any other higher order interaction.[12]

In sum, while experts showed a reliably higher rate of tapping in all three tasks (Prediction 7), differences between age-groups were not reliable. Predictions 4 and 6 involving the age factor were not confirmed for the tapping tasks. Alternate tapping, while being a very simple task, imposes higher demands on coordinative abilities compared to repeated tapping with the same finger. At the same time, alternate tapping provides an opportunity to overlap movements between alternate fingers in time, which makes overall movement speed faster (Prediction 3). As expected, the cognitively more complex alternate tapping task revealed a stronger skill advantage than the single-finger tasks (Prediction 5). It is worth noting that this result argues strongly against proportional differences because skill differences were smaller for the task which yields *longer* latencies. This pattern suggests that skilled mechanisms enhanced performance at the level of qualitative differences in movement coordination rather than only along the speed continuum.

Complex Movement Coordination: Experiment 1 (Transcription)

Mean interstroke latencies averaged across correct trials and the number of errors from the last block in each task were analyzed. Individual mean interstroke latencies were log-transformed prior to analysis. Manipulation of coordination complexity (*single-hand* performance, *mirror-image movements,* and *different movements* in opposite hands) was included as a within-factor in the design. Data from the first measurement only in the *single-hand* condition were used and were averaged between the left and right hands.[13] The effect of experimental complexity manipulations was tested by

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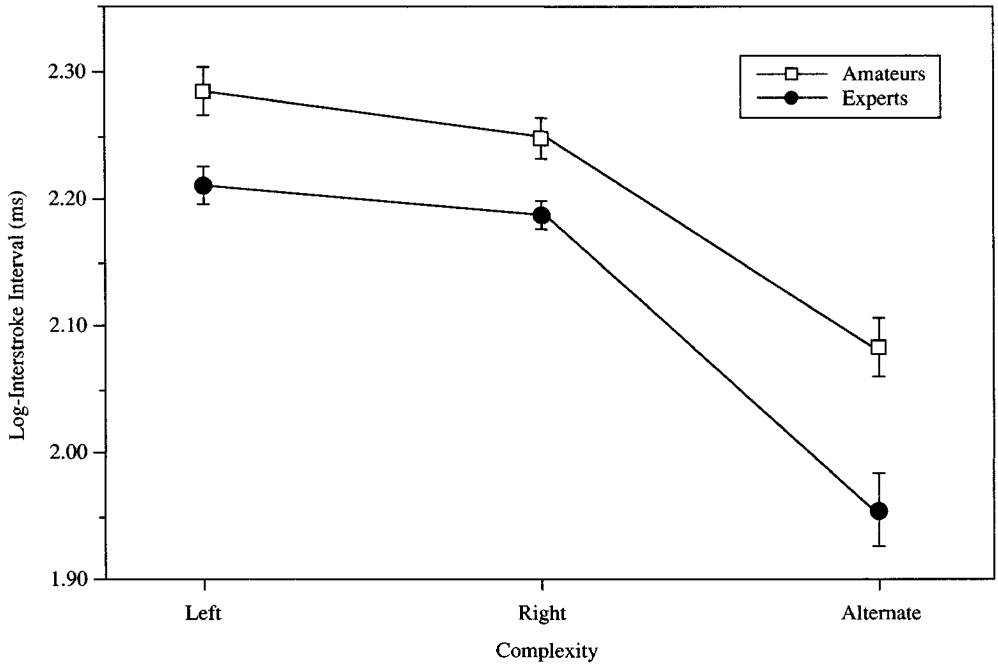
[11] None of the reported findings was changed when subjects' handedness was taken into account instead of the left-right contrast.

[12] Reliability coefficients were computed in order to assess the degree to which interindividual differences in three different tapping measures reflected the same dimension. Overall, reliability was very high given the small number of "items." *Cronbach's alpha* was .855 for all subjects, .843 and .870 for young and elderly subjects respectively; it was .748 for amateurs and .713 for expert pianists. Reliability coefficients at the level of single groups were .770, .657, .693, and .759 for young amateurs, young experts, elderly amateurs, and elderly experts respectively.

[13] Reliability coefficients computed for the four single-hand measures yielded a *Cronbach's alpha* of .970 for the total sample. Coefficients for the various subgroups were also reasonably high: .925 (amateurs), .889 (experts), .965 (young subjects), .970 (elderly subjects), .900 (young amateurs), .789 (young experts), .887 (elderly amateurs), .912 (elderly experts).

Figure 9
Tapping Speed as a Function of Task Complexity



Note. Mean log-interstate intervals (in ms) in three tapping tasks separated for experts and amateurs. Error bars indicate 95 percent confidence intervals.

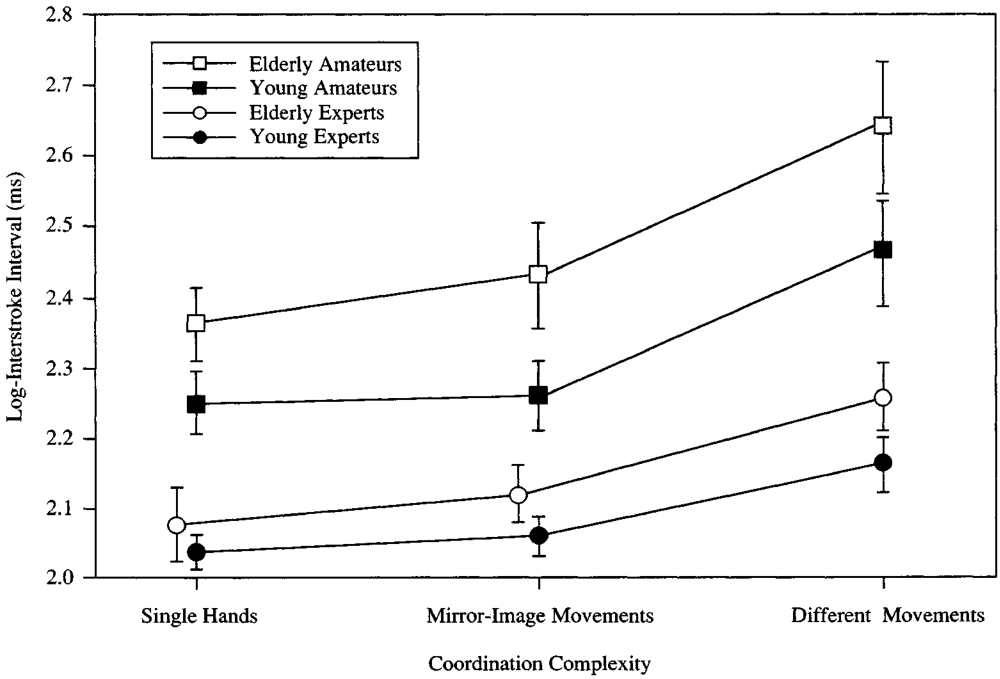
two orthogonal contrasts comparing *single-hand* tasks to the average of the two *bimanual* movement conditions (contrast 1) and contrasting the two *bimanual* conditions—namely, *mirror-image* movements with *different* movements (contrast 2). Reliability of higher order interactions was tested as described earlier using an adjusted alpha level of .016 for the comparison of young and elderly experts, elderly experts versus young amateurs, and young versus elderly amateurs. Reliability of three-way interactions involving the task complexity factor was tested by subsequently adjusting the alpha level to .008. (Note that there were two measures involved in each within-contrast, requiring the subsequent division of alpha by two for the three-way interaction.)[14]

[14] Considering the movement sequences in each condition as single items, reliability coefficients are informative with regard to the stability of subjects' ranking across tasks. The single-hand condition included four sequences, the two bimanual conditions consisted of two sequences each. *Cronbach's alphas* computed on the basis of these eight items were .972 (total sample), .925 (amateurs), .888 (experts), .973 (young subjects), .968 (elderly subjects), .921 (young amateurs), .824 (young experts), .857 (elderly amateurs), .889 (elderly experts).

Age-groups and skill-groups did not differ reliably in terms of error rates. Subjects made more errors in the *bimanual* tasks compared to the *single-hand* tasks (contrast 1: $F(1,44) = 9.16$; $MSe = 987$; $p < .005$). The average error rate was higher for the different movements condition than for the mirror-image movements condition (contrast 2: $F(1,44) = 16.0$; $MSe = 2{,}188$; $p < .001$). Mean error rates were 8.9 percent ($SD = 8.7$), 9.7 percent ($SD = 11.1$), and 19.3 percent ($SD = 16.9$) for the three conditions respectively. There was no indication of speed-accuracy trade-offs. Correlations between interstroke latencies and the number of errors were positive, but nonsignificant, indicating that, if anything, the slower subjects tended to make more errors.

Means for log-transformed interstroke latencies are shown in Figure 10 below. Means and standard deviations for raw and log-values are given in Appendix C. Movement speed clearly depended on the complexity of coordination required in performing a given sequence. Both within-subjects contrasts were highly significant (contrast 1, *single-hands* vs. *bimanual movements:* $F(1,44) = 195$; $MSe = .45$; $p < .001$; contrast 2, *mirror-image* vs. *different movements:* $F(1,44) = 89.7$; $MSe = .65$; $p < .001$),

Figure 10
Speed as a Function of Coordination Complexity in Experiment 1



Note. Mean log-interstate intervals (in ms) for all groups in the three conditions of the transcription experiment. Error bars indicate 95 percent confidence intervals.

indicating that overall the experimental manipulation acted as predicted. As the next step, it was determined whether the complexity manipulation was effective for all subjects. Four pairwise t-tests were performed in order to test the generalizability of results for each contrast: Interstroke latencies for *single-hand* and *bimanual* tasks and *mirror-image movements* with *different movements* in opposite hands were compared within each group. All differences within groups were reliable, $t(11) > 4.2$; $p < .002$, confirming the predicted effect of coordination complexity (Prediction 3). Bimanual tasks were slower than single-handed performance, and mirror-image movements were faster than different movements in opposite hands, and this was true for all four groups of subjects.

Contrast 1 (*single-hand* vs. *bimanual* tasks) showed a significant interaction with skill level, $F(1,44) = 9.00$; $MSe = .02$; $p < .005$, and also with age-group, $F(1,44) = 8.46$; $MSe = .02$; $p < .01$. The contrast between the two *bimanual* tasks showed a significant interaction with skill level (contrast 2: $F(1,44) = 6.31$; $MSe = .05$; $p = .05$). Both contrasts indicate that expert pianists were less slowed by the additional complexity involved in coordination than amateurs, as was predicted (Prediction 5). No other higher order interactions were significant. Post-hoc t-tests revealed that young expert pianists were reliably faster than elderly expert pianists in the *bimanual* tasks, $t(22) = 2.70$; $p < .05$. Closer inspection revealed that this difference was due to elderly experts' higher interstroke latencies in the *different movements* condition, $t(22) = 2.68$; $p < .05$, while both expert groups were similar in the *mirror-image* movements condition. Thus, there was no effect of age in the expert group in the two simpler tasks, but differences between the two groups were reliable in the most complex condition. Elderly amateurs' interstroke latencies were larger compared to those of younger amateurs in all three tasks, $t(22) > 2.9$; $p < .01$. The age-by-complexity interaction may thus be interpreted as reliable within skill levels (Prediction 6).

Elderly experts outperformed young amateurs in all tasks, $t(22) > 3.8$; $p < .001$. Given the reliable differences between young amateurs and elderly experts at all levels, the main effect of skill level, $F(1,44) = 141$; $MSe = 2.88$; $p < .001$, can be interpreted (Prediction 7). Although the age-group by skill interaction failed significance by a slight margin, $F(1,44) = 3.55$; $MSe = .07$; $p < .067$, and none of the three-way interactions were significant, the main effect of age-group, $F(1,44) = 21.0$; $MSe = .43$; $p < .001$, must be interpreted separately for the two skill levels considering the two higher order interactions.

The results of Experiment 1 support the hypothesis that the ability to coordinate complex movements between different fingers is correlated with skill in playing the piano (Prediction 7). Increasing the task complexity by varying the demand imposed on coordinating opposite hands affects movement speed in all groups (Prediction 3). Slowing due to increased complexity is, however, reduced in expert pianists compared to amateurs (Prediction 5). An additional illustration for the interaction of task complexity and skill located in contrast 1, based on data aggregated across the two *bimanual* tasks, is provided in Appendix C. A similar line of argument applies to age (Prediction 6): Elderly subjects were more impaired by the increase in coordination complexity within each skill level. The predicted three-way interaction between age, skill level, and task complexity (Prediction 4) was not confirmed. Elderly subjects were outperformed by their younger counterparts at all levels of complexity in the amateur group. Elderly experts were only slower than younger experts in the most complex condition.

Complex Movement Coordination: Experiment 2 (Memorization)

The number of trials subjects needed to produce three successive correct performances was analyzed in a similar way as described for the latencies in the first experiment. Learning-to-criterion trials were averaged for the left and right hands for the first administration of the procedure only in order to exclude effects of relearning. Subjects took reliably more practice trials for memorization in the *bimanual* tasks than in the *single-hand* tasks (contrast 1: $F(1,44) = 14.4$; $MSe = 77.1$; $p < .001$). Memorization of sequences requiring *different movements* in both hands was more difficult compared to *mirror-image* movements (contrast 2: $F(1,44) = 23.33$; $MSe = 230$; $p < .001$). These findings indicated that the complexity manipulation acted on rehearsal difficulty as predicted (Prediction 8). As predicted (Prediction 9), expert pianists took fewer trials than amateurs, $F(1,44) = 5.25$; $MSe = 62.3$; $p < .05$. Differences between age-groups were not reliable. None of the higher-order interactions was significant. The results are shown in Table 1. The absence of the predicted skill-by-complexity interaction (Prediction 10) indicates that the complexity manipulation acted similarly on both experts and amateurs.

Error rates for the last block of criterion trials in the memorization experiment were higher in the bimanual tasks than in the *single-hand* tasks (contrast 1: $F(1,44) = 47.0$; $MSe = 3{,}025$; $p < .001$) and lower for *mirror-image* movements than for *different movements* in opposite hands (contrast 2: $F(1,44) = 43.9$; $MSe = 7{,}526$; $p < .001$). Overall, amateurs made more errors than the experts, $F(1,44) = 5.10$; $MSe = 2{,}101$; $p < .05$, and this main skill effect interacted with contrast 1, $F(1,44) = 4.85$; $MSe = 312.5$; $p < .05$, and also with contrast 2, $F(1,44) = 8.16$; $MSe = 1{,}400$; $p < .01$. No other higher order interactions for the analysis of error rates were significant.

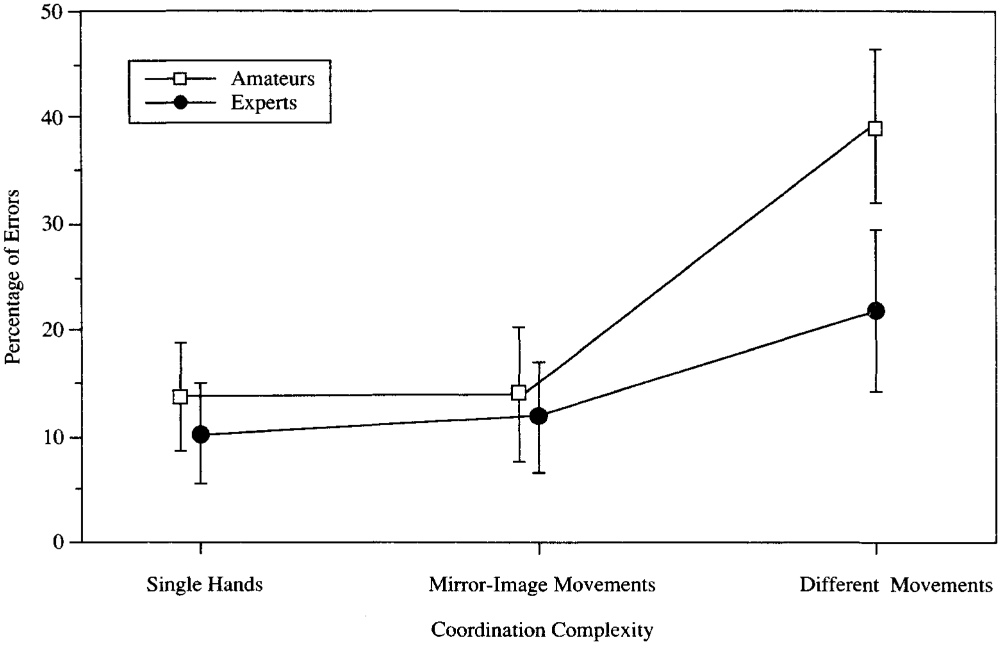
Table 1
Number of Trials to Criterion in Memorization Task

	Single Hands	Mirror-Image Movements	Different Movements
Amateurs	5.09 (2.17)	4.94 (2.63)	8.44 (4.74)
Experts	3.83 (1.07)	4.00 (1.48)	6.69 (4.05)
Total	4.46 (1.81)	4.47 (2.17)	7.56 (4.45)

Means and Standard Deviations·

Note that 3 is the minimum value attainable, given that this was the learning criterion.

Figure 11
Errors as a Function of Coordination Complexity in Experiment 2



Note. Mean percentage of errors in the three conditions. Error bars indicate 95 percent confidence intervals.

Post-hoc comparisons revealed that error rates did not differ between skill levels for the *single-hand* tasks, but were reliably different from each other for the mean of the two *bimanual* tasks, $t(46) = 3.33$; $p < .002$. Similarly, skill differences were not reliable in the *mirror-image* condition but differed reliably from each other in the *different movements* condition, $t(46) = 2.52$; $p < .02$. Mean percentages of error in experts and amateurs are shown in Figure 11.

Correlations between the number of errors and interstroke intervals were positive in all three conditions and significant for the *different movements* condition, $r(46) = .42$; $p < .01$. This indicates that the faster subjects also made fewer errors.

Mean log-interstroke latencies from the last block of criterion trials were analyzed in exactly the same manner as described for Experiment 1.[15] The overall pattern of

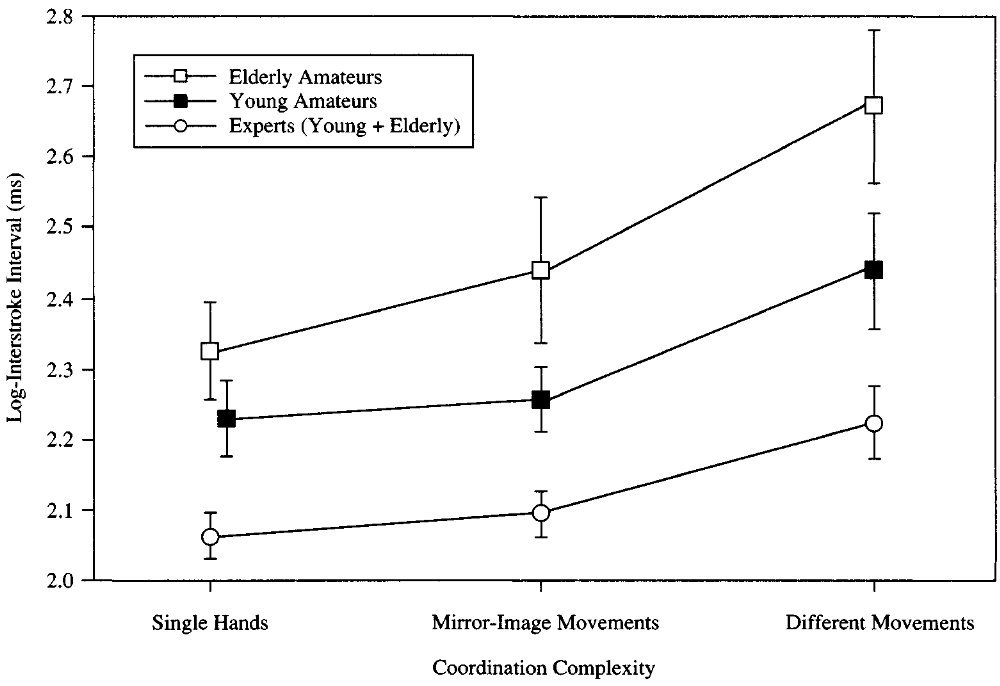
[15] Aggregation of the four single-hand sequences was justified on the basis of high internal consistency; *Cronbach's alpha* values were .936 (total sample), .866 (amateurs), .848 (experts), .903 (young subjects), .948 (elderly subjects), .765 (young amateurs), .670 (young experts), .883 (elderly amateurs), and .883 (elderly experts).

Considering the eight sequences used for the complete complexity manipulation in this experiment, *Cronbach's alphas* were .959 (total sample), .892 (amateurs), .914 (experts), .956 (young subjects), .958 (elderly subjects), .893 (young amateurs), .807 (young experts), .838 (elderly amateurs), .937 (elderly experts).

results from the analyses of log-interstroke latencies is illustrated in Figure 12. Mean raw and log-latencies are provided in Appendix C. Differences between experimental conditions as indicated by the two contrasts were reliable. Speed in the *single-hand* tasks was faster compared to *bimanual* tasks (contrast 1: $F(1,44) = 184$; $MSe = .58$; $p < .001$. *Different movements* in opposite hands were reliably slower compared to *mirror-image* movements in opposite hands (contrast 2: $F(1,44) = 101$; $MSe = .68$; $p < .001$. Pairwise t-tests conducted for each group indicated that the complexity manipulation was effective for subjects in all groups, $t(11) > 4.3$; $p < .002$, as was predicted (Prediction 3).

Contrast 1 (*single-hand* vs. *bimanual* tasks) showed a significant three-way interaction with age-group and skill level, $F(1,44) = 8.47$; $MSe = .03$; $p < .01$. Subsequent post-hoc comparisons revealed a straightforward picture. None of the comparisons between the two expert groups was significant, $t(22) < 1.7$; $p > .1$. The differences between elderly expert pianists and young amateurs were reliable in all task conditions, $t(22) > 3.3$; $p < .002$. Elderly amateurs were similar to young amateurs in the *single-hand* condition, but reliably slower in both *bimanual* tasks, $t(22) > 3.3$; $p < .005$, giving way to the predicted three-way interaction reported above (Prediction 4).

Figure 12
Speed as a Function of Coordination Complexity in Experiment 2



Note. Mean log-interstate intervals (in ms) in the three conditions of the memorization experiment. Data are averaged for young and elderly experts. Error bars indicate 95 percent confidence intervals.

The significant interaction between skill level and complexity located in contrast 1, $F(1,44) = 15.3$; $MSe = .05$; $p < .001$, and contrast 2, $F(1,44) = 5.39$; $MSe = .04$; $p < .05$, may also be considered reliable in light of these findings (Prediction 5), giving way to a main overall effect of skill level, $F(1,44) = 77.5$; $MSe = 2.56$; $p < .001$. The effect of skill level may thus be generalized, as was predicted (Prediction 7). The interaction between age-group and contrast 1, $F(1,44) = 7.68$; $MSe = .02$; $p < .01$ (Prediction 6) and the main effect for age-group, $F(1,44) = 13.2$; $MSe = .44$; $p < .002$, need to be interpreted in light of the reported higher-order interactions. The interaction between age-group and skill level was significant, $F(1,44) = 4.15$; $MSe = .14$; $p < .05$, and can be considered reliable from the above results. No other higher-order interactions were significant. Appendix C includes two additional figures illustrating the interactions between skill level and task complexity for the means aggregated accordingly.

To test whether group differences might be accounted for by different amounts of training received during the learning-to-criterion procedure, correlations between number of trials required for memorization and later performance were calculated. All correlations were positive and significant for the *single-hand,* $r(46) = .47$; $p < .01$, and the *mirror-image* conditions, $r(46) = .51$; $p < .01$, indicating that those subjects who received more training during learning-to-criterion were nonetheless slower later on. Further correlational analyses revealed that those subjects who needed more practice in order to memorize the sequences were nonetheless more likely to make errors in later testing. Correlations between the percentage of errors in criterion trials and number of trials required to attain the memorization criterion were significant for the *single-hand,* $r(46) = .42$; $p < .01$; the correlations for the *bimanual* tasks were also positive, but not significant.

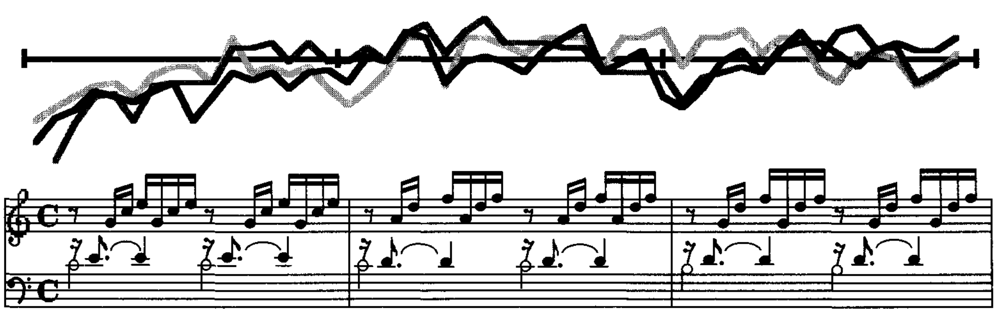
The memorization task may be considered a conservative estimate of group differences with respect to the speed of performance in the different conditions. While the performance demands imposed by playing from memory were probably higher compared to the transcription experiment, subjects had additional practice in the course of the learning-to-criterion procedure. The memorization experiment was administered during the second experimental session, so any transfer from the first experiment would enhance performance in the memorization task. The number of trials necessary to attain memorization depended on the complexity of the task (Prediction 8). Experts were generally more effective in memorizing the movement sequences (Prediction 9). There was no additional skill advantage with respect to the number of trials needed for rehearsal in the more complex conditions (Prediction 10 not confirmed). The effect of the complexity manipulation on the speed of performance in the memorization experiment was basically identical to the transcription task, with speed being sensitive to coordination complexity in all four groups, as was predicted (Prediction 3). Similarly, experts outperformed the amateur groups in all complexity conditions in both experiments (Prediction 7). There were no reliable age effects within the expert group in the memorization experiment. However, the effect of age was pronounced in the more complex conditions for the amateur subjects, as was predicted (Prediction 4). Except for the *single-hand* condition, elderly amateurs were outperformed by their younger counterparts.

Musical Performance Task

The computerized analysis of the three performances was favored by the completely linear musical structure of the Prelude (i. e., only one note onset at a time). Figure 13 illustrates the musical structure and the logic of analyses. The left hand plays the first two notes in each half-bar, which are the two lowest tones of the respective chord, followed by six semiquaver notes (i. e., the sixteenth part of a whole-note duration) played by the right hand. The second half-bar is an exact repetition of the first half-bar with respect to the score. The two bass notes for the left hand are a half note and a prolonged quaver note which are sustained while the remaining six notes of each half-bar are played. A *deadpan* (purely metrical) performance would imply identical time intervals between onsets of successive notes. One way to perceive this structure is to consider half-bars as broken chords arpeggiated in performance. The musical structure of the piece is identical across the first 32 of 35 bars, and only these were included in the analyses for this reason, providing three series of 512 data points for each subject or 511 for interkeystroke intervals (IKIs). The score given to participants did not include additional notations with respect to tempo or interpretation which were also not included in Bach's original composition.

All subjects knew the piece. Seven subjects (14.6%) had never played it before but had listened to recordings of the piece by professional musicians. Five of the seven subjects who could not recall having played the piece themselves were expert pianists, and two were amateurs. The average time since the last performance of the piece was one and a half years for the amateurs and seven years for the experts. Twenty-five subjects (52%) reported never to have practiced the piece in the sense of working at details of performance. Thirteen of these participants were experts, twelve were amateurs. Almost all of them claimed that the piece constituted too little challenge in order to have attracted their attention. For the remaining subjects, the average time

Figure 13
Dynamic Variations in Musical Performance Task



Note. First three bars of J. S. Bach's Prelude No. 1 ("Wohltemperiertes Clavier," Vol. 1). The three lines refer to three successive performances and represent the force applied in each of the 16 keystrokes per bar. The solid line in the upper panel represents the individual mean force averaged across the three performances. Data are from an elderly expert pianist.

passed since they had practiced the piece was 8.75 years for the amateurs and 27 years for the expert group, almost all of whom had, if at all, practiced the piece during their earliest piano lessons. Those subjects who had not played the prelude before could play it at first sight or were able to play fluently through it after 15 minutes of practice, with the exception of those three subjects who were excluded from all analyses of the study, as was initially mentioned.

We analyzed errors, force (i. e., loudness), speed, variability of force and speed, and the consistency of variation in force and IKIs—that is, timing—in the three successive performances of the prelude. Repeated measures ANOVAs were conducted using the three interpretations as within-subjects factor. Force applied to a keystroke was assessed as an integer value ranging from 1 to 127 by the hardware. IKIs were log-transformed at the level of single transitions. Table 2 provides summary statistics for the analyses of the musical performance task.

Error rates were very low; however, experts made fewer errors ($M = .10\%$; $SD = .20$) than amateurs ($M = 1.41\%$; $SD = 2.43$), $F(1,44) = 6.65$; $MSe = 61.5$; $p < .05$. Two levels of analysis with respect to the consistency of variations in force and timing were considered, namely the level of single keystrokes within each bar, and the level of bar means. The first measure was assumed to mirror the fine-grained variations. The latter measure reflects systematic variation of larger units, like phrases, which are approximated by bars in the piece selected. Wrong notes and keystrokes immediately following an error were not included in the analysis; only bars with a maximum of one error were considered. The percentage of strokes which had to be excluded according to the above criterion was higher for amateurs ($M = 9.80\%$; $SD = 13.6$) than for experts ($M = 1.7\%$; $SD = 2.37$), $F(1,44) = 7.85$; $MSe = 787$; $p < .01$. Overall, expert pianists applied more force than amateurs in all three performances, $F(1,44) = 12.1$; $MSe = 1{,}917$; $p < .005$. Tempo as assessed through log-IKIs was faster for experts than for amateurs, $F(1,44) = 4.83$; $MSe = .17$; $p < .05$. This was also true when the total playing time for the analyzed segment was expressed in seconds, $F(1,44) = 4.92$; $MSe = 6{,}527$; $p < .05$.

Consistency of variation at the level of single strokes within each bar was assessed through three coefficients reflecting the correspondence between the three performances. Pearson correlation coefficients based on single keystrokes in each bar were computed, z-transformed, and averaged across the 32 bars. The reliability of the three aggregated z-coefficients was high for the measure of force control (*Cronbach's alpha* = .965) as well as for the control of timing variation (*Cronbach's alpha* = .959).[16]

Experts' consistency with respect to varying force at this level was higher than that of amateurs, $F(1,44) = 13.15$; $MSe = 6.01$; $p < .005$. This was the case despite the fact

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[16] Reliability coefficients for the three measures of force variation based on single strokes at the level of subgroups were .973 (amateurs), .904 (experts), .974 (young), .947 (elderly), .974 (young amateurs), .921 (young experts), .973 (elderly amateurs), and .844 (elderly experts).

Coefficients for the three measures of timing variation based on single strokes at the level of subgroups were .970 (amateurs), .925 (experts), .958 (young), .963 (elderly), .966 (young amateurs), .939 (young experts), .976 (elderly amateurs), and .912 (elderly experts).

The pattern was similar for the timing data. *Cronbach's alpha* was above .86 for the total sample. Subgroups: skill level (alpha > .62), age-groups (alpha > .86), single groups (alpha > .39).

Table 2
Summary Statistics for Musical Performance Task (Means and SDs)

	Amateurs	Experts	Total
Force (1–127)	74.48 (6.29)	81.78 (8.64)	78.13 (8.33)
Playing Time for Analyzed Segment (in Seconds)	126.1 (49.9)	102.8 (15.4)	114.5 (38.4)
Tempo (Log-IKI in Milliseconds)	2.368 (.141)	2.298 (.069)	2.333 (.115)
SD around Bar Means for Force Applied to Single Strokes	7.11 (1.55)	5.38 (1.00)	6.25 (1.56)
Correlation of Force Applied to Single Strokes within Bars	.402 (.135)	.515 (.075)	.458 (.122)
z-Correlation of Force Applied to Single Strokes within Bars	–.224 (.483)	.185 (.268)	–.020 (.438)
SD around Bar Means of IKIs for Single Strokes	.054 (.039)	.042 (.008)	.048 (.029)
Correlation of IKIs for Single Strokes within Bars	.330 (.154)	.374 (.084)	.352 (.125)
z-Correlation of IKIs for Single Strokes within Bars	–.078 (.517)	.064 (.277)	–.007 (.417)
SD Bar Mean Force	9.17 (2.10)	8.98 (2.42)	9.07 (2.24)
Correlation of Bar Means (Force)	.635 (.173)	.842 (.079)	.739 (.169)
z-Correlation of Bar Means (Force)	–.565 (.942)	.565 (.423)	0.0 (.921)
SD of Bar Means (Tempo)	.060 (.040)	.045 (.008)	.052 (.030)
Correlation of Bar Means (Tempo)	.384 (.243)	.340 (.204)	.362 (.223)
z-Correlation of Bar Means (Tempo)	.089 (.960)	–.089 (.812)	0.0 (.884)

that the overall variability in terms of force applied to single strokes within each bar (i. e., the average of all standard deviations around the related bar means) was higher in amateurs than in experts, $F(1,44) = 21.09$; $MSe = 108.2$; $p < .001$. The correlation between overall variation applied and average z-scored consistency was negative, but nonsignificant, $r(46) = -.201$. To adjust for interindividual differences with respect to how much variation was applied in the first place, an additional analysis of variance was conducted using the averaged standard deviation as a covariate. The covariate did not have a significant impact nor change the pattern of significant findings.

The variability of timing single keystrokes did not differ reliably between groups. Consistency of timing was substantially lower and did not differ between groups. The correlation between overall variation applied and average z-scored consistency was sizeable and significant, $r(46) = .535$; $p < .01$. Consequentially, variability had a significant effect as a covariate, $F(1,43) = 24.9$; $MSe = 2.89$; $p < .001$; when individual variability was adjusted for in the analysis of covariance, the effect of skill level was significant, $F(1,43) = 6.36$; $MSe = .74$; $p < .05$, indicating that experts' timing consistency when adjusted for overall variability ($M = .120$) was higher than that of amateurs ($M = -.134$).

Consistency of force and timing applied at the macrolevel was assessed as the correlation of the 32 bar means across the three successive performances. The reliability was slightly higher for the three coefficients, reflecting consistency of force variation (*Cronbach's alpha* = .911), than for the consistency of timing control (*Cronbach's alpha* = .860).[17]

A repeated measures ANOVA of z-transformed correlation coefficients yielded a main effect of skill level, $F(1,44) = 29.87$; $MSe = 46.03$; $p < .001$, for consistency of mean force applied across bars. Expert pianists were more systematic in their variation than amateurs. Variability of force applied at the macrolevel—that is, the standard deviation of bar means from the grand mean—did not differ between groups. The way elderly subjects played varied more in terms of loudness during the first performance compared to the other two, as was indicated by a reliable interaction between age-group and performance for this measure, $F(2,88) = 5.95$; $MSe = 2.21$; $p = .005$. The standard deviation of means around the grand bar mean was uncorrelated with the average of the three consistency measures, $r(46) = .073$, and thus did not have a significant effect as a covariate; the pattern of reliable findings did not change when overall variability at this level was statistically controlled for.

No group differences emerged when the consistency of timing was analyzed. Variation of timing as assessed through the standard deviation of bar means for log-IKIs from the grand mean did not differ between groups. Variability and the average of the consistency measures were basically uncorrelated, $r(46) = .132$. Controlling for individual variability by means of an analysis of covariance did not change the pattern of results.

The results revealed higher proficiency of experts as reflected in the number of errors made during performance (Prediction 12). Higher consistency in the successive

[17] Reliability coefficients in subgroups for the three measures of force variation assessed at the level of bar means were .884 (amateurs), .723 (experts), .932 (young), .890 (elderly), .907 (young amateurs), .776 (young experts), .853 (elderly amateurs), and .653 (elderly experts).

Subgroups' reliability coefficients for the three measures of timing variation at the level of bar means were .926 (amateurs), .785 (experts), .881 (young), .839 (elderly), .913 (young amateurs), .877 (young experts), .949 (elderly amateurs), and .627 (elderly experts).

performances of expert pianists with respect to intentional variation was demonstrated for dynamic changes in force at the level of single keystrokes and at the level of bar means; timing variation at the level of single keystrokes was more consistent in experts once overall variability was controlled for. These effects confirmed Prediction 11. The most common interpretation of the piece as a typical example of Baroque music probably led participants to concentrate on dynamic force changes rather than varying the tempo to a degree which is more typical of Romantic music. This conclusion is supported by the comparison of coefficients among measures.

Perceived Relevance of Experimental Tasks

Subjects evaluated the abilities challenged by the six different experimental tasks regarding their relevance for playing the piano. The scales used ranged from zero (low relevance) to ten (high relevance). Mean relevance ratings for each experimental task separated by groups are given in Appendix C. Two different sum scores were computed to obtain indicators of subjects' perception of the experimental tasks: The first score was averaged for those tasks which were not predicted to show effects of skill level—namely, digit-symbol substitution and two-choice reaction time. The second score was averaged for the remaining four tasks (transcription experiment, musical performance, finger tapping, and memorization experiment) which were presumed to reflect skill in terms of playing the piano. A repeated measures ANOVA was performed using presumed relevance for the skill as a two-level within-subjects factor. The analysis revealed a main effect of age, $F(1,44) = 9.61$; $MSe = 57.82$; $p < .005$, and type of task, $F(1,44) = 15.2$; $MSe = 54.00$; $p < .001$. No higher order interactions were significant.[18] Those tasks which were hypothesized to be relevant to the skill were rated higher ($M = 7.38$; $SD = 1.55$) compared to the presumably nonrelevant tasks ($M = 5.88$; $SD = 2.89$), indicating that subjects' perception reflected the theoretical distinction. Overall, elderly subjects rated the tasks higher ($M = 7.55$; $SD = 1.37$) in terms of relevance than young subjects ($M = 6.20$; $SD = 1.65$). No differences associated with skill level emerged from these analyses.

It is worth noting that while digit-symbol substitution and choice-reaction time have the lowest means in young subjects, elderly subjects rated the two-choice reaction time task as being more relevant than finger tapping. This indicates that the picture is not as clear-cut as suggested by the overall analysis. One might argue that elderly subjects were more sensitive to their perceived decline in simple cognitive-motor functioning as reflected in the two-choice reaction time task. The higher relevance attributed to the choice-reaction time task by elderly subjects could reflect the attempt to compensate in those functions which are more sensitive to "normal aging." The basis for this evaluation, however, most likely came from experiences outside the context of the investigation; otherwise one would have expected a similar finding for the digit-symbol substitution task which showed similar performance differences between age-groups. Experiments were done in single-subject sessions and participants thus

[18] The same pattern of reliable findings emerged when ratings were analyzed using the six scales as a within-subjects factor: Effects of age ($F[1,44] = 9.19$; $MSe = 130.7$; $p < .005$) and task ($F[1,44] = 11.3$; $MSe = 65.96$; $p < .001$) were significant, but none of the higher order interactions was reliable.

had no reference group. Skill level did not have any reliable impact on the perceived relevance of the tasks, and overall, subjects considered the skill-related tasks as clearly related to the skill. The differences in perception are most likely related to general aging stereotypes which seem to exist regardless of skill level.

The relevance ratings provide an interesting source of evidence in order to compare different experimental manipulations. An important question in this context was whether the two major experiments, the transcription and the memorization experiment, would differ in terms of the subjects' evaluation. The two experiments were both designed to be maximally sensitive to age- and skill-related performance differences and did not differ in their basic set-up. A repeated measures ANOVA on ratings for the two experiments revealed a main effect of experiment, $F(1,44) = 5{,}73$; $MSe = 12.04$; $p < .05$, indicating that subjects judged the memorization experiment ($M = 8.40$; $SD = 1.89$) as more relevant to playing the piano than the transcription experiment ($M = 7.69$; $SD = 2.34$). The overall effect of age-group was also found to be significant for the average of these two measures, $F(1,44) = 8.49$; $MSe = 51.04$; $p < .01$, but did not interact with the type of the task. No other main effect or higher order interactions were significant. This finding was in line with the discussion of validity of the tasks in the theory section. Memorization is the normal case in public performance for pianists, and thus it is more relevant to playing the piano than to typing or other transcription skills. The stimulus format (numbers assigned to the different fingers) is not typical of sight-reading performance, and so memorization during the learning-to-criterion task probably enforced recoding into more familiar memory representations. Subsequent speeded performance from these codings may be assumed to be more challenging compared to the transcription task; at the same time, Experiment 2 probably had a higher ecological validity than the transcription experiment with respect to piano-playing skill.

Summary: Group Differences in Skill-Related Tasks

The decomposition of the skill of playing the piano described in the theory section suggested three levels of analysis: peripheral, motoric factors as reflected in finger-tapping speed; the efficiency of movement coordination as reflected in the two experiments challenging speed in complex single-hand and bimanual movements; the ability to systematically vary expressive variation in musical performance as measured by the consistency of repeated performances of the same piece. At the most general level, it can be summarized that experts outperformed amateurs in all skill-relevant tasks, as was predicted. The findings from the analysis of performance in skill-related tasks are listed in Table 3 along with the other group differences reported so far.

Alternate tapping was found to be faster than single-finger tapping in all groups. Speed was higher in experts for left, right, and alternate index-finger tapping. No age effects could be found for these tasks. The finding that tapping speed is correlated with proficiency in playing the piano is in line with the results from typewriting research (e.g., Salthouse, 1984). A skill advantage for pianists in single-finger tapping tasks was reported in an earlier study (Telford & Spangler, 1935). The findings on tapping presented in this study, however, went beyond these earlier results. The ability to overlap subsequent movements in time was highlighted in the theory section as one of

Table 3
Analyses of Group Differences (Summary)

Variable	Procedure	Effects
Current Practice Skill-Related Activities Amount of Leisure Time	Diary (Hours per Week)	Skill, Age × Skill Skill Age × Skill
Past Practice	Retrospective Estimates (Hours Accumulated)	Skill, Age, Age × Skill
General Cognitive-Motor Speed	Digit-Symbol Test (Number of Items Correct)	Age
	Two-Choice Reaction Time (Mean Response Time in ms)	Age
Peripheral Motor Efficiency	Right, Left, Alternate Tapping (Log-Interstroke Interval in ms)	Complexity Skill Skill × Complexity
Speeded Performance of Coordinated Movements (Transcription)	Experiment 1 (Log-Interstroke Interval in ms)	Complexity Skill Skill × Complexity Age × Complexity
	Errors (Percent)	Complexity
Memorizing Movement Sequences	Experiment 2 (Number of Trials to Criterion)	Skill, Complexity
Speeded Performance of Coordinated Movements (after Memorization)	Experiment 2 (Log-Interstroke Interval in ms)	Complexity Skill Skill × Complexity Age × Skill × Complexity
	Errors (Percent)	Complexity, Skill Skill × Complexity
Consistency of Dynamic Variations in Musical Performance	Three Performances Bach Prelude	
	Force Applied to Single Strokes Timing of Single Strokes Average Force in Bars (z-Scored Correlations)	Skill
	Errors (Percent)	Skill

the most important aspects of rapid, fluent motor performance. This aspect is documented by the significant interaction between skill level and task complexity in tapping and complex coordination tasks. Even at the simplest level of coordination, alternate finger tapping, pianists show a proportionally higher performance gain by overlapping movements in time.

The experimental manipulation in the complex movement coordination experiments acted as predicted. Bimanual movements were slower compared to the average speed of single-hand movements, and mirror-image movements were faster than different movements in opposite hands. This was true for all four groups of subjects in both experiments. Skill advantages were found to be reliable at all levels of analysis in both experiments. Both orthogonal contrasts specified in order to assess the effect of complexity showed reliable interactions with the skill level factor, indicating that skill advantages increased with complexity in both experiments. Expert pianists were found to be reliably more efficient when memorizing movement sequences.

Elderly subjects showed no performance deficit with respect to the number of trials needed to memorize a given movement sequence in Experiment 2 (memorization). Elderly amateurs were reliably slower than their younger counterparts in all conditions of the transcription experiment and in the two conditions requiring the coordination of bimanual movements of the memorization experiment. Elderly experts were outperformed by their young counterparts only in the most complex condition of Experiment 1, where differences between age-groups were reliable. This was not true for Experiment 2. It needs to be stressed that elderly experts were reliably better than young amateurs in all skill-relevant tasks yielding significant effects of age, which illustrates the magnitude of the relative contributions of skill and age factors. Post-hoc analyses of relevance ratings suggested that Experiment 2 (memorization) can be considered as the task with the highest ecological validity with respect to playing the piano among all tasks. The reliable difference between young and elderly experts in Experiment 1 thus must be interpreted with care, given that it was not obtained in Experiment 2.

Expert pianists were clearly more consistent in applying dynamic changes of loudness in the musical performance task (Bach prelude). In addition to this, experts made fewer errors during performance. No differences between age-groups emerged from these analyses.

Accountability of Skilled Performance through Deliberate Practice

Hierarchical linear regression techniques were applied to test the relative contributions of design and practice variables to interindividual differences in performance. At the onset, the successive implementation of three regression models based on design factors and a set of four practice variables reflecting training at different phases of skill development is described. The approach permits us to address the two critical questions: (1) whether interindividual differences within groups could be accounted for with respect to amounts of deliberate practice (Hypothesis 13) and (2) whether the variance associated with age and skill level factors could be equally well accounted for by amount of deliberate practice activities (Hypothesis 14). Results of regression analyses performed on data from the tapping experiments, the complex movement coordination tasks (Experiments 1 and 2), and the consistency of varying dynamic force changes in the musical interpretation task are reported in the following sections.

Along with each set of analyses, three further aspects are addressed in the context of additional analyses. First, the influence of within-group differences in subjects' exact age is examined; the potential source for related effects is that age-related decline might proceed more rapidly during the sixth decade of life. Second, it was examined whether differences between age-groups at the two skill levels remained or emerged after all effects of practice intensity were controlled for. Third, it was tested which phase of skill development was most critical in accounting for interindividual differences in performance.

Residuals from all analyses were analyzed to evaluate the explanative power of a model based only on practice variables for the performance of each group. Explorative analyses reported in an extra section illustrate the potential shortcomings of the described approach and their implication for the interpretation of findings. A summary of results from the regression analyses is provided on page 135.

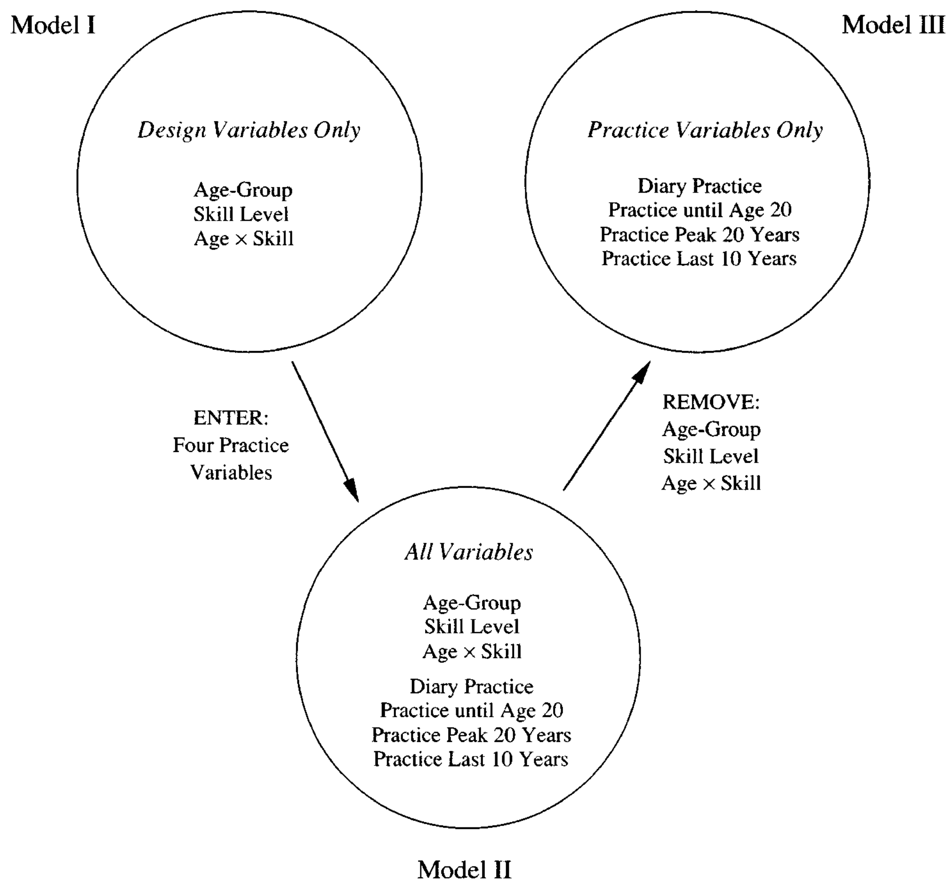
Implementation of the Regression Models

The design factors (effect-coded) skill level, age-group, age-group by skill level, provided the first set of predictor variables. Given that there was the same number of subjects in each group, the design variables were completely orthogonal, and their effects could therefore be considered as independent. Four different measures of deliberate practice during various phases of skill development were used as the second set of predictor variables. The number of hours practiced alone during diary week was used as an indicator of current practice intensity. Three measures of past training covered the first 20 years of life, the 20 years of highest practice intensity, and the last 10 years prior to investigation. While these phases naturally overlap in young subjects, they were assumed to reflect phases of early skill acquisition, peak involvement, and maintenance training in elderly subjects. The duration of phases was chosen with respect to the age of the youngest subjects in each age-group. The distinction among practice variables permits us to test whether interindividual differences in performance were related to early training, highest level reached, or maintenance practice, or whether they reflected current levels of practice. The three measures of past amounts of practice were log-transformed to conform to the assumptions of power-law practice gains. Means, standard deviations, and the correlations among predictor variables are given in Appendix C.

The high colinearity among practice variables and, presumably, between practice variables and design variables suggested a hierarchical regression approach to test the critical hypotheses (Cohen & Cohen, 1975). Three regression models differing with respect to the sets of predictor variables included were used on each dependent variable. The regression module in SPSS-X (SPSS-X Inc., 1988) was used to this end. The models were successively derived from each other by adding or subtracting predictor variables to the equation. At the level of a specific model, each variable included is separately removed from the complete equation in order to derive estimates for the unique variance associated with it. The models and their successive implementation are illustrated in Figure 14.

Model I includes only the design variables—namely, age-group, skill level, and their interaction—which were entered simultaneously into the regression equation. As these

Figure 14
The Three Regression Models and Their Successive Implementation



factors were orthogonal, this method provided an estimate for the amount of variance uniquely associated with each of the design variables. In Model II, the four practice variables were added simultaneously to the design variables in Model I. The difference in R^2 (variance explained) between Model I and Model II provides an estimate of the variance explained by the practice variables not yet captured by the design variables—that is, a test of Prediction 13. Removing each design variable from the extended model yields a conservative estimate of the unique variance associated with each factor when the influences of the other variables are statistically controlled for. Joint removal of all three design variables finally results in Model III. Model III includes only the four practice variables, and thus provides a measure of the amount of variance which can be accounted for if only differences in the amounts of deliberate practice are used for predicting performance in the different tasks (test of Prediction 14). Similar to Models I and II, variables are removed separately to estimate unique variance.

To check whether within-group variance related to subjects' exact biographical age had any effect on task performance or impacted on the amount of variance associated with practice measures, subjects' exact age was entered prior to adding the four practice variables to the design factors (transition from Model I to Model II) in a control analysis.

Further analyses focussed on an account which was based on interindividual differences in practice intensity at various phases (Model III). Two comparisons between young and elderly experts and young and elderly amateurs were contrast coded and added separately to Model III. This method permits us to determine whether any differences between age-groups at a given skill level remain, or emerge, after all possible influences of practice have been statistically controlled for. The additional step seemed appropriate given that one of the practice variables (practice during peak involvement) showed a positive, though not significant, correlation with the age factor (see Appendix C). Its influence within the set of practice variables on the variance related to age is difficult to evaluate from Model II alone.

Finally, to determine which of the four practice variables showed the strongest relation with performance in the different tasks, stepwise regression analyses were performed. Using a 5 percent alpha level as a cut-off criterion, those variables with reliable contribution to the variance explained are reported.

Regression Analysis of Finger-Tapping Speed

The three tapping tasks were analyzed separately. Table 4 gives the variance explained (R^2) by each model and the single variables in the three equations for the mean log-interstroke latencies in the three tapping tasks. The table is organized according to the different steps related to the successive implementation of the three models illustrated in Figure 14. R^2s and significance tests in the first line of each panel refer to the F-test for the complete model when all specified variables are in the equation. In the case of Model I this means that the three design variables skill level, age-group, and their interaction were entered simultaneously as a first step; the asterisks after the R^2s refer to the F-test for the joint variance accounted for by the three variables. The lines below (labeled *unique variance*) refer to the change in variance when a single variable is removed from the complete model. The related statistics reflect the unique contribution of a given variable in the context of the complete model.

The regression fit for Model I was significant for all three tapping tasks: right-finger tapping, $F(3,44) = 15.33$; $MSe = .016$; $p < .001$, left-finger tapping, $F(3,44) = 12.86$; $MSe = .022$; $p < .001$, and alternate tapping, $F(3,44) = 16.83$; $MSe = .070$; $p < .001$. Most of the variance explained was associated with the skill-level factor, as can be seen from the R^2 for unique variances. Age-group and the interaction of group factors did not significantly contribute to the model, as was already evident from the ANOVA analyses.

The transition from Model I to Model II involved adding the four practice variables to the three design variables. The effect of adding the four variables to Model I is illustrated by the statistics in the first line of the middle panel (labeled *additional variance practice variables*). Regression fits for Model II with the four practice variables added to the three design variables were significant: right-finger tapping,

Table 4
Regression Analyses for Three Tapping Tasks

		Right	Left	Alternate
MODEL I	Three Design Variables	.51***	.47***	.53***
Unique Variances	Skill Level	.48***	.46***	.50***
	Age-Group	.02	.00	.03
	Age × Skill	.01	.00	.00
	Additional Variance Practice Variables	.01	.03	.10*
MODEL II	3 Design Variables + 4 Practice Variables	.52***	.50***	.64***
Unique Variances	Skill Level	.09**	.08*	.03
	Age-Group	.01	.00	.00
	Age × Skill	.00	.00	.01
	Practice Until Age 20	.00	.00	.00
	20 Most Intense Years	.00	.01	.01
	Practice Last 10 Years	.01	.03	.07**
	Current Practice	.00	.01	.00
	Variance Removed with Design Variables	.13*	.09	.05
MODEL III	Four Practice Variables	.39***	.41***	.59***
Unique Variances	Practice Until Age 20	.00	.00	.00
	20 Most Intense Years	.02	.03	.00
	Practice Last 10 Years	.01	.01	.08**
	Current Practice	.02	.00	.01

R^2s for variables and their combination in each model; * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

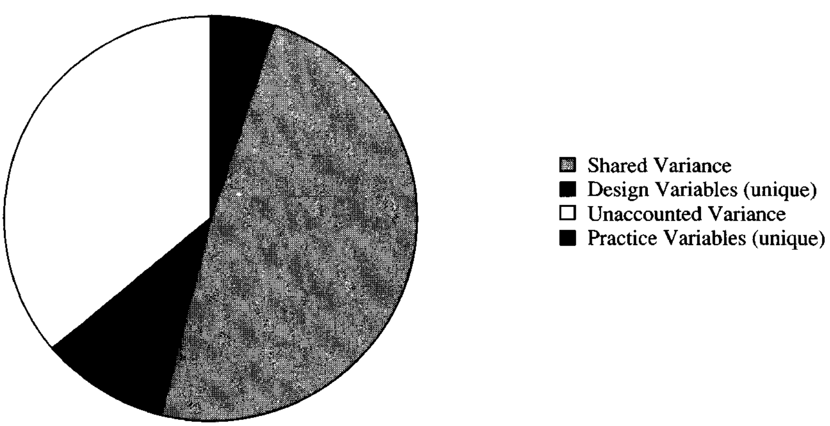
$F(7,40) = 6.18$; $MSe = .007$; $p < .001$, left-finger tapping, $F(7,40) = 5.71$; $MSe = .010$; $p < .001$, and alternate tapping, $F(7,40) = 10.02$; $MSe = .036$; $p < .001$. The related R^2s can be derived from the line labeled Model II. Only in the case of alternate tapping, however, did the addition of practice variables lead to a significant improvement of the model, *F-change* = 2.82; $p < .05$. Inspection of the beta-weights indicated that this was mainly due to the variable practice over the last ten years. Those subjects with higher practice showed the better performance.

The lines in the middle panel (labeled *unique variance*) illustrate the changes in the fit of Model II when each of the seven variables is separately removed. The unique variance associated with the skill factor in Model I was markedly decreased by the presence of the practice variables in Model II. Only in predicting performance in the two single-finger tapping tasks did the skill factor retain reliable unique variance. The only variable with unique variance related to alternate tapping speed was practice over the last ten years. This analysis illustrates the colinearity between skill level and the practice variables. Adding subjects' exact biographical age to Model I prior to the practice variables did not lead to an improvement of the model; the joint impact of the four practice variables dropped by 0.5 percent, reducing the alpha-level for the above effect to .054. Note, however, that the unique contribution of practice over the last ten years in Model II was still significant. The other effects remained unchanged.

The transition from Model II to Model III consisted of the joint removal of the three design variables: namely, skill level, age-group, and their interaction. The regression fit of Model III was significant for all three variables, as can be seen from the related R^2s: right-finger tapping, $F(4,43) = 6.75$; $MSe = .009$; $p < .001$, left-finger tapping, $F(4,43) = 7.36$; $MSe = .015$; $p < .001$, and alternate tapping, $F(4,43) = 15.16$; $MSe = .058$; $p < .001$. Only in the case of right-hand tapping did removal of the design variables lead to a significant decrease in explanatory power, *F-change* $= 3.73$; $p < .05$. Standardized beta-coefficients in Model III were negative for three variables and close to zero for practice accumulated until age 20, indicating that those subjects who practiced more during the different phases had the better performance. The small unique variances associated with the four practice variables within Model III illustrate the high colinearity among these measures. Only practice over the last ten years had significant unique variance associated with it in the alternate tapping condition. The two comparisons between age-groups revealed no reliable effects when practice was statistically controlled for.

The four practice variables did as good a job as the design variables for left index and alternate finger-tapping speed; the amount of skill variation captured by the practice variables was considerable in the case of right index tapping speed. However, there seemed to be reliable differences between experts and amateurs in right-finger tapping which could not be accounted for by differences in practice. In the case of alternate tapping, on the other hand, predictive power could clearly be improved by reference to the amount of practice. Figure 15 reflects the commonality of variances associated with design and practice variables in Model II for the alternate tapping condition. The black area is the variance that is uniquely associated with practice variables within Model II; the size of the area reflects the R^2-change when adding the four practice variables to Model I, thereby generating Model II. Note that the contri-

Figure 15
Commonality of Variances in the Alternate Tapping Task



bution of practice which is independent of the design variables cannot be derived from adding up unique variances in Model II because of the high colinearity among practice measures. The light grey area relates to the unique contribution of the design variables. The large area in between the two small portions is shared variance which could either be accounted for by practice or design variables.

Stepwise regression analyses on the three tapping variables were performed to determine which of the four practice variables showed the highest correlation with task performance. The findings were clear-cut; practice over the last ten years was always the first variable entering the regression equation. The model based solely on the amount of practice over the last ten years accounted for 34 percent of the variance in right-finger tapping, $F(1,46) = 24.23$; $MSe = .033$; $p < .001$, 38 percent in left-finger tapping performance, $F(1,46) = 27.65$; $MSe = .054$; $p < .001$, and 58 percent of the variance in alternate tapping performance, $F(4,43) = 63.23$; $MSe = .228$; $p < .001$. No other variable surpassed the 5 percent cutoff-criterion for the alpha level of model improvement thereafter. Figure 16 illustrates the correlation between performance in the three tapping tasks and the log-amount of practice over the last ten years.

Regression Analysis of Speed in Complex Movement Coordination (Experiment 1)

Performances measured as mean log-interstroke latencies in the criterion blocks of the three conditions in Experiment 1 were analyzed separately; Table 5 shows the amount of variance explained (R^2) and the significance level of F-tests associated with each model along with the unique variance associated with each single variable within a given model. Model I provided a significant fit for all three tasks: single hands, $F(3,44) = 44.68$; $MSe = .277$; $p < .001$, mirror-image movements, $F(3,44) = 37.08$; $MSe = .327$; $p < .001$, and different movements in the two hands, $F(3,44) = 36.95$; $MSe = .552$; $p < .001$. Skill level had the most unique variance associated with it, but the unique contribution of age-group was also reliable in all three conditions. Only in the mirror-image movements task did the interaction contribute reliable unique variance (note that the age-by-skill interaction term in this analysis is not analogous to the interactions reported on the ANOVAs, which were done as repeated measures analyses involving all three conditions at the same time).

The four practice variables added significantly to the variance accounted for by the design variables in the most complex condition, *F-change* $= 4.52$; $p < .005$. The complete Model II involving all design and practice variables had a significant fit in all three conditions: single hands, $F(7,40) = 21.06$; $MSe = .124$; $p < .001$, mirror-image movements, $F(7,40) = 15.70$; $MSe = .144$; $p < .001$, and different movements in the two hands, $F(7,40) = 23.49$; $MSe = .266$; $p < .001$. Inspection of the unique variances associated with variables in Model II, when everything else was statistically controlled for, shows that the skill factor retains small, but reliable unique variance associated with it. Most of the skill variance, however, can be accounted for by the practice variables in the model. The same was true for the age-group factor; the age-by-skill interaction was even slightly boosted by the presence of the practice variables. In comparing the contribution of single factors in the context of different regression models, one has to be aware that very small portions of accounted variance are significant once the explanative power of a model becomes very good. The only

Figure 16
Mean Log-IKIs in Three Tapping Tasks as a Function of Practice over the Last Ten Years (Log Hours)

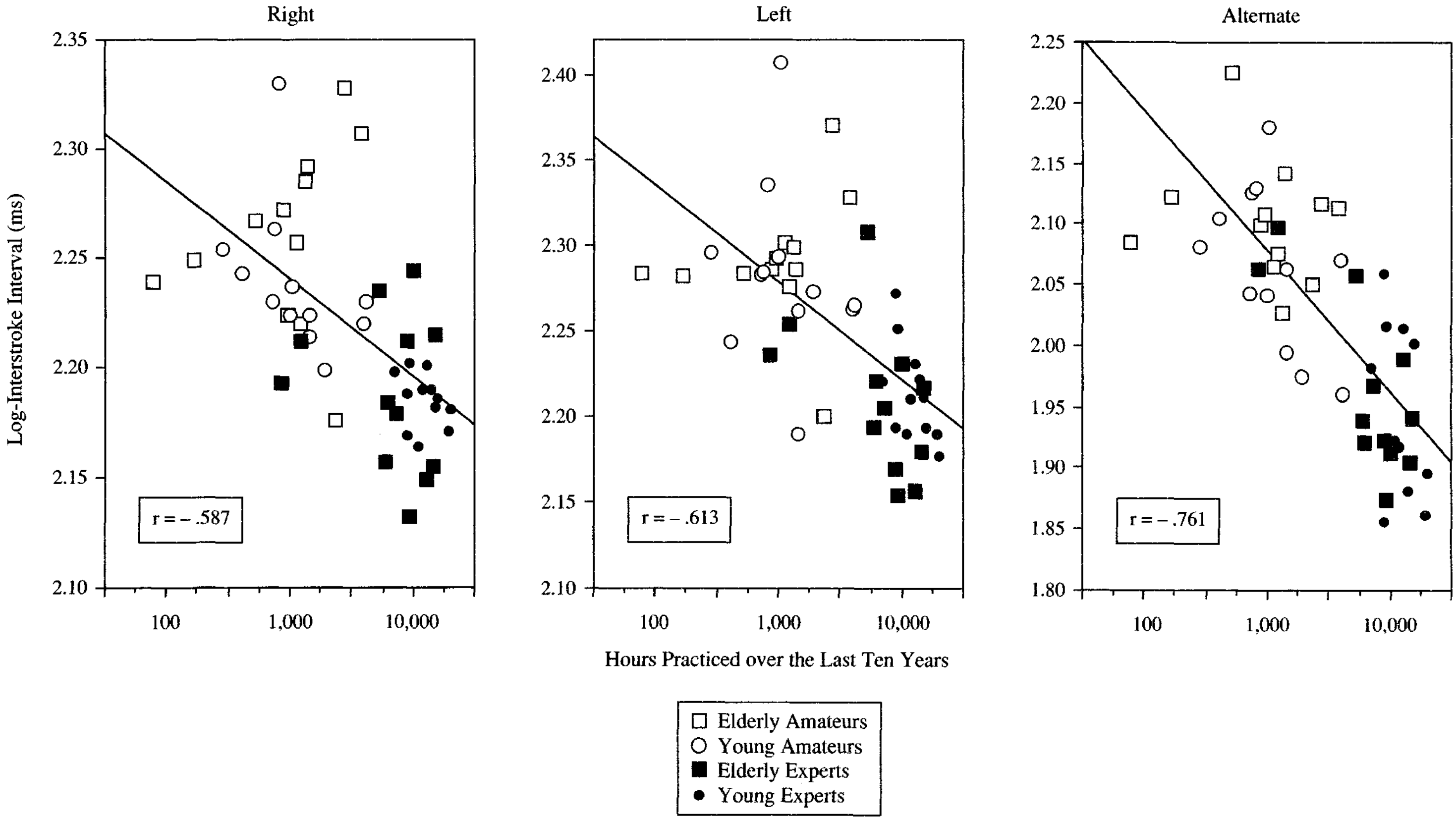


Table 5
Regression Analyses for Three Conditions in Experiment 1 (Transcription)

		Single Hands	Mirror Image	Different Movements
MODEL I	Three Design Variables	.75***	.72***	.72***
Unique Variances	Skill Level	.67***	.57***	.61***
	Age-Group	.06**	.12***	.10***
	Age × Skill	.02	.03*	.01
	Additional Variance Practice Variables	.03	.02	.09**
MODEL II	3 Design Variables + 4 Practice Variables	.79***	.73***	.80***
Unique Variances	Skill Level	.06**	.05**	.03*
	Age-Group	.01	.03*	.06**
	Age × Skill	.03*	.04*	.01
	Practice Until Age 20	.01	.00	.03*
	20 Most Intense Years	.00	.00	.00
	Practice Last 10 Years	.01	.00	.01
	Current Practice	.00	.00	.00
	Variance Removed with Design Variables	.16***	.20***	.15***
MODEL III	Four Practice Variables	.63***	.53***	.66***
Unique Variances	Practice Until Age 20	.00	.00	.02
	20 Most Intense Years	.01	.00	.00
	Practice Last 10 Years	.02	.02	.05*
	Current Practice	.05*	.06*	.01

R^2s for variables and their combination in each model; * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

practice variable which had unique variance associated with it was practice accumulated until age 20 in the different movements condition. Clearly, the skill factor and the practice variables were highly colinear—that is, they largely captured the same variance. Adding subjects' exact biographical age to Model I did not add reliable variance; when the exact age was present in Model II, the unique variance associated with practice until age 20 dropped slightly and was no longer significant. None of the other effects changed.

Joint removal of the three design factors lead to a significant decrease in predictive power in all three conditions: single hands, *F-change* = 9.71; $p < .001$; mirror-image movements, *F-change* = 10.00; $p < .001$, and different movements in the two hands, *F-change* = 10.06; $p < .001$. The fact that the R^2s to be removed for the design variables in Model II do not add up to the total R^2 when all three of them are removed together in the last step points to suppressor/enhancement constellations between design variables on the one side, and practice variables on the other. This means that Model II accounts for interindividual differences by the joint presence of two variables, neither one of which could capture the related differences on its own. The variance shared between design and practice variables included in the illustration of commonality of variances in Figure 17 thus also incorporates variance accounted for through these effects. Furthermore, Figure 17 shows the considerable additional variance captured by the four practice variables (black area) that had not been accounted for by the design variables; however, sizeable amounts of variance remain associated with the design factors (dark grey area) that are not covered by practice. The largest portion of the variance is clearly shared between design and practice variables (light grey area).

In general, Model III did significantly worse than Model II for all tasks. Nonetheless, the fit of Model III was significant in all three conditions: single hands, $F(4,43) = 18.40$; $MSe = .174$; $p < .001$, mirror-image movements, $F(4,43) = 12.27$; $MSe = .183$; $p < .001$, and different movements in the two hands, $F(4,43) = 20.56$; $MSe = .380$; $p < .001$. Standardized beta-coefficients were negative for all four variables in all three conditions, indicating that the relation between practice intensity and performance was indeed as predicted. Practice over the last ten years had reliable unique variance associated with it in the most complex task condition, as did practice during diary week for the single-hand and the mirror-image movement condition.

Contrasting young and elderly experts after the influence of the four practice variables was statistically controlled for did not reveal any effects, *F-change* < 2.2; $p > .1$. Note that the beta-weight for this contrast was negative (single hands, mirror-image movements) or zero (different movements) when included in the regression, indicating that controlling for practice overadjusts for age-effects within the expert group. At the same time, all of the differences between young and elderly amateurs were significant, *F-change* > 14.4; $p < .001$, beta-weights indicating that adjusted performance was worse for elderly than young amateurs.

Practice over the last ten years was the best predictor among practice measures regarding performance in this experiment, accounting for 56 percent of the variance in the single-hand tasks, $F(1,46) = 59.65$; $MSe = .622$; $p < .001$, 47 percent of the variance in the mirror-image movements task, $F(1,46) = 41.15$; $MSe = .647$; $p < .001$, and

Figure 17
Commonality of Variances in the Different Movements Condition from Experiment 1

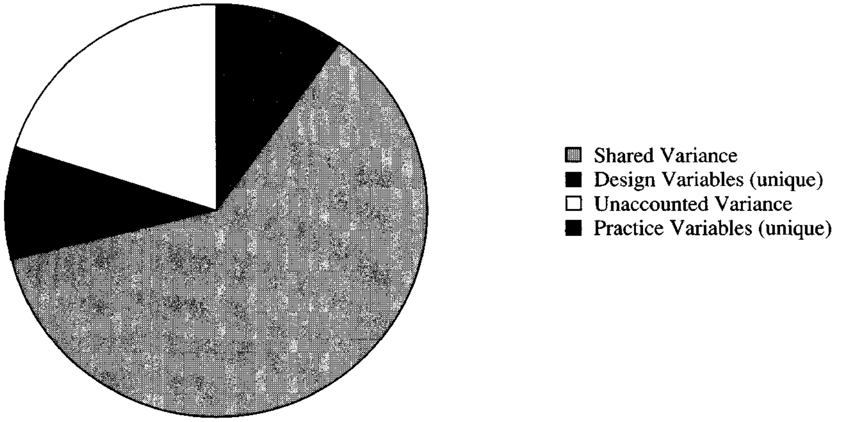
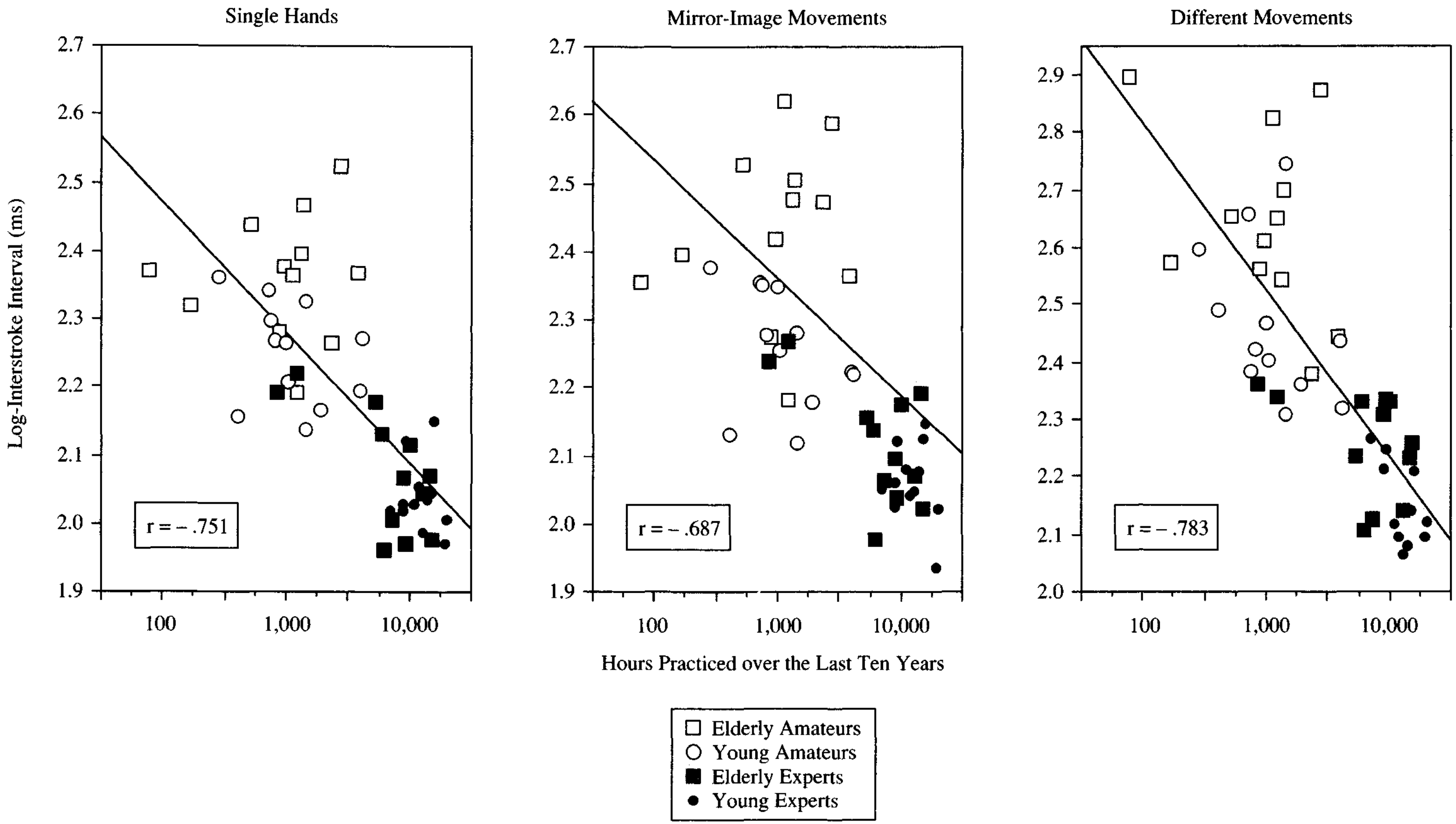


Figure 18
Mean Log-IKIs in Three Conditions of Experiment 1 as a Function of Practice over the Last Ten Years (Log Hours)



61 percent in the different movements condition, $F(1,46) = 73.02$; $MSe = .747$; $p < .001$. Practice during diary week added another significant 4 and 5 percent to the model for single-hand and mirror-image performance respectively, $F\text{-}change > 4.9$; $p < .05$, when entering the regression in the second step. Finally, practice accumulated until age 20 turned out to contribute an additional 3 percent to the reliable variance in the different movements condition, $F\text{-}change = 4.15$; $p < .05$. No other variable surpassed the 5 percent criterion. The correlation between practice over the last ten years and individual performance in Experiment 1 is shown in Figure 18.

Regression Analysis of Speeded Performance after Memorization (Experiment 2)

Performance in Experiment 2 was analyzed in exactly the same way as described for Experiment 1. The resulting statistics are provided in Table 6. Model I provided a significant fit for all three tasks: single hands, $F(3,44) = 23.77$; $MSe = .208$; $p < .001$, mirror-image movements, $F(3,44) = 27.42$; $MSe = .331$; $p < .001$, and different movements in the two hands, $F(3,44) = 24.99$; $MSe = .552$; $p < .001$. Skill level had the most unique variance associated with it: The influence of age-group was smaller, but reliable in all three conditions. The interaction was significant for the two bimanual tasks.

Table 6
Regression Analyses for Three Conditions in Experiment 2 (Memorization)

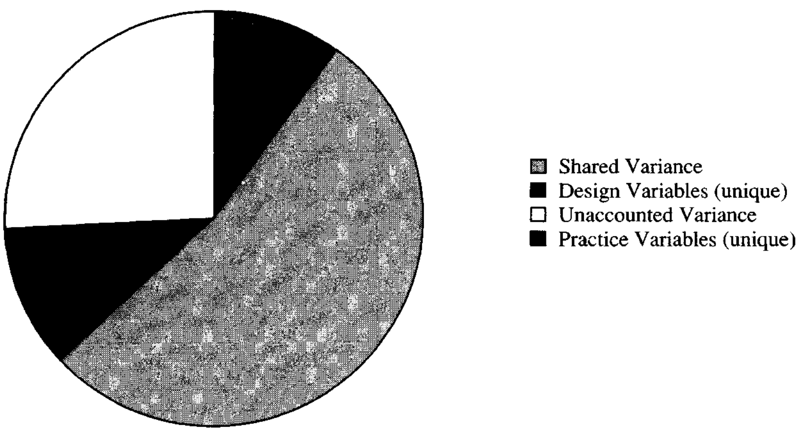
		Single Hands	Mirror Image	Different Movements
MODEL I	Three Design Variables	.62***	.65***	.63***
Unique Variances	Skill Level	.55***	.51***	.50***
	Age-Group	.06**	.11***	.09**
	Age × Skill	.01	.04*	.04*
	Additional Variance Practice Variables	.07	.04	.11**
MODEL II	3 Design Variables + 4 Practice Variables	.69***	.69***	.74***
Unique Variances	Skill Level	.06*	.03*	.04*
	Age-Group	.01	.05*	.02
	Age × Skill	.01	.04*	.04*
	Practice Until Age 20	.04*	.03	.02
	20 Most Intense Years	.02	.00	.01
	Practice Last 10 Years	.02	.00	.06**
	Current Practice	.00	.00	.01
	Variance Removed with Design Variables	.13**	.20***	.16***
MODEL III	Four Practice Variables	.56***	.49***	.58***
Unique Variances	Practice Until Age 20	.03	.01	.01
	20 Most Intense Years	.00	.00	.00
	Practice Last 10 Years	.03	.02	.11**
	Current Practice	.03	.03	.00

R^2s for variables and their combination in each model; * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

Adding the four practice variables to Model I led to a significant improvement in the most complex condition: different movements, *F-change* = 4.11; $p < .01$. Model II, based on all predictor variables, provided a significant fit in all conditions: single hands, $F(7,40) = 12.49$; $MSe = .099$; $p < .001$, mirror-image movements, $F(7,40) = 12.93$; $MSe = .151$; $p < .001$, and different movements in the two hands, $F(7,40) = 16.09$; $MSe = .277$; $p < .001$. Unique variance associated with age and skill factors was reduced considerably by the presence of practice variables in the regression; the interaction term was left unaffected. Practice until age 20 had unique variance associated with it in the single-hands condition as had practice over the last ten years in the different movements task. Adding participants' exact age to Model I prior to entering the practice variables neither improved predictive power nor changed any of the reported effects. Figure 19 shows the degree to which variables accounted for shared and unique variance.

Removing the three design variables from Model II led to a significant loss in predictive power in all three conditions: single hands, *F-change* = 5.45; $p < .01$, mirror-image movements, *F-change* = 8.90; $p < .001$, and different movements in the two hands, *F-change* = 8.26; $p < .001$. Comparing the sums of unique contributions in Model II and the total variance removed with the design variables indicates that suppressor and enhancement constellation similar to Experiment 1 existed in the data from Experiment 2 as well. Model III based on the four practice variables only provided a significant fit for all conditions: single hands, $F(4,43) = 13.56$; $MSe = .141$; $p < .001$, mirror-image movements, $F(4,43) = 10.28$; $MSe = .186$; $p < .001$, and different movements in the two hands, $F(4,43) = 14.58$; $MSe = .378$; $p < .001$. Standardized regression coefficients for the four practice variables were mostly negative; only in two cases related to practice during the 20 most active years were they positive but close to zero, pointing to a slight overadjustment. Practice over the last ten years was the only

Figure 19
Commonality of Variances in the Different Movements Condition from Experiment 2



variable which had unique variance associated with it—namely, in the different movements condition.

No differences between young and elderly experts emerged after differences in practice were statistically controlled for, *F-change* < 1.7; $p > .2$. Again, all related regression coefficients were negative, indicating that control for practice leads to an overadjustment with respect to age-effects in the expert group. All of the adjusted differences between young and elderly amateurs were reliable, however, *F-change* > 7.9; $p < .01$.

Stepwise regression analyses provided a straightforward picture; practice over the last ten years was the first and only variable entering the regression equation, accounting for 50 percent of the variance in the single-hand tasks, $F(1,46) = 45.39$; $MSe = .501$; $p < .001$, 44 percent of the variance in the mirror-image movements task, $F(1,46) = 35.52$; $MSe = .664$; $p < .001$, and 57 percent in the different movements condition, $F(1,46) = 59.83$; $MSe = 1.49$; $p < .001$. Practice over the last ten years thus showed the strongest correlation with performance in Experiment 2 among the practice measures. The correlation is illustrated in Figure 20.

Regression Analysis of Consistency of Variation in Musical Performance

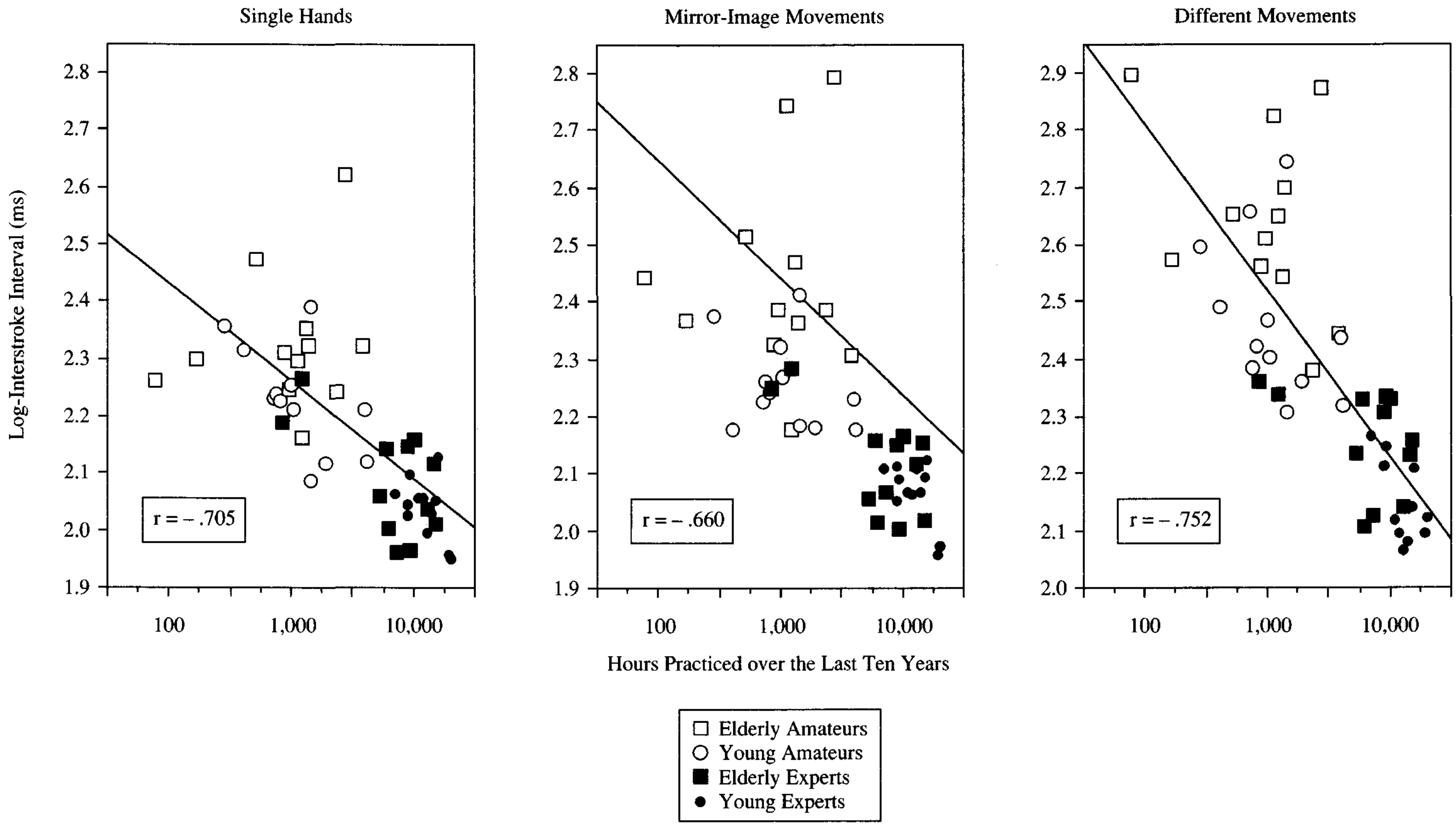
The averaged z-score for the consistency of force changes at the level of bar means in three successive performances of the Bach prelude was used as a dependent variable because of its highest validity in terms of group differences. The design variables entered in a first step accounted for 43 percent of the total variance, $F(3,44) = 11.2$; $MSe = 5.76$; $p < .001$. Only the main effect of skill level had reliable unique variance (38%) associated with it. Subjects' exact biographical age did not add reliable variance to Model I. Adding the four practice variables to Model I did not yield a significant increase in variance explained; nonetheless, Model II provided a significant fit, $F(7,40) = 4.78$; $MSe = 2.59$; $p < .001$. None of the variables in the complete model retained reliable unique variance. When practice was controlled for, the design variables could be removed from the complete Model II without significant loss in variance explained, *F-change* < 1.9; $p > .15$, leaving 38 percent of the variance accounted for by the four practice variables alone, $F(4,43) = 6.62$; $MSe = 3.80$; $p < .001$. Practice accumulated until age 20 showed a standardized beta-weight close to zero; the other three practice variables were related to the dependent variable in the predicted fashion (range: .13 to .32), indicating that those subjects who had higher amounts of practice were also more consistent across repeated performances.

None of the four practice variables had reliable unique variance associated with it in Model III. No reliable differences between age-groups within skill levels emerged after practice was statistically controlled for. Practice over the last ten years was the best predictor of performance differences among the practice variables, accounting for 35 percent of the variance, $F(1,46) = 25.1$; $MSe = 14.1$; $p < .001$. No other variable entered the regression equation thereafter.

Differences in Model Fit between the Four Groups

As a last step within the regression approach to performance in skill-related tasks, the amounts of variance left unexplained by Model III—that is, the residuals for each

Figure 20
Mean Log-IKIs in Three Conditions of Experiment 2 as a Function of Practice over the Last Ten Years (Log Hours)



group when interindividual differences in the four practice variables were controlled for—were further analyzed. Note that the error variance used for these analyses is the same as for the two age-related contrasts in Model III. The additional advantage of the following analyses is that they include the skill-level distinction and the group-factor interaction and allow a direct comparison among task conditions, providing for a greater generalizability of findings. At the same time, however, starting out with the residuals as dependent variables frees additional four degrees of freedom. Furthermore, no specific hypotheses had been formulated to start with. To take these two restrictions into account, a conservative alpha level of .01 was adopted.

As a first step, it was determined whether the model based solely on practice variables (Model III) provided similar over- or underestimates of individual performances across the three levels of complexity in the tapping tasks and Experiments 1 and 2. Note that while this is implied by the high reliability of task conditions, it does not automatically follow from those findings because the regression coefficients were estimated separately for task conditions. In a second step, standardized residuals were analyzed with repeated measures ANOVA using task complexity as within-subjects factor. Similarly, the overall fit of Model III across conditions was compared using the absolute value of standardized residuals as dependent variables. There was naturally no within-subjects factor for the musical performance task.

The differences between observed values and those predicted by Model III at the level of individuals were very similar across complexity conditions in the three tapping tasks. *Cronbach's alpha*, computed for standardized residuals, was .822 for the complete sample, .782 for experts, .834 for amateurs, .763 for young, and .857 for elderly subjects. Coefficients were above .747 at the level of single groups. No reliable differences regarding over- or underestimates emerged from the repeated measures ANOVA. Elderly experts' performance tended to be underestimated by the model as was indicated by negative residuals ($M = -.264$; $SD = .721$), while residuals for elderly amateurs were always positive ($M = .378$), due to the fact that these subjects performed worse than was predicted. Residuals for the two young groups were negative, but very close to zero. When the fit for the three groups was compared using absolute values for residuals as a measure, a significant age-group by task interaction emerged, $F(2,88) = 5.82$; $MSe = 1.17$; $p < .005$, due to the fact that Model III provided a reliably worse fit for elderly ($M = .984$; $SD = .646$) compared to young subjects ($M = .447$; $SD = .483$) in the right-hand tapping task, $t(46) = 3.26$; $p < .005$. No age-effects for model fit emerged in the other two conditions. Presumably, specific factors which were not captured by the practice variables were relevant in the right-hand condition in elderly subjects. Given the opposite direction of divergence from predicted performance in the two skill-groups, the nature of these effects remains unclear, however.

The consistency of divergence from predicted performance was also very high for the three conditions of Experiment 1. *Cronbach's alpha* was .888 for the total sample, .805 for experts, .905 for amateurs, .812 for young, and .895 for elderly subjects. Reliability at the level of single groups was above .740 for single groups. Analysis of the standardized residuals across conditions revealed a significant age-group by skill-level interaction, $F(1,44) = 14.69$; $MSe = 22.3$; $p < .001$. No higher order interactions were significant. Inspection of group means provided a straightforward picture; performance in elderly amateurs was clearly overestimated—that is, worse than predicted—as was indicated by positive residuals in all three conditions ($M = .857$; $SD = 1.03$). Young experts' residuals were very close to zero, while elderly experts and young amateurs actually performed better than predicted by the model. No signifcant differences emerged between these three groups ($M = -.286$, $SD = .579$); however, all three group means were reliably different from that for the elderly amateurs, $t(22) > 2.87$; $p < .01$. The differential fit provided by Model III with respect to single groups was illustrated in the analysis of absolute values for standardized residuals. The fit was best for young experts, very similar for elderly experts and young amateurs, and worst for elderly amateurs. Effects of age-group and skill level both failed the adjusted alpha level criterion only by a slight margin. Model predictions tended to be better for experts than for amateurs, and also better for young compared to elderly subjects.

Subjects showed a very similar ordering across conditions in Experiment 2 with respect to their deviation from predicted performance. *Cronbach's alpha* was .914 for the total sample, .828 for experts, .930 for amateurs, .719 for young, and .939 for elderly subjects. Reliability at the level of single groups was above .620 for single groups. With respect to systematic over- or underestimating of performance in the four groups, the same pattern as in Experiment 1 emerged. Elderly amateurs performed worse than predicted, as was indicated by positive residuals in all three conditions ($M = .795$; $SD = 1.249$) and a significant interaction between age-group and skill level, $F(1,44) = 12.45$; $MSe = 21.5$; $p < .005$. No higher order interactions were significant. Performance was underestimated in the three other groups, with mean residuals being close to zero in the young expert group and more strongly negative for the young amateurs. Young and elderly experts did not differ reliably on this measure ($M = -.165$; $SD = .542$), while there were clear differences between young ($M = -.464$; $SD = .415$) and elderly ($M = -.795$; $SD = 1.249$) amateurs, $t(22) = 3.31$; $p < .005$. No effects significant at the adopted alpha level emerged from the analysis of absolute values for standardized residuals. Similar to Experiment 1, the fit was worst for elderly amateurs, similar for young amateurs and elderly experts, and best for young experts.

No evidence for systematic over- or underestimation of performance in the four groups emerged from the analysis of residuals for the consistency of force variation at the bar level in the musical performance task. However, overall model fit was better for experts ($M = .487$; $SD = .377$) than for amateurs ($M = .985$; $SD = .684$), as was indicated by the analyses of absolute values for the standardized residuals, $F(1,44) = 9.55$; $MSe = 2.97$; $p < .005$.

To investigate whether a marker of general cognitive-motor ability and age-related slowing could capitalize on the residual variance under consideration, correlations between residuals and digit-symbol substitution (DS) rate were computed.[19] No significant correlations were found for the three tapping tasks and the musical performance task, as could be expected from the above results. Residuals from the three conditions of Experiment 1 were negatively correlated to the DS measure; the correlation was

[19] Using choice reaction time as a correlate yielded similar results as for the DS, although the effects were less pronounced.

significant in the most complex condition, $r(46) = -.315; p < .05$. While the pattern was similar in Experiment 2, none of the correlations reached significance. This finding indicates that interindividual differences in performance which were not captured by practice measured can be accounted for in terms of general cognitive-motor capacity. Those subjects with a lower DS had a performance disadvantage relative to their expected performance based on amounts of training. When the same correlations were computed separately for amateur and expert groups, a more clear-cut picture emerged. None of the correlations from Experiments 1 and 2 was significant in the expert group; five out of six coefficients were positive, indicating that the DS would adjust predicted performance in the opposite direction of what would be assumed on the basis of any reasonable theory. The picture was different in the amateur group. All coefficients were negative; correlations were significant in the most complex condition of Experiment 1, $r(22) = -.669; p < .01$ and the two bimanual conditions of Experiment 2: mirror image, $r(46) = -.413; p < .05$, and different movements, $r(46) = -.417; p < .05$.

In sum, the model based on practice measures alone falls short of accounting for performance differences due to unspecific age-related slowing in the amateur group. These effects were not relevant in the expert group, where practice intensity appears to be a sufficient predictor for performance in both age-groups.

Summary: Accountability of Skilled Performance through Deliberate Practice

It was predicted that the practice variables would be effective in explaining additional variance in performance on skill-related tasks beyond the group factors (Prediction 13). Furthermore, it was predicted that measures of practice intensity would account equally well for performance differences in these tasks as the design variables (Prediction 14). The findings from the reported regression analyses provided support for Prediction 13 for the most complex conditions of speeded tasks—that is, finger tapping, complex movement coordination in Experiment 1 (transcription), and complex movement coordination based on performance from memory (Experiment 2). Practice measures accounted for additional variance within groups. The four practice variables were shown to account for considerable differences between skill-groups in all conditions; unique variance associated with the skill factor was reduced by more than 80 percent in all cases. Effects of skill level were completely accounted for by practice in the alternate tapping and the musical performance task; however, it is important to keep in mind that there was small but reliable variance left which was related to skill level and could not be accounted for by practice measures. Though not literally in its strong form, but from the logic of the argument, Prediction 14 was thus largely confirmed with respect to the skill factor.

The picture was more complex with respect to differences in performance between age-groups. In three out of six conditions in Experiment 1 and 2, age-effects were reduced to nonsignificance by the presence of practice variables. In the remaining cases, unique variance was considerably reduced. More important, however, age-effects remained in the amateur group after practice was controlled for, but were accounted for by differences in amounts of deliberate practice in the one condition where elderly experts performed worse than young experts. The analyses of residuals provided further evidence that differences in practice intensity could not account for age-effects in the amateur sample. Prediction 14 was not confirmed in this regard.

A closer inspection of correlations between task performance and the amounts of deliberate practice as reflected by the four variables (see Tables C16 to C19 in Appendix C) suggests that practice over the last ten years is most critical in accounting for interindividual differences in the elderly expert group. Five out of six correlations in the different conditions of Experiments 1 and 2 were significant in this group, while none of the other practice variables showed reliable correlations here. The correlational patterns in the young expert group were less pronounced and pointed to a higher relevance of practice during the first 20 years of life. These findings suggest that maintenance practice is indeed the most important fact in accounting for elderly expert performance, while accumulated practice during skill acquisition suffices to account for expert performance in young adults, as was already shown in the study by Ericsson, Krampe, and Tesch-Römer (1993).

The reported findings can be summarized as follows. A model based on amounts of practice during different phases of development provides the best predictions for the young expert group and fares worst when it comes to predicting performance in elderly amateurs. This is especially true for the complex movement coordination tasks in Experiments 1 and 2. The most prominent result is that performance in elderly amateurs is considerably worse than is predicted from the practice model. Elderly experts, on the other hand, actually perform slightly better than can be expected on the basis of practice measures alone. The latter argument also applies to young amateurs. The quality of the model with regard to both groups, however, was by and large within the same range as for the young experts. One possible explanation of differences in quality of predictions between the four groups could be that the reliability of practice estimates is higher in experts than in amateurs. This idea is not in line with the analysis of agreement between estimates for current practice intensity and diary data reported earlier, but might play a role when individuals have to look back on many years. Alternatively, practice in elderly experts might be more efficient than in younger experts so that the measures applied actually underestimate the amount of training that went into the maintenance of skills in this group. None of these accounts can sufficiently explain the pattern of results, however. Most likely, the practice model is more tuned to high levels of training than to skills exercised only on an infrequent basis, as this was true for the amateur sample. The findings in the amateur group could probably be equally well accounted for by a model of age-related slowing, given that the patterns were similar in the skill-related and the transfer tasks. This was clearly not the case for the expert group.

Discussion

The discussion section starts with a summary of the main findings and their interpretations regarding changes in skill-related activities during expertise development, the effects of skill level and age on cognitive-motor performance, and the role of deliberate practice in accounting for expert performance. Subsequently, alternative accounts in terms of talent concepts, preserved differences, and general age-related loss of resources are evaluated with respect to the presented findings. The discussion of alternative models is complemented by some considerations of conceptual problems inherent in the study of age and expertise. A brief discussion of potential limitations of this study is provided followed by the conclusions and future perspectives for related research. The chapter is brought to a close by some concluding remarks.

Summary of Main Findings

Changes in Skill-Related Activities during Expertise Development

The amount of practice involved in becoming an expert pianist is stunning. The average amount of practice already accumulated by young expert pianists in the course of professional training by far surpassed that which subjects in the elderly amateur group had accumulated throughout six decades of practicing with lesser intensity. Development of practice intensity turned out to be very similar for the two expert groups regarding the first two and a half decades of life. The accordance between young and elderly expert groups in this respect supports the validity of these estimates. The data in this study are in line with the original proposal by Simon and Chase (1973; see also Ericsson & Crutcher, 1990), who suggested that at least ten years and approximately 10,000 hours of intensive preparation are necessary in order to attain exceptional levels of performance. The results of this study clearly replicate earlier findings by Ericsson, Krampe, and Tesch-Römer (1993) with respect to the developmental trajectories toward adult expertise.

Analyses of measures for past and current practice intensity indicated that elderly expert pianists decreased their amount of active practice at the piano after the end of formal training. The level of training maintained, however, is still clearly above that which most amateurs ever attained for longer periods. The total amount of music-related activities was equally high in both expert groups and did not change with age. During later phases of adulthood, experts' time is mostly taken up by giving lessons. At the same time, elderly experts spend more time on health and body care compared to their younger counterparts. In this regard the elderly pianist group behaves very much like the control subjects of the same age.

Little change in practice intensity across the life span was found in the amateur group. This was partly due to the lack of systematic variation across individuals. While there may have been ups and downs in the intensity of practice for each individual, the overall level of training was clearly far below the expert level at any point in development. Elderly amateurs were similar to their young counterparts with respect to current practice intensity and involvement in other musical activities.

Effects of Skill on Cognitive-Motor Performance

Three levels of inquiry were suggested from the review of the literature and existing concepts of skill in playing the piano: peripheral motor factors, efficiency in coordinating complex movements, and the ability to intentionally vary aspects of expressive performance. Expert pianists showed superior performance compared to the amateur group with respect to all three aspects. The outcome was different for general markers of cognitive-motor speed: The digit-symbol substitution test and the two-choice-reaction time experiment as far transfer tasks did not reveal differences between skill-groups. This pattern of findings supports the assumption of skill-specific mechanisms underlying expert performance in those measures hypothesized to reflect skill in playing the piano.

The finding that expert pianists achieved a higher speed of repetitive finger tapping replicates and extends the earlier finding reported by Telford and Spangler (1935). Contrary to their results, however, the presented data support the notion of higher skill advantages in tasks of increasing coordination complexity. The interaction between skill level and coordination complexity emerged even at the level of simple finger tapping. Expert pianists had an additional performance advantage when the task required alternation between forefingers. Alternate tapping may be considered the simplest form of bimanual movement coordination. The magnitude of differences between skill levels was illustrated by the finding that the left index finger tapping rate of expert pianists was reliably faster than the right index finger tapping rate of amateurs while the differences between hands were significant within groups.

The pattern of results in Experiments 1 and 2 shows that the ability to coordinate multiple finger movements between opposite hands is strongly correlated with skill as a pianist and thus provides a valid reflection of expertise. The experimental control of motor difficulty across sequences permits the conclusion that the difficulty of coordinating movements between opposite hands accounts for the decrease in speed found in all four groups in the more complex conditions. Experts outperformed amateurs at all levels of complexity. The speed of performance of expert pianists was less affected by increasing coordination complexity, indicating that professional pianists could compensate for the performance constraints resulting from interference between opposite hands to a far larger degree than amateurs. Superior coordination ability constitutes an extra skill advantage in addition to the higher efficiency of peripheral motor components observed in the tapping tasks. The term coordinative skills refers to overlapping subsequent movements by advance preparation, as was illustrated by the single-hand tasks, as well as to the coordination between opposite hands required by the two bimanual conditions.

Experiment 2 illustrated clear skill advantages in terms of the superior ability of expert pianists to memorize movement sequences and later play them from memory. The performance from memory measured in Experiment 2 can be considered the ecologically more valid task with respect to pianists' skills. It was argued in the theory section that pianists more often play from memory rather than from a score, especially when it comes to working toward the fluent performance of difficult passages. Subjects' ratings regarding the relevance of tasks with respect to playing the piano validated this assumption.

The musical performance task revealed that expert pianists were more consistent across repeated performances of the same piece. This finding speaks for more elaborated motor programs controlling the translation of musical ideas into movements. While these results are in line with Shaffer's earlier research (1981), this data add a systematic comparison between expert and amateur pianists in those regards which has not so far been available in the literature. The ability to intentionally control the variation of movement parameters has a high face validity for playing the piano. In the context of this consideration the differences between skill-groups may appear quite small. Analyses of correlations between single bars showed that the measures used were highly reliable excluding measurement errors as a plausible account. One reason for the small effect size is probably the simplicity of the piece in musical terms. The prelude turned out to be neither technically nor musically challenging enough to have previously attracted the attention of the professional musicians in the study. It is important to keep in mind that the piece was selected to permit comparisons between experts and amateur level performers and facilitate computer analysis of recordings. Most likely, intensive practice at details of the piece would have increased the differences between skill levels. Little research has been done so far on isolating the empirical correlate for the communication of musical ideas in piano performance. Larger units, like phrases including more than one bar, appear to be critical in communicating a given interpretation, as Shaffer (1980) pointed out. He was successful in demonstrating that the covariance between repeated performances increases with the size of the musical unit taken into account. The presented analysis of concordance at the level of bars is just a first approach which can certainly be improved if higher level units, like musical phrases, are considered.

Age-Related Changes in Cognitive-Motor Performance

The two markers of general cognitive-motor functioning, the digit-symbol substitution test and the two-choice-reaction time task, revealed clear evidence for an age-related decline in speed. These results are in line with numerous findings from the cognitive aging literature (Salthouse, 1985a, 1985b). The presence of reliable age differences in these tasks implies that expert pianists undergo the same age-related change in these functions as normal adults. This pattern of results was predicted from a skill perspective, given that these tasks were assumed to have little if any relevance to the skill.

Remarkable savings in terms of skill were evident from the analysis of peripheral motor components (finger-tapping speed). This result is somewhat surprising, given numerous findings from the literature which point to age-related declines in these measures. One could argue that age differences become more pronounced in the sixth decade of life, and subjects in the study presented here were a little too young to show age-related decline. Skill differences increased with complexity, and alternate tapping was about as skill-sensitive as the far more complex bimanual movement tasks. This was also true for the correlation between practice variables and performance. These findings suggest that the transfer between practicing the piano and single-finger tapping is limited, given that repetitive finger tapping may not be what pianists practice as such. This argument amounts to the assumption that a certain speed of repetitive tapping is sufficient at most levels of skill, while the real technical challenges amount to multiple-finger coordination. This was also implied by the much lower values for the tapping tasks in the rated relevance for the skill. Several subjects mentioned that they would have preferred to have given separate evaluations for single and alternate tapping tasks, given that the latter task was more relevant. A plausible explanation for the reported findings would be that the elderly amateurs were still sufficiently trained in order to compensate for the small age-related declines found in normal subjects.

No differences between age-groups were found for the number of trials necessary to attain the prescribed memorization criterion in Experiment 2. This is plausible, given that subjects were allowed to do the task at their own speed, and accuracy was the only requirement. The critical factor in this task was probably the knowledge brought to bear on the movement sequences in order to encode them into meaningful and memorable patterns.

There was clear evidence for age-related performance decline in elderly amateurs compared to their younger counterparts in Experiments 1 and 2. The only exception was the single-hand condition of the memorization experiment. The magnitude of age-effects increased with complexity and was pronounced in the most difficult conditions of both experiments, as predicted. It is worth noting that the use of log-transformed latencies confers this age by complexity interaction against accounts based on a proportional age-related slowing of processes. The presumably higher mental effort involved in coordinating movements between opposite hands worked against elderly amateur subjects, with motor requirements being compatible across complexity conditions. Age-sensitive performance declines in the ability to coordinate bimanual movements were also reported by Stelmach, Amrhein, and Goggin (1988) using a different paradigm. Note, however, that their task was related to lateral movements of varying distance and did not address aspects of general slowing.

Elderly experts differed from their young counterparts only in the most complex condition of Experiment 1 (transcription). This finding was not obtained in the second experiment (performance from memory). Based on the theoretical discussion of skill components and subjects' task evaluation, Experiment 2 may be considered the more natural task, as was mentioned above. The stimulus presentation format (number strings instead of notes) was also chosen in order to prevent a bias against amateurs, as it was supposed that they would not be as skilled in reading music. It is plausible to assume that the unusual format might have worked against the elderly experts to some degree in the first experiment. This group would most likely have the most experience in reading music and thus have greater problems coping with the experimental situation. The memorization procedure in the second experiment forced subjects to leave the unfamiliar display in the first place and to rely more heavily on their encoding and memorization skills. Ultimately, this may have led to the relatively better performance of elderly experts in Experiment 2.

Measures of consistency between repeated interpretations of the same piece showed skill advantages. No differences between age-groups were found for this measure. The latter finding was predicted and is plausible, given that the task does not require speeded performance and should also heavily rely on knowledge brought to bear in interpreting the piece.

The Role of Deliberate Practice in Accounting for Expert Performance

The regression analyses revealed that most of the performance differences between skill-groups could be accounted for by differences in amounts of deliberate practice. Small but reliable amounts of variance associated with the skill and the age factor remained after controlling for interindividual differences in practice intensity in several tasks or task conditions. Practice measures accounted for interindividual differences in performance beyond the group main effects. While a model solely based on the amounts of practice during different phases provided a reasonable account of performance in young subjects and elderly experts, it was clearly insufficient to explain age-related performance changes in the amateur group. The main finding with respect to skill maintenance was that high-level skills, once acquired, must be maintained through deliberate practice. The amount of maintenance practice is more critical in determining performance in late adulthood than practice during the acquisition phase. In that regard, the presented findings convey a different message than earlier research on skill maintenance (e.g., Bahrick, 1984; Bahrick & Hall, 1991).

To summarize, four different accounts of elderly skilled performance were outlined at the end of the theory section. The presented findings are not compatible with the first account—namely, that general cognitive-motor dispositions are responsible for high-level skills in young and elderly experts. Both related measures (digit-symbol substitution and choice reaction time) showed a different pattern of age-related effects from the one obtained with skill-related tasks. The second account—namely, that a skill once acquired can be easily maintained—is also at odds with the findings presented here. While elderly experts had considerably decreased their amounts of deliberate practice, interindividual differences in performance were related to the amount of maintenance practice. The results of this study support the third account—namely, that elderly experts selectively maintain those skills relevant to their profession through deliberate practice efforts. The specific amount of maintenance training and, consequentially, the level of skill maintained is probably determined by the specific professional requirements and aspirations for each individual. In the context of the proposed framework, these findings can be interpreted as evidence for continued adaptation to the constraints of expertise development in later adulthood. With respect to compensatory mechanisms, as implied by the fourth account, the findings are inconclusive. No age effects emerged in the simple tapping tasks which could have been related to performance in more complex tasks. The finding that elderly experts performed worse than young experts in Experiment 1 but not in Experiment 2 suggests that performance from memory was more tuned to specific skills and mechanisms in the elderly professionals. Any interpretation of this pattern in terms of compensation, however, must remain tentative.

Alternative Accounts

Talent Concepts

The presented findings with respect to the effects of practice on performance can hardly be reconciled with the talent perspective; more specifically, they just do not follow from related assumptions. Talent conceptions derive much of their appeal from the presumed parsimony of the argument. The implied parsimony, however, is more at the level of psychometric constructs than at the level of specific genetic mechanisms which could provide proper causal explanations. A frequent alternative account of findings relating performance level and practice intensity is that the more talented individuals receive more encouragement and thus practice more than less skilled individuals. One is tempted to ask why reinforcement by other people should encourage practice, given that the talent ideology supports the notion of practice as a compensation for lack of talent. The practice variables constitute the same kind of correlational evidence for which intelligence research has often been criticized (Howe, 1988a, 1988b). Intelligence research was successful in providing methodological tools that permit a measure of underlying capacity to be derived. Talent research has not yet provided anything remotely similar in this regard, and original proposals for respective tests have failed rather pathetically, especially in the domain of musical skill. Contrary to the notion of talent or intelligence, however, the proposed framework presumes that specific skills and mechanisms are trained and developed in the course of practice. The correlational nature of the evidence presented here can be supplemented by a large body of research demonstrating the effectiveness of learning mechanisms. No similar process correlate has been demonstrated for talent. The controversy between general factor models and learning theories is often misconstrued as the competition between physiological and mental accounts. The proposed framework gains part of its appeal by having incorporated the long-term adaptation to multiple domain-specific constraints into the skill acquisition approach. The claim that accumulated practice results in dramatic changes in performance is totally in line with assuming a physiological processing basis. Research in sports impressively demonstrated the concordance between long-term adaptation and physiological perspectives: Physiological changes which are relevant to the skill are a result of long-term practice.

The central question regarding a talent perspective remains: What is talent, or what might it be? The presented data do not support the notion of a general cognitive-motor disposition accounting for skilled performance. Even if one does not accept the two control measures employed (i.e., the digit-symbol substitution test and the two-choice-reaction time task) as reasonable indicators of talent or general cognitive-motor ability, it was clear that experts were only superior to amateurs with respect to a set of functions which were specified from a theoretical analysis of the skill. Any talent concept would have to be more specific in nature, such as a talent to acquire skills in playing the piano. There is no convincing evidence in the literature supporting the idea of such a specific disposition.

A different perspective suggests that talent facilitates the acquisition of skills through practice and is critical in determining individual differences at the extreme end of the performance distribution. This view is at odds with research in behavioral genetics (Coon & Carey, 1989), which has shown that innate factors seem to play a larger role in less skilled individuals. The findings of this study also argue against this version of the talent view. The relation between practice intensity and performance is, if anything, stronger in expert subjects compared to amateurs, as was shown from the analysis of regression residuals. Similar to findings reported by Ackerman (1988) and Coon and Carey (1989), the presented findings suggest that general dispositions or age-related changes can account for interindividual differences in little skilled performance; however, related models miss the most important influences when it comes to the acquisition and maintenance of high-level skills.

This study, along with earlier work by Ericsson, Krampe, and Tesch-Römer (1993), does not permit genetic explanations for the acquisition of high-level skills to be directly rejected. However, it provides data and an alternative model which have no match in the talent tradition so far.

Differential Preservation versus Preserved Differences

The preserved differences account (Salthouse et al., 1990) suggests that superior performance in elderly experts compared to age-matched controls reflects differences in stable dispositions which already existed at a younger age. The preserved differences perspective does not explicitly cite innate dispositions as a theoretical explanation of interindividual differences, but it is clear in denying the role of experiential factors in maintaining cognitive functions throughout adulthood. The absence of reliable differences between experts and amateurs in both age-groups for digit-symbol substitution rate and choice-reaction time in the presence of clear differences in all skill-related tasks does not support that notion. In the context of this research, the preserved differences view amounts to the claim that the elderly expert group, at young ages, was far superior to the young experts. The biographical data available for the young experts make this claim little plausible. In addition to this, the developmental trajectories with respect to practice intensity were very similar for both groups. (This is of course a moot point if one does not believe in the relation between practice and later performance level.)

Age-Related Loss in General Resources

The pattern of findings in skill-related and far-transfer tasks was similar in the amateur group and resembles what one would predict from the assumption of a general age-related reduction in processing capacity (Cerella, 1990; Myerson et al., 1990; Salthouse, 1985a). The findings in the expert group are not in line with related models, however. In principle, one would at least assume two different slowing functions to relate young and elderly performance in the amateur and the expert groups. The slope for the expert sample would not be significant, however. Note also that the ordinal interactions related to the task complexity manipulations in Experiments 1 and 2 were based on log-transformed data, which protects them against reduction to linear age-related slowing models. A further proof of specific age-related processing deficits in the elderly amateur group would require the application of the process-dissociation approach as it was demonstrated for age-comparisons by Kliegl, Mayr, and Krampe (1994) and Kliegl, Krampe, and Mayr (1993). While the presented data in principle fulfil the requirements for this method, the related analysis was beyond the scope of this study.

At a more general level Baltes and Baltes (1990) have proposed a framework incorporating positive aspects of aging along with negative age-related decline in the available mental, physiological, and social resources. There are several relevant implications for the development of high-level skills in late adulthood from these models. The framework presented by Ericsson, Krampe, and Tesch-Römer (1993) suggests that the acquisition of high-level skills involves the long-term adaptation to the demands, mental and physiological, of intensive practice. Vice versa, physiological and mental capacities are assumed to decrease when practice intensity is reduced. The slow build-up of relevant capacities requires a well-organized daily life and considerable social support. Professional pianists have to earn a living from their skill, and society provides only very scarce resources for pianists living on concert performances alone. None of the elderly expert pianists in this study lived only from performing. While the extreme popularity of the instrument and its musical literature attracts many students, the number of professional positions is limited. One important aspect in this regard is that the piano is a genuine solo instrument, so that there are no permanent positions for pianists in orchestras. The market requires extreme flexibility and social skills on the part of the pianist in arranging for public performances and managing his reputation. All of these activities are highly time- and energy-consuming. The social network in terms of performance occasions, competitions, and grants is well organized for young pianists during their formal training. This situation changes dramatically after the end of formal education. The profession of being a pianist clearly involves a considerable reduction in social support with age. There are some hints that a bias exists toward elderly individuals in the musical profession. Most music academies have maximum starting ages regardless of performance level. The prejudices are even more pronounced toward women. Female pianists in Germany are officially allowed to change their exact ages in their curricula vitae within a range of five years in order to compensate for these biases. The biographies of elderly experts clearly illustrate that at some point many individuals are faced with the choice of taking positions as professional teachers which allow them to earn a living and support a family on a more solid and predictive basis, or of remaining free-lance public performers. Many elderly pianists reduce their concert activities, making room for younger pianists who have more time to adapt to the constraints in terms of pay, travel, and repertoire. The stress involved in a public performance requires a level of physiological functioning which constitutes a special constraint on elderly experts not investigated in this study. Several accounts of pianists who have suffered from strokes during or after public concerts were reported by participants. At the same time, public concerts may constitute the greatest challenge and motivation for practice.

The data presented in this study do not support the claim of inevitable, global decline in performance due to biological changes in the aging brain. Elderly experts are well able to perform at levels comparable to their young counterparts. It is most likely that the decline in general resources and specific skills, which need to be maintained through active practice, go hand in hand. According to their own accounts, elderly experts felt that they had clearly improved the efficiency of their practice compared to the time when they were students. At the same time, available time for practice decreases due to other professional requirements and increased health and body care. Elderly expert pianists have the least amount of sleep and reliably less leisure time compared to the other groups. These two activities can be considered as providing recuperation from effortful practice activities. The interplay between these factors was nicely illustrated by an elderly expert pianist's comments when asked whether he saw chances to compensate for any age-related decline in his skills: "If I had the time and the energy to practice as much as I did when I was young, I would certainly play as well."

Conceptual Problems for the Study of Aging and Expertise

The discussion of age-comparative studies and the comparison between developmental and cognitive models of skill in the theory section has contrasted the acquisition of specific mechanisms with interindividual differences in general dispositions. Many theorists in research on aging acknowledge that the effects of training by far surpass the effects of "normal aging." At the same time, a considerable number of developmental researchers concerned with aging tend to account for interindividual differences in achievement at older ages with reference to stable, more global factors. In those respects aging research continues along the lines of intelligence and personality research. The more recent attempts to relate young and elderly performance in speeded tasks by mathematical models with few parameters impress by their parsimony; at the same time these models offer little theoretical appeal. After all, they do not have to offer any explanation for the observed phenomena other than that there appears to be a regularity. Delegating the job of explaining complex phenomena to biology and neurophysiology has a highly disputed tradition in psychology. Parsimony must not conceal the fact that the correspondence between neural events and performance needs to be explained in detail. This point of view does not in any sense debate the neural basis of psychological processes. More recent studies have shown that the developmental changes are clearly not as uniform as was implied by several proponents of the general slowing approach. However, the general slowing models constitute a challenge to experimental psychologists in the sense that age-by-task complexity interactions should be conferred against single-factor slowing accounts.

The contrast between "developmental theories" and models of skill acqusition proposed in the theory section served illustrative purposes and does not do justice to many approaches in both fields. A similar modification of arguments is in place with respect to the presumed overall decline of functions with age. Throughout the discussion of findings from age-comparative studies, the term "developmental theories" was largely associated with stable intellectual dispositions and decline. It needs to be pointed out that modifiability and learning gains play an important role in certain models of life-span development (Baltes, 1987; Baltes & Baltes, 1990). Extensive training studies have demonstrated that subjects of various ages can dramatically improve their performance in different intelligence tests (c.f. Baltes, Dittmann-Kohli, & Kliegl, 1986; Baltes, Kliegl, & Dittmann-Kohli, 1988; Schaie & Willis, 1986). In these studies, the focus of investigation was on identifying certain components and mechanisms underlying intellectual functioning in specific domains and their sensitivity to aging and training. The findings clearly indicated that intelligence must be considered as a multidimensional construct with a limited transfer of training gains between different components. Baltes, Kliegl, and Dittmann-Kohli (1986) suggested that elderly subjects can easily improve their test performance if they have sufficient opportunity for practice and can rely on strategies and mechanisms from their available repertoire. These approaches, although different in their theoretical and methodological orientation, share important similarities with models of skill acquisition and maintenance.

Limitations of this Study

Apparatus and Experimental Tasks

The piano used for the experiments was certainly no match for the instruments used in public concerts. Experts should have been more affected by the limitations of equipment than amateurs, given that their training was most likely carried out on better instruments, and the equipment used could impose constraints on the range of their skills. The likelihood that elderly subjects might have had experiences with similar instruments was also lower than for the young participants, given the recency of technical advances in this regard. Subjects' comments during the experiments indicated, however, that they felt quite comfortable with the device and enjoyed the experiments very much. All of the critique with respect to the instrument related to the sound, while the keyboard mechanics were considered quite acceptable. One important difference in the mechanics noticed by subjects was that a grand piano would not produce a sound before the key was depressed beyond a certain range. In this regard the equipment used was actually more sensitive to errors and slight inaccuracies, given that the slightest touch would trigger a computer recording. It needs to be pointed out that all experimental tasks were designed with regard to the limitations of the equipment.

A genuine question concerns the relevance of the experimental tasks with respect to the skill of playing the piano. The ratings given by participants indicated that subjects felt that the presumably skill-related tasks had a high relevance for playing the piano. While the three levels of investigation proposed from the theoretical decomposition might cover a considerable range of aspects, none of the levels is sufficiently general to provide a single valid scale of achievement. Furthermore, there are certainly additional aspects of the skill which are not covered by any of the measures included. The quality of a musical interpretation will probably depend on the individual knowledge and understanding of a certain composer's style and his emotional and cultural background. It could be argued that these aspects are highly subjective and escape controlled assessment. Irrespective of this, the presented study did not address these issues. The ability to communicate with an audience would most likely involve additional skills like expressive body movements, control of performance anxiety, and the ability to spontaneously adapt an actual performance to the specific characteristics of the instrument, the audience, and the concert location. It was also pointed out that social skills might play an important role in terms of managing ones career. The skill of making one's social life compatible with a career as a musician has rarely been addressed in the existing research.

Measures of Practice Intensity

The restricted definition of practice and the distinction between practice and other skill-related activities has proved useful in scrutinizing the development of skilled individuals. The measures of past and current practice intensity can certainly be improved in several regards, however. First of all, it would be desirable to have more than a single week of diary recordings taking variability at the individual level into account. The reconstruction of individual development in terms of past practice intensity constitutes a challenge to the accuracy of a subject's memory. Data from this research as well as from earlier studies on violinists (Ericsson, Krampe, & Tesch-Römer, 1993; Heizmann, Krampe, & Ericsson, 1993) speak for the validity of the measures derived from retrospective estimates. When it comes to comparing different age-groups and the generalizability across the life span, it seems desirable to have similar groups of middle-aged individuals (range 30 to 50) and adolescents in order to fill the gaps existing in the available evidence. Data from subjects who are older than the described sample would improve the scope of the model with respect to the development of a skill long after presumed retirement.

One underlying assumption implicit in this research was that the amount of time invested in practice reflects practice intensity (in fact, the terms intensity and amount have been used synonymously in different contexts). This strategy seems justified as a first approach, but it is certainly an oversimplification when it comes to precise estimates of effort and training. The question arises as to whether the amount of time spent on practice is a sufficient indicator to capture the relevant developmental changes. The research presented by Hagberg and his collaborators (described in Ericsson, 1990) illustrates the importance of the theoretical distinction between amount and intensity of practice. Young master athletes were found not only to spend more time on running, but also absolved a larger amount of practice in terms of average pace. Skill level and age differences might well be related to the intensity of practice in a similar way that these factors affect the sheer amount of training. The finding that performance was better predicted from practice for the experts than for the amateurs points in that direction. The effective duration of solo practice sessions or the need for recovery may change with age and/or skill level. Age-related changes could be positive or negative, or even in opposite directions depending on the level of skill. Most elderly experts pointed out during the interview part of the second session that they felt that they had improved the efficiency of their practice and would nowadays take less time to acquire a new piece compared to when they were students. An interesting aspect pointed out by participants in this regard was that learning at a younger age was dominated by the "motoric" mastery of a piece while his life-long experience was effective in providing the necessary knowledge for more effective learning. The first form of learning amounts to acquisition through mere repetition, whereas the advanced form is more based on an analytical approach. At a more general level it is likely that the relation between practice intensity and learning gain is not identical at all levels of age and/or accomplishment. Further research on these issues is certainly needed.

Conclusions

Expertise in playing the piano comprises higher efficiency of peripheral motor functions, superior abilities to memorize movement sequences, and higher speed and accuracy in rapid performance of complex finger movements. Superior movement control in professional pianists is most pronounced when it comes to the coordination of different movements in opposite hands. Expert pianists are able to intentionally control dynamic variations in musical performance to a larger degree than amateurs.

The reported performance advantages can be attributed to specific skilled mechanisms in the absence of differences in general markers of cognitive-motor intelligence between skill-groups. The pattern of age-effects in skill-related tasks is in contrast to the marked age-related slowing in general markers of cognitive-motor functioning which was similar in expert and amateur pianists. In line with earlier findings reported by Charness (1981a, 1981b), processes of little relevance to the skill showed marked age-related decline, while skill-relevant processes were preserved at high levels of functioning in elderly experts.

The acquisition of high levels of performance in real-life skills requires a continuous increase in practice intensity starting from an early age. Increasing professional requirements in terms of teaching are mainly responsible for a continuous decrease in the amount of active practice at the piano after the end of formal training. The finding that elderly experts had reliably less leisure time compared to the other groups can be interpreted as an attempt to free time for practice in addition to their multiple professional requirements and responsibilities. Elderly experts selectively maintain relevant skills through deliberate practice. A model solely based on amounts of deliberate practice is appropriate for the development of high-level skills in pianists until the seventh decade of life, but does not improve accountability for age-related changes in less skilled individuals. Compensatory mechanisms in elderly experts were implied by the outcomes but were not conclusively demonstrated in this study. The pattern of findings is compatible with a life-long adaptation to the constraints of skill development as it was proposed in an extension of the Ericsson, Krampe, and Tesch-Römer (1993) framework. The finding that practice is related to interindividual differences in the performance of skilled subjects while more general dispositions can account for unskilled performance is in line with training research (Ackerman, 1988) and findings from behavioral genetics (Coon & Carey, 1989).

Future Perspectives

The research presented here provides clear evidence for a shift in focus of activities occurring at an elderly age. In addition to reflecting shifts in general time constraints, it is plausible to assume that this development at least partly reflects changes in the motivational structure of elderly experts. The large number of well-trained pianists competing for public performance opportunities constitutes a certain pressure to find additional sources of income to earn a living. These sources mainly involve teaching. In the course of development, the focus of activities might continuously shift from working at one's own performance toward teaching. In a recent study Heizmann, Krampe, and Ericsson (1993) collected retrospective estimates of deliberate practice activities from middle-aged professional violinists from two orchestras with international reputation provided in the same manner as in the presented research. In line with the reported findings on professional pianists, a decrease of amounts of deliberate practice after the mid-20s was observed in their sample. Violinists in the Heizmann et al. study started to decrease solitary practice after they had attained their first permanent appointment with an orchestra. Presumably, related professional requirements and a motivational shift from soloist aspirations to less prestiguous, but occupationally safe, opportunities as an orchestra member determined the change in professional activities. In the same study, Heizmann et al. compared biographical data from world-famous violinists and pianists to those from the middle-aged professional violinists and elderly expert pianists in this study. Interestingly, world-famous soloists had started practice even earlier than the professionals in our studies. This and related findings provide a starting point for an extension of the Ericsson, Krampe, and Tesch-Römer (1993) framework toward eminent performance. More recently, Krampe and Ericsson (1994) have described a life-span approach to the development of musical skills incorporating the findings from the studies mentioned here.

The focus of the research presented here was on developmental changes in practice intensity and its effects on performance. While the decomposition of skill has clearly provided a number of skill-sensitive components, the exact nature of underlying mechanisms awaits further investigation. A number of relevant questions can be addressed with the available data. As an example, verbal protocols collected on subjects' attempts to recall the movement sequences from the memorization experiment, and not reported in this thesis, provide evidence for the nature of integrated representations formed by expert subjects during rehearsal. These data could provide a first step toward scrutinizing the coding mechanisms supporting complex performance in skilled musicians.

Two important features of human movement coordination which are central to playing the piano have been investigated more extensively in unskilled subjects and were not included in this study. The first feature is the timing and accuracy of lateral, bimanual movements (Kelso, Southard, & Goodman, 1979). Speed and accuracy of lateral movements are severely affected when goals of varying sizes or at diverging distances have to be reached simultaneously with opposite hands. The difficulty of coordinating these tasks has been found to be pronounced in elderly subjects (Stelmach, Amrhein, & Goggin, 1988). The second feature relates to the independent timing of movements in opposite hands (Klapp, 1979; Shaffer, 1981; Summers, et al., 1993). This latter facet of skill emerges when pianists play polyrhythms (e.g., 3 against 4). In a recent study Krampe, Kliegl, and Mayr (1993) were able to relate past amounts of deliberate practice to performance in bimanual rhythm generation tasks. Future studies of specific aspects of skilled performance in pianists can provide deeper insights into the mechanisms enabling expert pianists to surpass the processing limitations found in unskilled subjects.

Concluding Remarks

This research has provided insights into the role of practice in acquiring and maintaining high levels of real-life skill. Taken together with results from earlier studies (Ericsson, Krampe, & Tesch-Römer, 1993), this research supports the notion of continuous adaptation to the demands of skill acquisition proposed by the framework. The precise nature of the relation between practice intensity and performance over the life course still needs to be determined. The effects of training intensity on interindividual differences in proficiency remain high even at an elderly age. In none of the skill-related tasks was the predictive power of age differences higher than that of past and current practice intensity. The rejection of disuse accounts with reference to the higher level of experience in elderly experts needs to be refined in the light of the present findings. On the other hand, it would certainly not be appropriate to say that past and current practice intensity was demonstrated to account for all differences between age and skill levels. Expert subjects undergo dramatic developmental changes with respect to the structure and intensity of skill-related activities. The question emerging from this study is how experts can maintain their level of skill despite the decline in practice?

The study presented here has provided several pieces of evidence relating to ways in which practice is effective in compensating for normal age-related decline in highly skilled subjects, at least up to the seventh decade of life. The relation between age, practice, and skill will eventually turn out to be much more complex than was proposed here. The question as to whether age-related decline is inevitable or can be completely compensated for will remain a highly disputed issue. This study cannot resolve this debate, nor was it designed for that purpose. The data presented in this thesis suggest that age-related declines in elderly experts might have been stronger if individuals had not been sufficiently motivated to accommodate to age-related changes. Practice might be the most important activity in this regard. Nobody has as yet demonstrated that negative changes at all ages can be compensated for by practice, nor has the opposite been sufficiently proven. It is this author's strong belief that those two questions are not the most important ones when it comes to the study of skill development in adulthood. The research presented here, like several studies before, has demonstrated the impressive achievements which elderly individuals are capable of. In addition to this it has provided clear evidence for the large amounts of time and effort involved in becoming an expert performer and maintaining one's skills. The most important factors, like time invested in acquiring and maintaining a skill, are under individual control and must be negotiated with respect to other life goals. After all, the question emerges as to why it would be desirable for an individual to maintain the same level of skill throughout his life. High qualities as a teacher of exceptional students are presumably based on experiences as a peak performer; at the same time, being an exceptional teacher probably does not require maintaining one's best level of performance throughout the life course. Future research should be directed at a better understanding of the motivational aspects which make people undertake the life-long endeavor of expertise and at the nature and stability of cognitive mechanisms supporting admirable performances at various ages.

Appendix A
Interview Procedures and Diary Instructions

Biographical Interview

(Begin of the first session)

Introduction
(Description of the institute and the purpose of the study, short-form of personal questionnaire about age, profession, health, education)

Biographical Information (Self-Report)
I would like to start out by asking you to tell about your personal biography. Please start from the time you consider your first contact with music, and concentrate on events which were related to playing the piano. There is no need to go into details at this point because I will ask about specific events later on. For now, it is important that you take about 10–15 minutes time and briefly touch upon those events you consider important.

— *Subject's report* —

Life Span Schema
I would now like to get a more detailed idea about the time when specific events in your development occurred. In order to do so, I will ask you to help me complete a form similar to a tabular curriculum vitae. I will focus on some events only, and ask you several questions with respect to those.

— *Experimenter produces life-span sheet* —

This form includes historical years and slots for your respective age. My questions are directed toward points and periods in time. It is most important that you try to recall as precisely as possible. Please mention if you feel uncertain about any of your memories. You already talked about some of the questions at the beginning. However, at this point we would like to have more detailed information about the time and duration of specific events.

PROFESSIONALS:
Do you recall when you started your studies at the music academy?
When?
(When was that, approximately?)

AMATEURS:
Do you recall, when you started training in your profession?
When?
(When was that, approximately?)

BOTH:
Did you ever participate in any competitions as a pianist?
Do you remember when you participated for the first time?
(When? When, approximately?)
Did you participate in further competitions?
Do you recall when you started practicing the piano?
(When? When approximately?)
Do you recall when you received your first instruction on the piano?
(When? When, approximately?)
Did your instructor change since then?
Do you remember when that was?
(When, approximately?)
Do you currently receive regular instruction?
When did you receive your last regular instruction?

PROFESSIONALS:
Can you remember when you decided to pursue music as a professional career?
(When, approximately?)
Do you recall events which were connected to that?
(Young: Did you already have a long-term—more than 6 months—appointment as a pianist?)
Do you recall when you got your first long-term appointment as a pianist?
When was that? (When, approximately?)

AMATEURS:
Can you remember when you decided to pursue X (participant's occupation) as a professional career?
(When, approximately?)
Do you recall events which were connected to that?
(Young: Did you already have a long-term—more than 6 months—appointment as an X [participant's occupation]?)
Do you recall when you got your first long-term appointment as an X (participant's occupation)?
When was that? (When, approximately?)

— Events and dates included on form sheet by the experimenter for each question —

Retrospective Estimates for Past Amounts of Practice Alone

Please try now to recall as accurately as possible how much time you spent on practicing the piano during an average week. Please restrict yourself to the hours you spent practicing on your own. Please include only the time you consider practice in the sense of activities directed at improving your skills; do not include merely playing for fun. Please start from the time you consider the beginning of serious practice and try to describe the phases and periods your estimates refer to. I will then include your estimates in the form sheet. I would also like to know how you derive your estimates—that is, whether they are based on daily, weekly, or whatever amounts. There is no need for you to do complex mental calculations; I will do that for you.

— Experimenter and subject complete estimates —

Figure A1
Example Form Sheet for the Retrospective Estimates of Practice

Year	Age	Life Event	Estimated Practice
1941	5	Start Practice, School	1 to 5 Hours × 7
1942	6		
1943	7		
1944	8		3 Hours × 7
1945	9	First Major Public Concert	4 Hours × 7
1946	10		
1947	11		
1948	12		4 to 6 Hours × 7
1949	13		
1950	14		
1951	15	End of Instruction Father	
1952	16	End School, Academy Prep	
1953	17	Start Academy	6 to 8 Hours × 7
1954	18		
1955	19	Participation Chopin Contest	
1956	20		
1957	21	Graduation from Academy	
1958	22		
1959	23		
1960	24		
1961	25	Birth of First Child	
1962	26		6 Hours × 7
1963	27		

Note. This form sheet was edited for illustration. Note that the original version ranged from ages 1 to 30.

Instructions and Training for Diary Procedure

(Following Experiment 1 at the end of first session)

Now I would like to go into more detail with respect to specific activities in your daily life. From earlier interviews, we have generated two lists of activities. The first one includes activities directly related to music, the second list consists of everyday activities probably relevant to most peoples' daily lives. I would now like to ask you to go through the lists and tell me whether you can make sense of the specific labels. I would also like to know whether you would add activities which are not included here but are important to your daily life.

— Participant reads through list; experimenter clarifies, if necessary —

I would now like to ask you about what you did yesterday. If there were activities which you do not want to tell about for personal reasons, just say that you did private things. Please try to remember the time and duration of activities as precisely as possible.

In order to help you to remember, I would ask you to use this form sheet, dividing the 24 hours of the day into 15-minute intervals.

— Experimenter produces diary sheet —

If you already slept at midnight, please start with the time you got up. Please try to distinguish the time you went to bed from the time you remember falling asleep, if you remember. The same distinction applies to waking up versus staying in bed and reading before getting up. Some events may comprise more than one activity, for example going to dinner and having a conversation with a friend. Please mention both activities in that case, and mark the prominent one with (A). We are mainly interested in activities. Please try to report whatever you can remember and fill in the respective activities in the relevant slots.

Do you have any questions about that?

— Subject completes form —

Now I want you to go through your records and try to classify each activity using the 22 categories from the lists. Please categorize main as well as sideline activities, if necessary. One remark concerning travel time: Necessary travel should be added to the activity constituting the purpose of travel. (If you go somewhere to do sports, the way to or from the respective place would be counted as "sports.") Travel related to musical activities, however, should be coded as "organizational" related to music—that is, category 12. If you encounter difficulties in trying to code a given activity, please explain your problem.

— Subject encodes activities —

Now I would like to invite you to participate in the diary part of our project. We would like you to keep a detailed diary for the next seven days. It is important that you keep this diary regularly and write down your daily activities the same evening. I will give you five addressed envelopes, which you may use to mail your daily diaries to us the following day. Please remember to bring the last two forms with you on the day of our next meeting because the mail might take too long otherwise.

Please remember the distinction between going to bed and falling asleep, which we discussed, and try to note both times, if possible. Please proceed as you did with the form sheet and describe the previous day's activities. I will give you another form summarizing these details. In addition to that, you will receive an envelope which you should open after having filled out the last form sheet. Please plan for around 30 Minutes to complete the task described in the included text. Please go through the list of instructions now and tell me if you have further questions.

Figure A2
Example Diary Form Sheet

Hours	Minutes	Type of Activity	
3 p.m.	00–15	Snack	17
	15–30		
	30–45	Afternoon Nap	18
	45–00		
4 p.m.	00–15		
	15–30		
	30–45	Drive to Concert Location	12
	45–00		
5 p.m.	00–15		
	15–30		
	30–45		
	45–00	Practice for Warming Up	1
6 p.m.	00–15		
	15–30		
	30–45		
	45–00	Dressing for Concert	12
7 p.m.	00–15		
	15–30		
	30–45		
	45–00		
8 p.m.	00–15	Concert Performance (Solo)	7
	15–30		
	30–45		
	45–00		

Note. This form sheet covers only the second half of the day. The second form sheet was identical to the one illustrated, except for the time-slot labels.

Debriefing for Diary Procedure

(Beginning of second session)

First, I would like to ask how you got along with doing the diary during the last seven days:

Did you encounter any problems in categorizing your activities?

_______ Yes _______ No (clarify)

How did you find keeping the diary in general? Did you feel it was disturbing or unnerving in any way?

_______ Yes _______ No

If yes, why?

____

Did you learn anything new when doing the diary?

_______ Yes _______ No

If yes, what exactly?

____

How would you describe last week? Was it typical or untypical?

_______ Typical _______ Untypical

— *Warm-up phase for musical interpretation task (Bach prelude) follows* —

Table A1
List of Musical Activities from the Diary Procedure

Code Number	Activity	Examples
1	Practice (Solo)	
2	Practice (with Others)	
3	Playing for Fun (Solo)	
4	Playing for Fun (with Others)	
5	Taking Lessons	
6	Giving Lessons	
7	Solo Performance	Including Recording Sessions
8	Performance with Orchestra/Group	
9	Listening to Music	
10	Activities Concerning Music Theory	Specialized Literature, Music Theory
11	Professional Conversation	
12	Organization and Preparation	Travel Time, Reserving Rooms for Practice, Organizing Performances, Maintaining Instruments

Table A2
List of Other Everyday Activities from the Diary Procedure

Code Number	Activity	Examples
13	Household Activities	Preparing Meals, Dishwashing, Housecleaning, Repairs, Washing
14	Childcare	Feeding, Washing, Changing Diapers, Reading Stories, Playing, School, Visits to Doctor, Kindergarten
15	Shopping	Daily Shopping, Shopping for Clothes and Furniture, Visits to Bank and Post Office, and Other Services
16	Work (Not Music Related)	Jobs, Searching for Employment
17	Body care and Health	Washing, Dressing, Eating, Visits to Doctor, Therapy, Medical Treatment
18	Sleeping	Night Sleep, After-Dinner Nap, Short Naps
19	Education (Not Music Related)	Seminars, Courses (e.g., Adult Education) Homework Assignments
20	Committee Work	Church, Political Parties, Unions, Citizens' Action Committees
21	Leisure	Movies, Theater, Talks, Reading, Hobbies, Friends, Parties, TV, Radio, Bars
22	Sports	Organized Sports, Jogging, Aerobics, Gymnastics, Swimming

Relevance Ratings for Experimental Tasks

(Following end of Experiment 2 in second session)

I would now like to know how relevant you consider the performance aspects involved in the different tasks related to playing the piano. For that purpose, I will ask you to use a 10-point scale. A "1" implies that the task has very little in common with playing the piano, a "10" means that it is very relevant to playing the piano. Please consider briefly which abilities may be challenged by a certain task and evaluate their relation to playing the piano when marking a respective number. We have used labels and short descriptions for each task. If you have problems remembering the details of a certain task, I will be happy to describe it further to you.

— *Experimenter presents rating form sheet* —

Active Performance Repertoire

(Following relevance ratings for experimental tasks in session two)

Present Repertoire
Now I would like to ask you some questions about your performance repertoire. In order to do so, we have come up with a limiting definition of the term. We would like to refer to all pieces which you would feel comfortable presenting in a concert or to an audience of unknown people. It does not matter in this context whether you play from a score or from memory. Please consider only solo pieces.

In order to illustrate what I have in mind, I would like to suggest a thought-experiment. Please imagine that you receive an offer for a recital which will take place the next day. You should select pieces which you could perform right away, but it is up to you whether you play from a score or from memory. There would be time to play through each piece once prior to performance but no occasion for specific practice. Can you imagine a situation like that?

How many pieces do you think your repertoire consists of according to the described criteria?

________ pieces

Could you try to estimate how much playing time this repertoire amounts to?

________ hours ________ minutes

How many of these pieces in your repertoire would you perform from memory?

________ pieces

We assume that working on a repertoire includes acquisition of new pieces as well as rehearsing and maintaining older ones.

Do you recall when you started working on a new piece in order to include it into your repertoire for the last time? Please use repertoire again in the sense described above.

_______ Yes _______ No (recollection impossible)

When was that?

_______ Last piece _______ Second to last piece

Past Performance Repertoire
Elderly subjects only: Try to think back to the time when you were in your last year at the music academy (*elderly amateurs:* when you were around 25 years old).

Do you recall how many pieces your repertoire at that time consisted of with respect to our criteria? (Remember: performance without additional preparation either from a score or from memory.)

_______ Yes _______ No (estimation impossible)

How many were there?

_______ pieces

Could you also try to estimate the total playing time for your repertoire at that time?

_______ Yes _______ No (estimation impossible)

_______ hours _______ minutes

How many of those pieces did you perform from memory?

_______ pieces

Is the absolute playing time of your current repertoire

_______ similar _______ longer _______ shorter

compared to the past?

Is the absolute number of pieces you perform from memory

_______ similar _______ larger _______ smaller than at that time?

Is the level of technical difficulty or the number of difficult pieces in your current repertoire

_______ similar _______ higher _______ lower

compared to that time?

Are there any differences between the time and effort you have to invest in order to acquire a new piece today and the time at the academy (*elderly amateurs:* when you were 25 years old)?

_______ Yes _______ No

If yes, what differences are there?

____

____

Is the effort for comparable pieces today

_______ similar _______ larger _______ smaller

compared to the past?

End questions only for elderly subjects

Practice Intensity and Goals in Practice

(Following active performance repertoire, second session)

Elderly subjects only: If you compare the nature and focus of your current practice activities with the time at the music academy (*amateurs:* when you were 25 years old), are there any differences?

_______ Yes _______ No

If yes, what are the differences?

____

Is the number of pieces which you work on at the same time

_______ similar _______ higher _______ smaller

compared to the past?

Continue all subjects

Would you say that your technical abilities in terms of virtuosity are still improving?

_______ Yes _______ No _______ maintain _______ decline

If yes *(elderly subjects):*

Is the amount of effort you have to invest in this

_______ similar _______ larger _______ smaller

compared to the past?

If no *(all subjects):*

Do you believe you could improve in principle?

_______ Yes _______ No

If yes, what would you have to do in order to do so?

____

Would you say that your musical abilities in terms of expressive skills are still improving?

_______ Yes _______ No _______ maintain _______ decline

If yes *(elderly subjects):*

Is the amount of effort you have to invest in this

_______ similar _______ larger _______ smaller

compared to the past?

If no *(all subjects):*

Do you believe you could do it in principle?

_______ Yes _______ No

If yes, what would you have to do in order to do so?

____

Only elderly subjects:

Are there changes in terms of intensity, nature, and amount of practice which you would especially attribute to getting older?

_______ Yes _______ No

If yes, are there positive aspects to this and if so, what are they?

____

Are there aspects which are more on the negative side?

_______ Yes _______ No

If yes, what are they?

____

If there are negative changes, are there ways to counteract or compensate for them?

_______ Yes _______ No

If yes, what are they?

____

– Continue general debriefing –

Appendix B
Materials

Movement Sequences in Bimanual Coordination Experiments

The design of the complex bimanual coordination tasks (Experiments 1 and 2) had to take several aspects into account, most of which were discussed already in the theory section. At this point several practical considerations will be listed to complement the theoretical background. In designing experimental tasks many decisions need to be based on compromise due to our limited knowledge about the detailed processes concerned. Several underlying rationales for these considerations are made explicit in the following.

Task Presentation Format

Musicians with a background in serious music and related training practice and perform using notes. The standard notational format provides two different line systems for left and right hand. The location of a note in this system depends on the pitch associated with a given note. Sequences of notes provide visual information about serial organization of pitch values and overall "shape" of a given melody. Previous research has shown that highly trained musicians are able to derive abstract encodings from these visual presentations, and they are also superior in terms of memorizing them (Sloboda, 1976; Halpern & Bower, 1982). A number of graphic features supports the grouping into meaningful units. This ability is most obvious in instrumentalists who play from scores or even sight-read pieces. The technical term "prima vista" performance explicitly refers to a performance of an unknown piece from a score. This latter ability, however, is beyond the scope of less-skilled musicians and is even considered exceptional among professionals when it comes to more difficult pieces. The main focus of this study with respect to skilled performance was on the ability to coordinate complex movements rather than on the ability to make use of visual features in musical notation. The complexity of the notational system and presumed skill differences in music reading which were beyond the described research interest were considered to be a problem for the experimental investigation. The alternative was to use "finger annotations." Annotated numbers indicating which finger is optimal in performance are a frequent supplement to the notes in standard sheet music. "1" refers to the thumb, "2" refers to the index finger, "3" to the middle finger, "4" to the ring finger, and "5" to the small finger. This reference system has several advantages: First, it is identical for the left and the right hands. This advantage is considerable, given that the investigation of interference between opposite hands requires compatibility of the tasks' presentation format. Second, one could argue that knowledge about harmonic relations may not be applied on the level of perceptual encoding of task materials but must be brought to bear in the course of practicing a sequence. This is not supposed to imply that this type of knowledge is irrelevant in the first place. One could rather assume that it has to be abstracted from motor performance parameters and auditory feedback in order to be efficient. Third, this notation does not require note-reading abilities and is conservative in terms of skill differences. It was assumed that this presentation format would, if anything, provide a disadvantage for skilled musicians.

Length of Sequences

It was argued in the theory section that the ecological validity of the tasks in Experiments 1 and 2 derived from a comparison with technical studies (études) or with practicing a difficult phrase in the context of a larger piece. Given that the main interest was in movement coordination, a sequence length was necessary which rendered simple memorization on the basis of rehearsing a limited number of elements in short-term memory impossible. (This is to say, it had to be longer than seven.) A weakness of this argumentation is that we know quite little about memory capacity when it comes to encoding tonal sequences or movement patterns. Another crucial aspect was that most music implies a rhythmic grouping into units of four or three. A third aspect was that tasks had to have a certain level of difficulty in terms of involving movement transitions between different fingers. These considerations and extensive pilot experiments favored nine strokes as the optimal length of patterns in these experiments.

Meaningfulness in Musical Terms

Musical meaning must be understood in terms of harmonic relations. These relationships derive from pitch relationships between tones played simultaneously or in a series. Tonal pitch values can be organized into scales. Only certain relations between a pair of tones from the same scale can be considered as harmonic, as an approximation. Not all intervals deriving from scale tones are considered to be equally "good" in terms of harmonics. The musical context and the precise harmonic "distance" between two consecutive or parallel tones impose further constraints. The criteria and conventions for "good" music also differ between epochs and styles. Jazz music is much more liberal in terms of harmonic combinations than serious or popular music. Previous research has shown that musicians rely on harmonic relations when memorizing visually presented note sequences. Their advantage compared to untrained subjects is reduced if harmonic conventions are violated by the stimulus material, but they still do considerably better. This implies that it is practically impossible to compose "meaningless" music. In order to minimize the influences of these aspects in the tasks, only tones from the C-major scale were used in the experiments. This was also a major advantage in terms of controlling motor and perceptual demands: The C-major scale includes only white keys on the piano. All sequences used in the experiments were musical in the sense that they were not considered unpleasant by trained musicians. This was especially important when sequences were combined in the two hands. The musical quality of the sequences was, of course, limited by the attempt to balance sequences with respect to motoric demands while having all finger transitions of interest occurring at the same time.

Number of Sequences Used in the Experiments

Ideally, an experimental psychologist would like to generalize his findings in terms of having multiple trials using the maximal possible range of proper task materials. The number of possible finger transitions and combinations in bimanual performance is striking, however. In order to optimize the outcome with respect to the theoretical questions, only four different sequences were constructed. This amounted to 64 different finger transitions (4 sequences $\times$ 2 hands $\times$ 8 transitions) just for the single-hand case. Each transition was represented as one measurement point in terms of onset latency and a measure of force applied. Anybody who assumes that the execution of nine finger strokes using all five fingers of either hand is a trivial task should consider the relevant difficulties. There were two good reasons for limiting the number of sequences to be used: First, it was extremely difficult to find sequences which were comparable in terms of motoric demands but still make pleasant combinations; and second, all sequences had to be practiced in order to stabilize performance.

Motoric Demands

It was already pointed out that one of the main points of consideration was to maximize the number of finger transitions occurring in the tasks. The sequences were designed in order to have approximately equal frequency of occurrence for a given finger. This means that no finger should be used more than twice in a given sequence, but at least once. Fingers which were used only once were not allowed to be initial strokes, given that the transition was considered to be important. Furthermore, a change in movement "direction" in terms of using adjacent fingers naturally had to occur after a maximum of two strokes, excluding sequences like 2-3-4, for example. Bimanual sequences were balanced with respect to parallel and divergent movements. In addition to restricting the patterns to the white keys on the piano, lateral movements were also excluded as a complicating factor. Consequently, only five white keys for each hand were used in the tasks.

The four sequences can be described in two ways: as movement patterns, and as respective tones. Note that identical movement patterns in the two hands lead to different tonal sequences when performed with the left or right hand respectively. The movement patterns selected were:

Experiment 1 (Transcription):

1 - 4 - 2 - 1 - 3 - 2 - 4 - 5 - 3

and

1 - 5 - 2 - 3 - 1 - 2 - 4 - 3 - 5

Experiment 2 (Memorization):

3 - 5 - 4 - 2 - 3 - 1 - 2 - 4 - 1

and

5 - 3 - 4 - 2 - 1 - 3 - 2 - 5 - 1

Note that the sequences used in Experiment 2 are just the reversed patterns (in motoric respects) used in Experiment 1. This strategy provided reasonable compatibility between experiments with respect to motoric demands. Another way to present the sequences is to write down the respective tones generated. The keys marked for the experiments were exactly one octave apart with respect to the two hands. This means that a "1" for the left hand maps on a "5" in the right hand, and vice versa, in harmonic terms. "2" maps onto "4", and the "3" leads to identical tones in both hands. Writing out the sequences as tones leads to the following series (order as in Experiment 2):

Sequence 1, right hand:
e - g - f - d - e - c - d - f - c

Sequence 2, right hand:
g - e - f - d - c - e - d - g - c

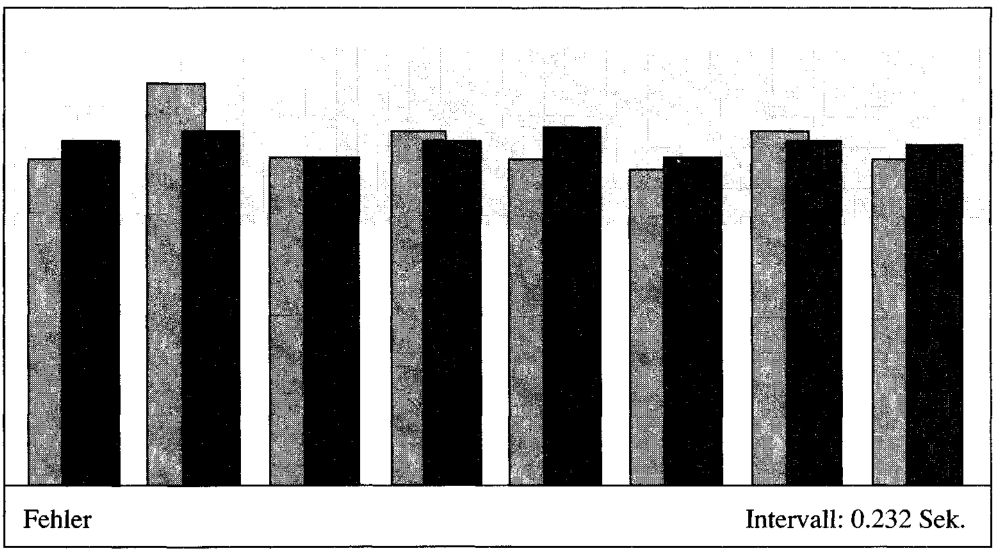
Sequence 1, left hand:
e - c - d - f - e - g - f - d - g

Sequence 2, left hand:
c - e - d - f - g - e - f - c - g

Table B1
Scales Used by the Expert Raters in Evaluating the Tape-Recorded Musical Performance

Appropriate Use of Dynamic Changes
Appropriate Use of Timing Changes
Articulation (Use of Legato-Staccato)
Selection of Appropriate Tempo
Evenness of Touch
Synchronization of Hands
Maintenance of Steady Tempo and Precision of Rhythm

Figure B1
Feedback Format in Experiments 1 and 2



Note. Example is taken from a condition requiring bimanual performance. Solid columns were blue in the original display and refer to the onset intervals between subsequent strokes in the left hand. Light columns were red in the original display and refer to the right-hand keystrokes. The height indicates duration of onset intervals scaled according to the individual performance mean during the first trial. The grey band represents 25 percent variation around the mean of a given trial. Error feedback (German: "Fehler") was given in the lower left of the display if a wrong key was struck. The average onset interval (German: "Intervall") was displayed in the lower right.

Appendix C
Supplementary Tables and Figures

Table C1
Time Spent on Music-Related Activities During Diary Week

	Young Amateurs	Young Experts	Elderly Amateurs	Elderly Experts	Total
Practice Alone	1.87 (1.95)	26.71 (8.66)	1.21 (1.30)	10.83 (7.56)	10.16 (11.84)
Practice with Others	.13 (.31)	1.67 (1.99)	.25 (.57)	1.19 (1.57)	.81 (1.42)
Playing for Fun (Alone)	.77 (1.29)	1.17 (1.55)	1.46 (1.59)	.33 (.78)	.93 (1.37)
Playing for Fun (Others)	.40 (1.04)	.17 (.34)	.02 (.07)	.00 (.00)	.15 (.56)
Taking Lessons	.33 (.61)	1.94 (1.05)	.08 (.29)	.00 (.00)	.59 (1.00)
Giving Lessons	.00 (.00)	3.65 (4.52)	.00 (.00)	21.23 (12.69)	6.22 (11.02)
Performance (Solo)	.08 (.29)	.38 (.78)	.02 (.07)	.77 2.67)	.31 (1.39)
Performance (Group)	.00 (.00)	.46 (.73)	.00 (.00)	.19 (.51)	.16 (.47)
Listening to Music	1.46 (1.90)	5.65 (4.11)	1.63 (3.35)	3.96 (4.48)	3.17 (3.90)
Music Theory	.00 (.00)	2.54 (3.55)	.23 (.72)	3.40 (5.71)	1.54 (3.59)
Professional Talk	.02 (.07)	1.69 (2.68)	.08 (.29)	2.75 (4.78)	1.14 (2.90)
Organization and Travel	1.17 (1.04)	10.25 (4.98)	1.00 (1.45)	15.54 (13.13)	6.99 (9.28)
Additional Instruments	.79 (1.99)	.50 (1.03)	1.81 (.00)	.00 (.78)	.78 (2.09)
TOTAL Music	7.02 (4.33)	56.75 (8.16)	7.79 (8.30)	60.19 (21.63)	32.94 (28.51)

Means and SDs (in hours).

Table C2
Time Spent on Other Everyday Activities During Diary Week

	Young Amateurs	Young Experts	Elderly Amateurs	Elderly Experts	Total
Household	4.27 (3.39)	5.25 (4.53)	12.60 (7.25)	5.31 (4.09)	6.86 (5.92)
Childcare	.00 (.00)	.00 (.00)	.67 (1.79)	.17 (.50)	.21 (.94)
Shopping	3.69 (2.80)	3.46 (2.38)	7.10 (4.68)	4.44 (3.11)	4.67 (3.56)
Work (Non-Music)	37.58 (13.86)	.06 (.16)	19.00 (17.84)	.94 (2.33)	14.40 (19.03)
Health and Body Care	14.56 (4.14)	12.40 (3.06)	17.90 (5.86)	18.13 (4.84)	15.74 (5.06)
Sleep	57.52 (5.36)	56.21 (4.52)	60.46 (4.62)	55.56 (8.18)	57.44 (5.98)
Education (Non-Music)	5.40 (10.05)	.44 (.95)	.67 (1.57)	.00 (.00)	1.63 (5.42)
Committee Work	.31 (1.08)	.00 (.00)	2.02 (4.36)	.81 (2.81)	.79 (2.68)
Leisure	34.10 (11.00)	31.15 (8.59)	36.48 (13.05)	18.92 (10.27)	30.16 (12.52)
Sports	2.60 (2.98)	.25 (.53)	.79 (1.73)	.71 (1.68)	1.09 (2.08)
TOTAL Everyday	160.04 (4.73)	109.21 (8.44)	157.69 (9.28)	104.98 (20.59)	132.98 (28.79)
Non-Codable	.94 (1.33)	2.04 (1.80)	2.52 (2.21)	2.83 (2.20)	2.08 (1.99)

Means and SDs (in hours).

Table C3
Digit-Symbol Substitution Scores

	Amateurs	Experts	Average Age-Groups
Young	66.9 (8.9)	71.2 (10.2)	69.0 (9.6)
Elderly	50.8 (9.3)	50.9 (12.8)	50.8 (10.9)
Average Skill-Groups	58.8 (12.2)	61.0 (15.3)	59.9 (13.7)

Means and SDs for four groups.

Table C4
Performance in the Two-Choice Reaction Time Task

	Amateurs	Experts	Average Age-Groups
Young	431 (43)	413 (45)	422 (44)
Elderly	518 (68)	518 (72)	518 (68)
Average Skill-Groups	475 (71)	465 (80)	470 (75)

Means and SDs (in ms).

Table C5
Interkeystroke Intervals in the Three Tapping Tasks

	Right Index Finger	Left Index Finger	Alternate Tapping	Average Skill-Groups
Amateurs	180 (16)	198 (22)	128 (18)	169 (15)
Experts	157 (10)	167 (16)	99 (14)	141 (12)
Total (Task)	169 (18)	183 (25)	113 (21)	155 (19)

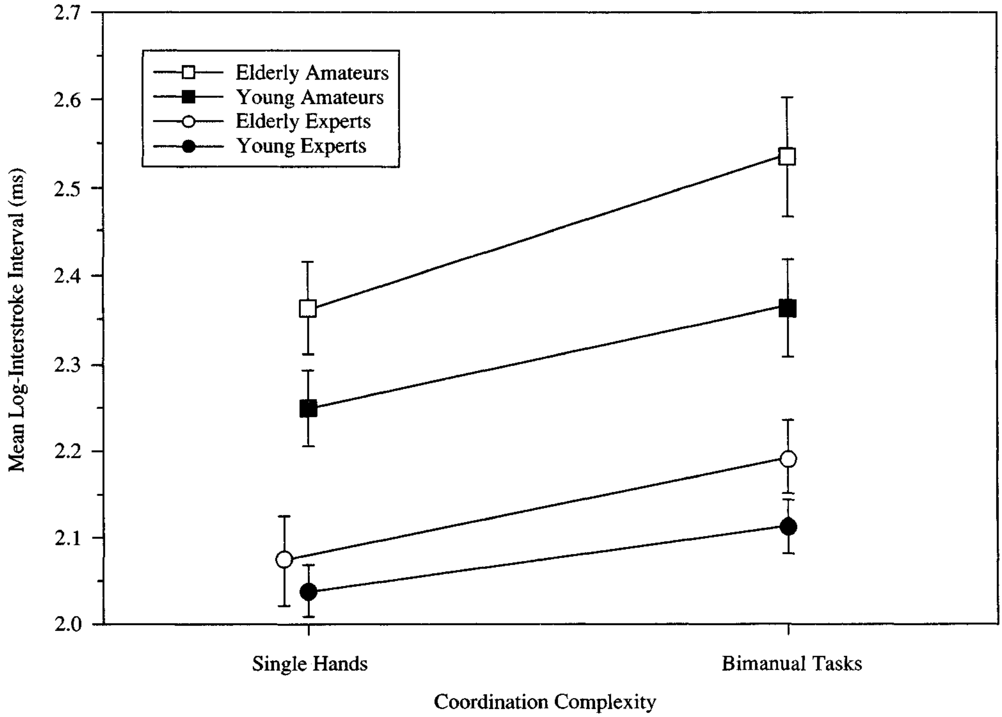
Means and SDs (in ms).

Table C6
LOG-Interkeystroke Intervals in the Three Tapping Tasks

	Right Index Finger	Left Index Finger	Alternate Tapping	Average Skill-Groups
Amateurs	2.249 (.038)	2.287 (.045)	2.083 (.061)	2.206 (.040)
Experts	2.187 (.026)	2.212 (.036)	1.954 (.069)	2.118 (.038)
Total Task	2.218 (.045)	2.249 (.055)	2.019 (.092)	2.162 (.059)

Means and SDs (in ms).

Figure C1
Speed of Performance in the Single Hand and the Bimanual Conditions of Experiment 1



Note. Mean log-interstroke intervals in ms. Data for bimanual performance are averaged for *mirror-image* and *different movements in opposite hands* conditions.

Table C7
Interkeystroke Intervals in the Three Conditions of Experiment 1 (Transcription Task)

	Single Hands	Mirror-Image Movements	Different Movements	Average Groups
Young Amateurs	184	187	317	184
($N = 12$)	(32)	(37)	(121)	(32)
Elderly Amateurs	242	293	485	242
($N = 12$)	(52)	(91)	(188)	(52)
Young Experts	112	118	153	112
($N = 12$)	(13)	(14)	(30)	(13)
Elderly Experts	125	138	198	125
($N = 12$)	(26)	(29)	(42)	(26)
Mean (Amateurs)	213	240	401	285
($N = 24$)	(52)	(87)	(177)	(93)
Mean (Experts)	118	128	176	141
($N = 24$)	(21)	(25)	(42)	(26)
Mean (Young)	148	153	235	179
($N = 24$)	(44)	(45)	(120)	(66)
Mean (Elderly)	183	216	342	247
($N = 24$)	(72)	(103)	(198)	(116)
Total (Tasks)	166	184	288	213
($N = 48$)	(62)	(85)	(171)	(99)

Means and SDs (in ms).

Table C8
LOG-Interkeystroke Intervals in the Three Conditions of Experiment 1
(Transcription Task)

	Single Hands	Mirror-Image Movements	Different Movements	Average Groups
Young Amateurs ($N = 12$)	2.250 (.088)	2.260 (.088)	2.466 (.136)	2.325 (.088)
Elderly Amateurs ($N = 12$)	2.363 (.091)	2.431 (.127)	2.643 (.162)	2.479 (.102)
Young Experts ($N = 12$)	2.038 (.051)	2.060 (.056)	2.163 (.081)	2.087 (.050)
Elderly Experts ($N = 12$)	2.077 (.090)	2.119 (.090)	2.258 (.092)	2.152 (.081)
Mean (Amateurs) ($N = 24$)	2.306 (.101)	2.346 (.138)	2.554 (.172)	2.402 (.122)
Mean (Experts) ($N = 24$)	2.058 (.074)	2.090 (.080)	2.211 (.098)	2.119 (.073)
Mean (Young) ($N = 24$)	2.144 (.125)	2.160 (.125)	2.315 (.190)	2.206 (.140)
Mean (Elderly) ($N = 24$)	2.220 (.171)	2.275 (.193)	2.450 (.235)	2.315 (.190)
Total (Tasks) ($N = 48$)	2.182 (.153)	2.218 (.171)	2.383 (.222)	2.261 (.174)

Means and SDs (in ms).

Table C9
Interkeystroke Intervals in the Three Conditions of Experiment 2
(Performance from Memory)

	Single Hands	Mirror-Image Movements	Different Movements	Average Groups
Young Amateurs	186	187	311	228
(N = 12)	(53)	(37)	(131)	(66)
Elderly Amateurs	229	310	548	362
(N = 12)	(81)	(153)	(264)	(150)
Young Experts	113	120	169	134
(N = 12)	(13)	(14)	(48)	(21)
Elderly Experts	132	138	193	154
(N = 12)	(29)	(29)	(66)	(39)
Mean (Amateurs)	208	249	430	295
(N = 24)	(71)	(125)	(237)	(132)
Mean (Experts)	122	129	181	144
(N = 24)	(24)	(24)	(58)	(32)
Mean (Young)	149	154	240	181
(N = 24)	(53)	(44)	(121)	(68)
Mean (Elderly)	180	224	370	258
(N = 24)	(78)	(139)	(261)	(151)
Total (Tasks)	165	189	305	220
(N = 48)	(68)	(108)	(212)	(122)

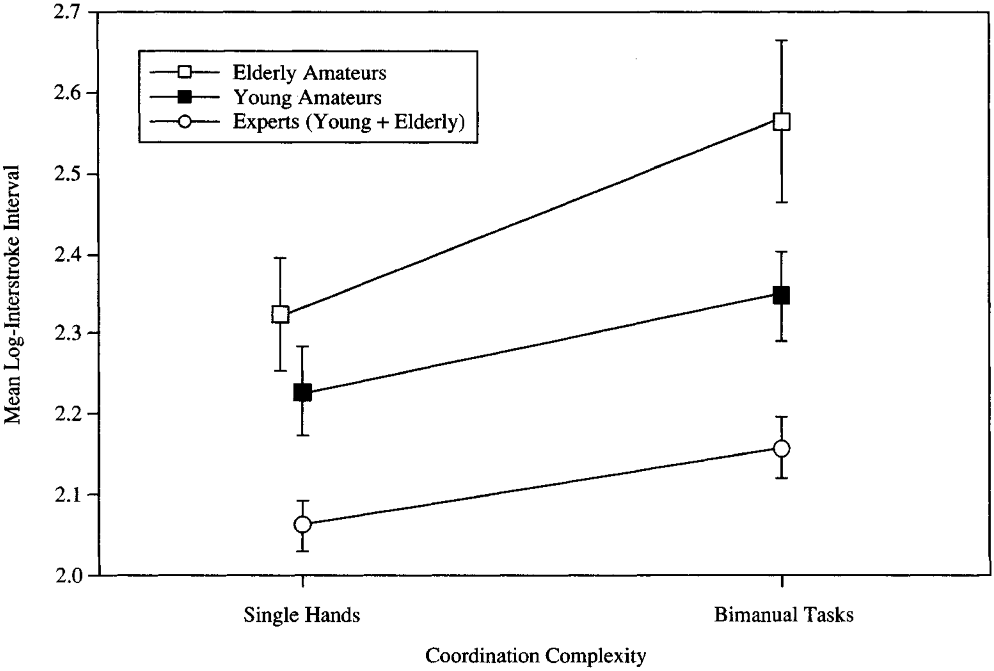
Means and SDs (in ms).

Table C10
LOG-Interkeystroke Intervals in the Three Conditions of Experiment 2 (Performance from Memory)

	Single Hands	Mirror-Image Movements	Different Movements	Average Groups
Young Amateurs (N = 12)	2.229 (.093)	2.225 (.079)	2.438 (.141)	2.308 (.093)
Elderly Amateurs (N = 12)	2.326 (.120)	2.440 (.176)	2.672 (.192)	2.479 (.147)
Young Experts (N = 12)	2.038 (.052)	2.068 (.053)	2.202 (.112)	2.103 (.059)
Elderly Experts (N = 12)	2.088 (.096)	2.120 (.091)	2.246 (.138)	2.151 (.102)
Mean (Amateurs) (N = 24)	2.278 (.116)	2.348 (.164)	2.555 (.204)	2.394 (.149)
Mean (Experts) (N = 24)	2.063 (.080)	2.094 (.078)	2.224 (.125)	2.127 (.085)
Mean (Young) (N = 24)	2.134 (.123)	2.162 (.116)	2.320 (.173)	2.205 (.130)
Mean (Elderly) (N = 24)	2.221 (.161)	2.280 (.213)	2.459 (.273)	2.315 (.208)
Total (Tasks) (N = 48)	2.170 (.147)	2.221 (.180)	2.390 (.237)	2.260 (.180)

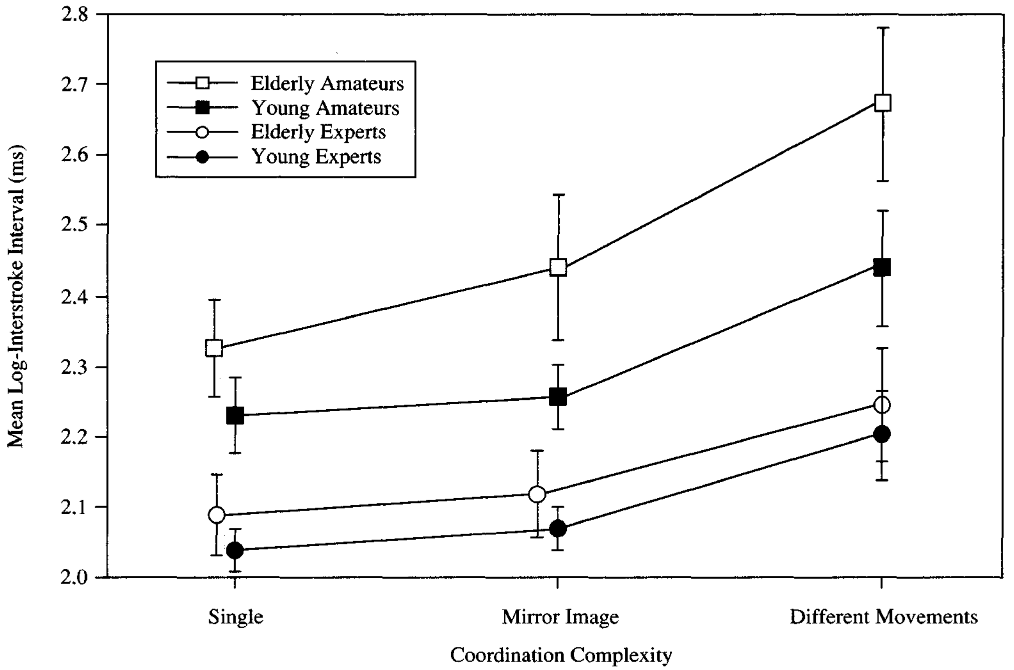
Means and SDs (in ms).

Figure C2
Speed of Performance in the Single Hand and the Bimanual Conditions of Experiment 2



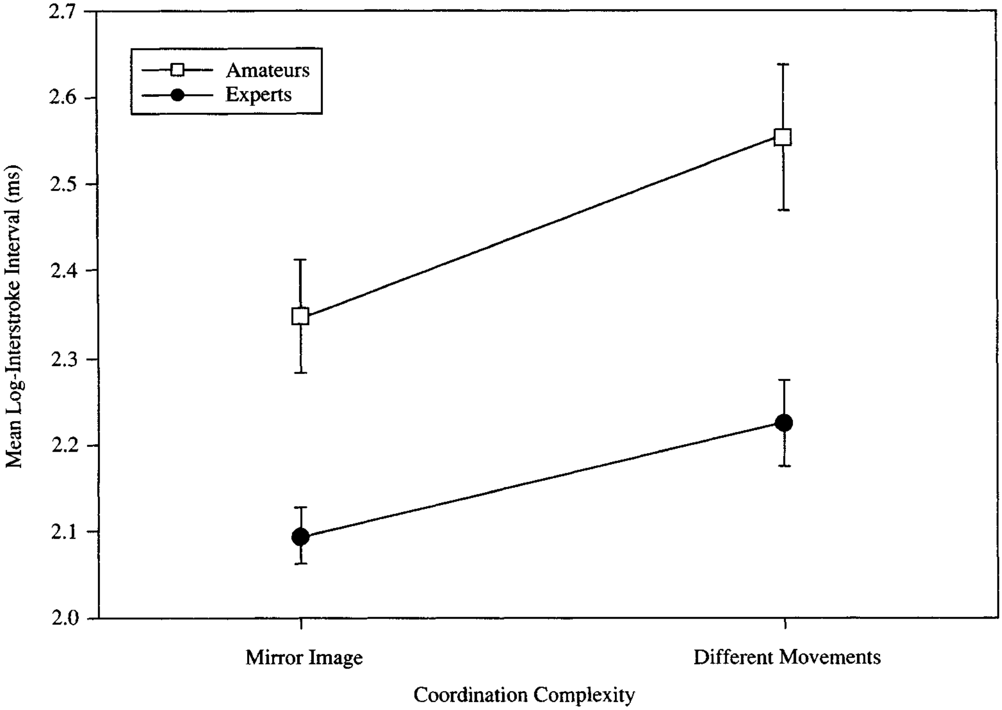
Note. Mean log-interstroke latencies (in ms). Data for bimanual performance are averaged for *mirror-image* and *different movements in opposite hands* conditions. Error bars indicate 95 percent confidence interval.

Figure C3
Speed of Performance in the Three Conditions of Experiment 2 (Single Groups)



Note. Mean log-interstroke latencies (in ms). Error bars indicate 95 percent confidence interval.

Figure C4
Speed of Performance in the Mirror-Image and the Different Movements in Opposite Hands Conditions of Experiment 2



Note. Mean log-interstroke latencies (in ms). Error bars indicate 95 percent confidence interval.

Table C11
Mean Relevance Ratings for the Six Experimental Tasks (Range of Scales: 1 to 10)

	Young Amateurs	Young Experts	Elderly Amateurs	Elderly Experts	Total Task
Transcription	7.58	6.75	7.58	8.83	7.69
Memorization	7.50	7.42	9.33	9.33	8.40
Tapping	5.83	4.92	7.25	5.42	5.85
Bach Prelude	6.83	8.42	8.50	6.50	7.56
CR-Time	5.08	4.58	7.58	8.00	6.31
Digit-Symbol	5.83	3.67	5.50	6.75	5.44
Total Skill-Related Tasks	6.94	6.88	8.17	7.52	7.38
Total Transfer Tasks	5.46	4.13	6.54	7.38	5.88
Total Group	6.44	5.96	7.63	7.47	6.88

Table C12
Means and SDs for the Four Practice Variables Used in the Regression Analyses

	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/Diary)
Young Amateurs ($N = 12$)	2.874 (1.074)	3.309 (.314)	3.048 (.349)	1.88 (1.95)
Young Experts ($N = 12$)	3.974 (.188)	4.223 (.149)	4.090 (.142)	26.71 (8.66)
Elderly Amateurs ($N = 12$)	3.269 (.357)	3.532 (.398)	2.964 (.487)	1.21 (1.30)
Elderly Experts ($N = 12$)	4.069 (.285)	4.477 (.124)	3.796 (.396)	10.83 (7.56)
Young Subjects ($N = 24$)	3.424 (.941)	3.766 (.525)	3.569 (.592)	14.29 (14.09)
Elderly Subjects ($N = 24$)	3.669 (.516)	4.005 (.562)	3.380 (.608)	6.02 (7.24)
Amateurs ($N = 24$)	3.071 (.808)	3.421 (.368)	3.006 (.417)	1.54 (1.66)
Experts ($N = 24$)	4.021 (.241)	4.350 (.187)	3.943 (.328)	18.77 (11.36)
TOTAL ($N = 48$)	3.546 (.761)	3.885 (.551)	3.474 (.601)	10.16 (11.84)

Table C13
Correlations between Predictor Variables in the Regression Analyses (Total Sample)

	Skill Level	Age-Group	Age by Skill	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)
Age-Group	.00					
Age × Skill	.00	.00				
Practice until Age 20	.631**	.163	−.100			
Practice during Peak 20 Years	.852**	.219	.014	.758**		
Practice over Last 10 Years	.787**	−.159	−.088	.609**	.830**	
Current Practice (Hours/Diary)	.735**	−.353*	−.325*	.431**	.544**	.740**

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 48$.

Table C14
Correlations between Predictor Variables in the Regression Analyses
(Age-Groups and Skill-Groups)

	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/Diary)
Young Subjects				
Practice Peak 20	.726**			
Practice Last 10	.632**	.964**		
Current Practice	.486**	.779**	.797**	
Skill Level	.598**	.889**	.898**	.900**
Elderly Subjects				
Practice Peak 20	.898**			
Practice Last 10	.768**	.838**		
Current Practice	.683**	.621**	.751**	
Skill Level	.791**	.859**	.699**	.680**
Amateurs				
Practice Peak 20	.556**			
Practice Last 10	.239	.690**		
Current Practice	–.390	.001	.313	
Age-Group	.250	.309	–.104	–.205
Experts				
Practice Peak 20	.515*			
Practice Last 10	.304	.035		
Current Practice	–.030	–.518**	.574**	
Age-Group	.202	.696**	–.458*	–.714**

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 24$.

Table C15
Correlations between Predictor Variables in the Regression Analyses (Single Groups)

	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)
Young Amateurs			
Practice Peak 20	.563		
Practice Last 10	.274	.791**	
Current Practice	–.464	.223	.356
Young Experts			
Practice Peak 20	.392		
Practice Last 10	.330	.985**	
Current Practice	–.283	–.361	–.350
Elderly Amateurs			
Practice Peak 20	.762**		
Practice Last 10	.484	.749**	
Current Practice	.047	–.104	.282
Elderly Experts			
Practice Peak 20	.688**		
Practice Last 10	.502	.496	
Current Practice	.516	.400	.785**

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 12$.

Table C16[20]
Correlations between Task Performance and Predictor Variables in the Regression Analyses (Total Sample)

	Skill Level	Age-Group	Age by Skill	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/ Diary)
Tapping							
Right	–.695**	.134	–.093	–.394**	–.562**	–.587**	–.512**
Left	–.682**	.020	–.049	–.410**	–.594**	–.613**	–.478**
Alternate	–.710**	.169	–.043	–.464**	–.636**	–.761**	–.614**
Experiment 1							
Single	–.821**	.252	–.123	–.557**	–.678**	–.751**	–.696**
Mirror	–.757**	.340*	–.166	–.459**	–.593**	–.687**	–.664**
Different	–.782**	.310*	–.093	–.620**	–.711**	–.783**	–.642**
Experiment 2							
Single	–.740**	.253	–.079	–.570**	–.612**	–.705**	–.631**
Mirror	–.711**	.332*	–.188	–.522**	–.590**	–.660**	–.601**
Different	–.708**	.296*	–.203	–.521**	–.621**	–.752**	–.569**
Musical Performance							
Consistent Force Variation	.620**	–.209	.069	.373**	.509**	.595**	.544**

Person r significant (two-tailed) at $* = p < .05$; $** = p < .01$; $N = 48$.

[20] *Remarks on Tables C16 to C22 on the following pages.* Design variables were effect-coded: skill level (–1 = amateurs; 1 = experts), age-group (–1 = young; 1 = elderly), age × skill (–1 = elderly amateurs and young experts; 1 = young amateurs and elderly experts). Dependent variables in the three tapping tasks and Experiments 1 and 2 were mean log-transformed interkeystroke latencies. Negative correlations thus indicate higher speed—that is, better task performance. The dependent variable in the musical performance task was the averaged z-scored correlation among bar means for force applied. Positive correlations thus imply higher consistency, that is—better performance.

Table C17
Within Age-Group Correlations between Task Performance and Predictor Variables in the Regression

	Skill Level	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/Diary)
Young					
Right Tapping	–.744**	–.451*	–.730**	–.789**	–.648**
Left Tapping	–.655**	–.373	–.653**	–.674**	–.496**
Alternate Tapping	–.685**	–.481*	–.721**	–.757**	–.578**
Single (Experiment 1)	–.862**	–.717**	–.868**	–.837**	–.785**
Mirror (Experiment 1)	–.816**	–.646**	–.866**	–.820**	–.754**
Difference (Experiment 1)	–.815**	–.785**	–.856**	–.848**	–.709**
Single (Experiment 2)	–.798**	–.802**	–.871**	–.868**	–.720**
Mirror (Experiment 2)	–.823**	–.847**	–.909**	–.835**	–.706**
Difference (Experiment 2)	–.696**	–.695**	–.701**	–.741**	–.560**
Musical Performance	.621**	.487*	.633**	.638**	.576**
Elderly					
Right Tapping	–.690**	–.504*	–.545**	–.455*	–.448**
Left Tapping	–.708**	–.558**	–.580**	–.566**	–.604**
Alternate Tapping	–.756**	–.612**	–.680**	–.751**	–.740**
Single (Experiment 1)	–.856**	–.655**	–.722**	–.693**	–.699**
Mirror (Experiment 1)	–.828**	–.611**	–.660**	–.617**	–.662**
Difference (Experiment 1)	–.837**	–.754**	–.830**	–.736**	–.569**
Single (Experiment 2)	–.753**	–.560**	–.596**	–.578**	–.581**
Mirror (Experiment 2)	–.767**	–.626**	–.661**	–.595**	–.619**
Difference (Experiment 2)	–.800**	–.683**	–.777**	–.778**	–.653**
Musical Performance	.650**	.402	.542**	.538**	.528**

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 24$.

Table C18
Within Skill-Group Correlations between Task Performance and Predictor Variables in the Regression

	Age-Group	Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/Diary)
Amateurs					
Right Tapping	.275	.166	.156	–.018	–.076
Left Tapping	.085	.117	.056	–.007	–.063
Alternate Tapping	.322	.091	–.021	–.334	–.280
Single (Experiment 1)	.577**	–.081	.088	–.105	–.077
Mirror (Experiment 1)	.632**	–.077	.170	–.052	–.328
Difference (Experiment 1)	.526**	–.320	–.206	–.387	–.135
Single (Experiment 2)	.425*	–.225	.065	–.113	–.044
Mirror (Experiment 2)	.579**	–.119	.063	–.070	–.166
Difference (Experiment 2)	.586**	–.126	–.065	–.387	–.105
Musical Performance	–.274	–.004	–.021	.270	.279
Experts					
Right Tapping	.077	–.323	–.139	–.227	.014
Left Tapping	–.045	–.295	–.267	–.426*	.088
Alternate Tapping	.168	–.401	–.212	–.628**	–.223
Single (Experiment 1)	.268	–.143	.038	–.634**	–.392
Mirror (Experiment 1)	.378	–.195	.096	–.620**	–.410*
Difference (Experiment 1)	.497*	–.036	.096	–.563**	–.288
Single (Experiment 2)	.321	–.115	.020	–.630**	–.330
Mirror (Experiment 2)	.340	–.247	–.046	–.685**	–.335
Difference (Experiment 2)	.178	–.218	.000	–.579**	–.169
Musical Performance	–.307	–.225	–.159	.103	.317

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 24$.

Table C19
Correlations between Task Performance and Practice Variables

		Practice until Age 20 (Log Hours)	Practice Peak 20 Years (Log Hours)	Practice Last 10 Years (Log Hours)	Current Practice (Hours/Diary)
Young Amateurs					
Tapping	Right	.023	–.212	–.428	–.326
	Left	.068	–.111	–.198	–.266
	Alternate	–.078	–.324	–.511	–.457
Experiment 1	Single	–.558	–.541	–.329	.101
	Mirror	–.338	–.608*	–.380	–.179
	Different	–.740**	–.475	–.410	.048
Experiment 2	Single	–.726**	–.612*	–.592*	–.015
	Mirror	–.859**	–.694*	–.333	.141
	Different	–.546	–.315	–.461	.141
Musical Performance	Consistency	.219	.247	.260	.027
Young Experts					
Tapping	Right	–.569	–.307	–.292	.111
	Left	–.354	–.575	–.556	–.346
	Alternate	–.557	–.435	–.429	–.024
Experiment 1	Single	–.418	–.131	–.133	.193
	Mirror	–.653*	–.301	–.228	.168
	Different	–.172	–.580*	–.670*	–.432
Experiment 2	Single	–.586*	–.502	–.489	–.027
	Mirror	–.796**	–.667*	–.608*	–.052
	Different	–.583*	–.097	–.132	.341
Musical Performance	Consistency	–.261	.119	.072	.424
Elderly Amateurs					
Tapping	Right	.371	.262	.265	.344
	Left	.254	.186	.194	.394
	Alternate	.369	.054	–.168	.209
Experiment 1	Single	.230	.165	.110	–.006
	Mirror	.290	.280	.214	–.386
	Different	–.396	–.441	–.385	–.136
Experiment 2	Single	.179	.250	.211	.129
	Mirror	.001	.038	.090	–.211
	Different	–.162	–.322	–.376	–.111
Musical Performance	Consistency	–.294	–.055	.250	.535
Elderly Experts					
Tapping	Right	–.310	–.318	–.207	–.008
	Left	–.267	–.175	–.505	–.380
	Alternate	–.396	–.505	–.779**	–.611*
Experiment 1	Single	–.130	–.298	–.704*	–.447
	Mirror	–.154	–.244	–.628*	–.328
	Different	–.020	–.215	–.405	.039
Experiment 2	Single	–.053	–.202	–.599*	–.260
	Mirror	–.169	–.290	–.651*	–.387
	Different	–.095	–.257	–.739**	–.406
Musical Performance	Consistency	–.134	.053	–.076	.172

Pearson r significant (two-tailed) at * = $p < .05$; ** = $p < .01$; $N = 12$.

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ISBN 3-87985-034-8

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Inventory of European Longitudinal Studies in the Behavioral and Medical Sciences.
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DM 58,–

Max-Planck-Institut für Bildungsforschung (Hrsg.)
Entwicklung und Lernen.
Beiträge zum Symposium anläßlich des 60. Geburtstages von Wolfgang Edelstein.
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Beiträge zum Symposium anläßlich des 75. Geburtstages von Dietrich Goldschmidt.
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Dietrich Goldschmidt und Peter Martin Roeder (Hrsg.)
Alternative Schulen?
Gestalt und Funktion nichtstaatlicher Schulen im Rahmen öffentlicher Bildungssysteme.
623 S. Stuttgart: Klett-Cotta, 1979.

Die Arbeit untersucht den Einfluß jahre- oder jahrzehntelangen Trainings im Klavierspielen auf die Entwicklung kognitiv-motorischer Fertigkeiten im Erwachsenenalter. Dabei wurden professionelle und Amateurpianisten im Alter von 20-30 bzw. 54-68 Jahren verglichen. Die Studie verbindet Fragestellungen aus der Expertise-Forschung und der Entwicklungspsychologie der Lebensspanne. Motorische Geschwindigkeit, Effizienz bimanualer Koordination, Memorisation und gezielte Variation in der musikalischen Interpretation wurden experimentell untersucht. Die Übungsintensität wurde durch ein Tagebuch und retrospektive Zeitschätzungen gemessen. Der zentrale Befund der Untersuchung ist, daß interindividuelle Unterschiede im Erwerb und Erhalt von Fertigkeiten, die eine hohe Relevanz für das Klavierspielen haben, wesentlich durch den investierten Zeitaufwand für gezieltes Üben (*deliberate practice*) am Instrument determiniert sind. Alterskorrelierte Veränderungen in pianistischen Fertigkeiten fallen daher geringer aus als bei Kontrollaufgaben. Die Rolle von Talent und Training im Zusammenhang mit der Entwicklung von Höchstleistungen (*peak performances*) wird diskutiert.

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