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Maintaining Excellence: Deliberate Practice and Elite Performance in Young and Older Pianists

Ralf Th. Krampe
Max Planck Institute for Human Development and Education

K. Anders Ericsson
Florida State University

Two studies investigated the role of deliberate practice in the maintenance of cognitive–motor skills in expert and accomplished amateur pianists. Older expert and amateur pianists showed the normal pattern of large age-related reductions in standard measures of general processing speed. Performance on music-related tasks showed similar age-graded decline for amateur pianists but not for expert pianists, whose average performance level was only slightly below that of young expert pianists. The degree of maintenance of relevant pianistic skills for older expert pianists was predicted by the amount of deliberate practice during later adulthood. The role of deliberate practice in the active maintenance of superior domain-specific performance in spite of general age-related decline is discussed.

Wilhelm Kempff, the famous pianist, decided to give up public performances when he felt his finger dexterity deteriorating and his memory becoming less reliable. At this point in his career he was no less than 85 years old. Numerous musicians continue in old age to amaze their audiences with performances that are far beyond the reach of most persons of any age. How are such extraordinary achievements possible for these individuals of advanced age? For a long time it has been assumed that elite performance or the ultimate level of achievement possible for any individual is constrained by inherent, presumably innate, general factors and capacities. In a similar line of thought, the consistent age-related decline in speeded cognitive–motor functions demonstrated in numerous studies (for a review, see Salthouse, 1985a) has been attributed to a single general factor reflecting inevitable biological deterioration of central processes. In this article, we question the common assumption that age-related decline in speeded performance is inevitable and report evidence for the role of continued practice in older professional pianists' maintenance of expert-level performance.

Ralf Th. Krampe, Max Planck Institute for Human Development and Education, Berlin, Germany; K. Anders Ericsson, Department of Psychology, Florida State University.

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Correspondence concerning this article should be addressed to Ralf Th. Krampe, who is now at the Department of Psychology, University of Potsdam, P.O. Box 60 15 53, D-14415 Potsdam, Germany. Electronic mail may be sent via Internet to krampe@rz.uni-potsdam.de.

The General Factor Account

Biological indicators of aging show that declines in some functions start at the beginning of adulthood or, as with hearing, even earlier (Fozard, 1990). Age-related decline in performance during middle age and late adulthood has been documented especially for tasks involving a speeded component in such different domains as perceptual, cognitive, or motor functioning (Hertzog, 1989; see Salthouse, 1985b, for a review). The assumption that most age-related differences in speeded performance have a single, common cause and are mediated by a reduction in processing speed is referred to in the literature as the *speed hypothesis of cognitive aging* or *general slowing.* Consistent with this hypothesis, meta-analyses of findings from numerous studies on a wide range of tasks and activities point to an almost uniform reduction of the speed of performance as a function of increasing age (Cerella, 1990; Myerson, Hale, Wagstaff, Poon, & Smith, 1990). Reduced working memory capacity and speed of processing (Salthouse, 1991c), increased deterioration of neural interconnectedness (Cerella, 1990), and decreased ability to ignore irrelevant information (Hasher & Zacks, 1988) have been proposed as the mediators of age-related decline in cognitive functioning. On the other hand, most researchers who are investigating aging acknowledge that some domains of cognitive functioning may be less affected than others, because of the compensatory effects of accumulated knowledge, for instance, in tasks requiring lexical decisions (Cerella & Fozard, 1984; Lima, Hale, & Myerson, 1991). This is especially true when performance on knowledge-based tasks is adjusted for age-related decrements in general speed (Hertzog, 1989; Schaie, 1989, 1990). The different patterns of age-related decline that have been found have led to the distinction between *crystallized* (i.e., mainly based on acquired knowledge) and *fluid* (i.e., challenging the speed of cognitive operations) components of intelligence (Horn, 1982).

More recent studies have shown, however, that essentially all age-related correlations in large samples can be accounted for by individual differences in measures of perceptual- and cognitive–motor speed, such as the Digit Symbol Substitution Test, a subtest of the Wechsler Adult Intelligence Scale (Wechsler, 1955, 1981), or composite measures of general processing speed (Salthouse, 1993, 1994). Using path analytic techniques, Salthouse (1993) demonstrated that the critical mental speed construct reflects not merely sensory or motor processes, but rather the speed of more fundamental, simple operations. Studies with very old adults beyond their 70s (Lindenberger, Mayr, & Kliegl, 1993) have also shown that even the crystallized components of intelligence can almost completely be accounted for by a general speed factor composed of speed measures like the Digit Symbol Substitution Test.

The general factor account can be easily extended to age-related decline in skilled performance. According to theories of skill acquisition (Anderson, 1982; Fitts & Posner, 1967), performance becomes automated after extended practice. However, even automated skilled performance remains mediated by a small number of basic perceptual–motor capacities, and individual differences in performance after training in the laboratory are correlated with the efficiency of basic perceptual–motor capacities and abilities (Ackerman, 1988). Deterioration of these capacities with age would produce a decline in many different types of performance.

Probably the most sophisticated version of this type of general factor account was proposed by Salthouse, Babcock, Skovronek, Mitchell, and Palmon (1990). According to their *preserved differentiation* account, the superior performance of older experts compared with age-matched controls reflects differences in stable abilities that existed before the onset of age-related decline. These superior abilities presumably enhanced the experts' initial performance and thus influenced their choice of professional careers. In support of this account, Salthouse et al. found that interindividual differences in spatial visualization appeared to be largely independent of the amount of recent experience that architects differing in age and proficiency reported having had with relevant activities. Although professional expertise yielded a performance advantage at each age level, parallel regression lines suggested that the rate of age-related decline in critical abilities was similar for architects and age-matched controls.

Two pioneering studies on the relation between aging and expertise have integrated the idea of age-related decline in general capacity with the acquisition of domain-specific compensatory mechanisms. In his study on expertise in chess, Charness (1981a, 1981b) found that the quality of the chess move that participants selected for an unfamiliar chess position was unrelated to age and closely linked to skill level (current chess rating). Detailed analysis of think-aloud protocols revealed that older experts engaged in less search than their younger counterparts did, suggesting that older players compensated for age-related declines with more refined knowledge-based processes. In support of the general factor account, Salthouse (1984) observed in two samples of typists that basic cognitive–motor functions reflected in finger-tapping speed, choice reaction time, and performance on the Digit Symbol Substitution Test deteriorated with age. Older typists attained the same typing speed as younger typists by more extensive anticipation, as shown by their longer eye–hand spans. Both studies suggest that older experts attain the same level of performance as young experts by means of different mechanisms (compensation). However, it is not possible from the available data to determine whether older individuals deliberately adopt compensatory mechanisms in response to aging or whether their performance at younger ages was already superior and these associated mechanisms are better preserved because of a slower age-related decline.

Researchers on expert performance (see Ericsson & Smith, 1991a, for a review) have recently taken issue with the modal view (Chase & Simon, 1973) that expert performance can be completely extrapolated from acquired mechanisms uncovered in laboratory studies of skill acquisition. Unlike skills acquired in 2–10 hr, expert performance can be attained only after years of training, and its complex acquired structure goes beyond mere automatization of cognitive processes and reliance on complex pattern recognition. Acquired memory representations and complex skills enable experts to perform tasks often in a qualitatively different manner from the way beginners and novices perform them. In chess and several other domains of expertise (Ericsson & Lehmann, 1996; Ericsson & Smith, 1991b), experts can internally represent information necessary for planning because they have learned to use their long-term memory to extend the storage capacity of their working memory (Ericsson & Kintsch, 1995). High-speed performance of many cognitive–motor skills has been linked to the advance preparation of movements (Gentner, 1988). This finding accounts for the fact that expert typists look further ahead at the text to be typed (i.e., have an extended eye–hand span) than do slower typists (Butsch, 1932; Shaffer, 1978) and for the fact that athletes can predict the trajectories of rapid projectiles such as tennis balls (Abernethy & Russel, 1987). It is assumed that advance preparation allows experts to circumvent limits imposed by serial reaction times and movements, which constrain novice performance (Salthouse, 1991b). Another important constraint on cognitive–motor performance is the coordination of concurrent movements in different hands and fingers (Kelso, Southard, & Goodman, 1979; Klapp, 1979). Experts have been shown to adopt specific mechanisms of movement timing and control (Deutsch, 1983; Ibbotson & Morton, 1981; Jagacinski, Marshburn, Klapp, & Jones, 1988; Summers, Rosenbaum, Burns, & Ford, 1993).

The Role of Experience and Deliberate Practice

Although it is generally agreed that individuals must gain relevant experience to improve their performance, reviews show that the correlation between amount of experience and performance is surprisingly modest and in many cases quite low (Ericsson, Krampe, & Tesch-Römer, 1993; Ericsson & Lehmann, 1996). This finding is inconsistent with the uniformly large improvements in performance observed in laboratory studies of skill acquisition (Newell & Rosenbloom, 1981). Ericsson et al. (1993) explained this inconsistency by showing that amateurs in a skill domain spent most of their time in inherently enjoyable, playful interaction that resulted in only limited improvement. For example, a recreational tennis player may miss a particular volley in a game and then not encounter a comparable situation for several weeks. In contrast, another player could practice that volley with a tennis coach until it was completely mastered. Similarly, most job-related experience is centered on the reliable and efficient generation of products and service using well-established methods, rather than on exploration and experimentation with alternative methods that might eventually lead to improvement. In distinction from leisurely or normal job-related experience, Ericsson et al. defined *deliberate practice* as a very specific activity designed for an individual by a skilled teacher explicitly to improve performance. They found that in a wide range of domains, the level of performance young experts had attained was related to the amount of deliberate practice they had accumulated over their entire careers.

Experts in their 60s may have actively engaged in a domain for more than 50 years. Given that the highest level of performance in most domains is frequently attained before the age of 40 and in vigorous sports typically before the age of 30 (Lehman, 1953; Schulz & Curnow, 1988), it is reasonable to split the 50-year career of older experts into a period of *acquisition* of expert performance and a subsequent period of maintenance of expert performance. The distinction between acquisition and maintenance is most clearly demonstrated in studies of long-term retention of highly practiced knowledge and skills (Bahrick, 1984; Bahrick & Hall, 1991; Conway, Cohen, & Stanhope, 1991; Farr, 1987). These studies show that highly practiced skills and frequently applied knowledge show relatively little decay over long periods (years and decades) of disuse. Although there have been no studies of the effect of disuse on very high (expert) levels of performance, the available evidence, discussed below, strongly suggests that regular efforts are necessary to maintain expert speeded performance.

Contrary to the general factor account, with its notion of fixed basic capacities, research on elite athletes has repeatedly demonstrated that anatomical and physiological variables, such as heart size and oxygen absorption by the lungs, change in response to intense physical activity, especially during adolescence, when the body is growing (for reviews, see Ericsson, 1990; Ericsson et al., 1993). Most important, these adaptations are not permanent but must be maintained through intense training. If training is terminated, these variables recede to their normal values over months and years or even within a week, as is the case for the respiratory capacity of swimmers' muscles (Reilly, 1990).

Disentangling the effects of expertise and pure aging requires consideration of several critical factors. Studies of master athletes show that the age-related decline of performance is much reduced for those athletes who remain active and continue to practice (Ericsson, 1990; Letzelter, Jungermann, & Freitag, 1986). Hagberg et al. (1985) found that their group of older but still active master athletes (runners) practiced considerably less than did a group of outstanding young athletes. A comparison of the older elite runners with young subelite runners matched according to current training levels suggested that high levels of most bodily functions (e.g., intake and metabolism of oxygen) were largely maintained through practice, while a small number of functions (e.g., maximal heart rate) seemed invariably to decline with age. Shephard (1994) demonstrated that, contrary to earlier beliefs, response to aerobic training was similarly effective for old and young adults. Shephard's review of earlier research also suggested that successful maintenance of aerobic capacity is possible and requires only one third of the training duration required for original acquisition, as long as the intensity of practice efforts remains the same.

In sum, a genuine understanding of older experts' performance requires a more detailed description of past and concurrent deliberate practice activities to distinguish decrements due to reduced practice levels from the inevitable decrements due to aging. In the present studies, we investigated the hypothesis that expert performance in older individuals is actively maintained by continued levels of deliberate practice once the acquisition phase has ended. We call this hypothesis the *selective maintenance* account.

Outline of the Empirical Investigations

It was essential to find a domain in which older experts continue to perform and in which they and their younger counterparts are evaluated according to similar criteria. In such a domain, active experts would remain motivated to maintain their highest level of attainable performance throughout their active professional lives. The domain of musical performance meets these criteria and has the advantage that a sufficient number of individuals at different levels of skill engage in playing music throughout their lives. In our main study, the level of piano performance (expert vs. amateur) and age (young vs. older) were varied in a factorial design.

Any test of the selective maintenance account requires that past and current deliberate practice be assessed. Ericsson et al. (1993) demonstrated that musicians' conceptions of "practice alone" corresponded closely to our definition of deliberate practice and that instrumentalists could give valid retrospective estimates of the amount of their past training efforts. Several studies since then have demonstrated high test–retest reliability (Lehmann & Ericsson, 1995) and validity (Heizmann, Krampe, & Ericsson, 1993) of deliberate practice measures for expert musicians and athletes in different age groups (Starkes, Deakin, Allard, Hodges, & Hayes, 1996). Given that the preferable alternative of conducting a 40-year longitudinal study with concurrent measures of practice and performance is unfeasible, we argue that these estimates are the best available information about past practice and music performance.

To assess the explanatory scope of the general factor account, we designed two experimental tasks that differed maximally in the extent to which they allowed participants to compensate for central speed limitations with accumulated knowledge or specific mechanisms. At one extreme, we measured finger-tapping rate, a standard measure of peripheral motor efficiency. Earlier research (Nagasaki, Itoh, Maruyama, & Hashizume, 1989; see Salthouse, 1985b, for an overview) showed that maximum tapping rate decreases with age. We argue that no reasonable knowledge-based processing mechanism can compensate for decrements. At the other extreme, we designed a musical interpretation task in which participants had to perform a technically simple piece at their own tempo and with a focus on consistent control of expressive musical phrasing. This task tested the ability to control timing and force variation in interpreting a musical piece (Prelude No. 1 from Bach's *Wohltemperiertes Clavier*), critical factors that reflect musical knowledge to a high degree (Palmer, 1989; Shaffer, 1976, 1981, 1982; Sloboda, 1983). This prelude does not tax virtuosity or technical skills, but it leaves considerable room for musical interpretation as famous soloists have demonstrated with their recordings of the piece. We selected this composition to allow for a comparison of pianists from a large skill range. Given the nature of the task and the lack of speed requirements, age-related performance declines are implicated by the general factor account to a less degree; however, as we described earlier, some versions of the general factor account also extend to more knowledge-based (crystallized) components of performance, at least for very old individuals.

A direct contrast of the general factor account and the selective maintenance account required two types of speeded cognitive–motor tasks, namely, marker tests of general processing speed and measures of speeded performance in critical components of piano playing skill. We measured general cognitive–motor capacity with two of the most common tests: the Digit Symbol Substitution Test and a test measuring two-choice reaction time. To challenge aspects of skilled performance, we selected tasks with components for which earlier research had demonstrated severe performance limitations in less skilled individuals and deterioration in efficiency with age. The speeded execution of hand and finger movements under different conditions of coordination constraints has exactly these properties (Haaland, Harrington, & Grice, 1993; Kelso et al., 1979; Light & Spirduso, 1990; Stelmach, Amrhein, & Goggin, 1988). In Study 1, we conducted two experiments designed on the basis of these considerations. The second experiment differed from the first in that participants performed from memory, a more challenging but also more natural situation for pianists, who normally give their public performances from memory. We contrasted the effects of age and expertise in these two criterion tasks with measures of general processing speed.

The general factor account asserts that superior general capacity is a prime mediator of older experts' superior performance. In its most straightforward extension to aging and expert performance, the general factor account predicts that age-related decline should be similar for the skill-related performance and measures of general processing speed, at least for a given level of expertise. This extrapolation is consistent with Salthouse's (1991d) review of age-related decline in the spatial ability of old architects, in which he argued "that the magnitude of the relations between age and measures of cognitive performance are similar regardless of one's occupation, and by inference, of one's pattern of experiences" (p. 152). Although the previously reviewed research allows us to infer significant cognitive mediation in expert and amateur music performance, we are far from explicit process models of different levels of music performance that specify the same or different roles of general capacity. On the basis of the available limited knowledge, we argue that the most reasonable and parsimonious prediction from the general factor model is that the rate of age-related decline (the size of the age effect) should be similar for experts and amateurs despite their different levels of music performance. Even if the rate of age-related decline in music-related performance differs for amateurs and experts, the general factor account would still predict an age-related reduction in general capacity and some amount of associated decrease in music-related performance for both amateurs and experts. Most important, however, this reduction should not be markedly altered by differences in experience, including individual differences in amount of deliberate practice. From now on we refer to the general factor model with these auxiliary assumptions as the *extended general factor account.*

In contrast, the selective maintenance account asserts that superior performance is the result of domain-specific mechanisms that individuals have acquired and must actively maintain through deliberate practice. This account predicts that age-related decline in general processing speed will be similar for expert and amateur pianists, assuming that the skill-specific mechanisms that distinguish experts from amateurs have little relevance for these tasks. Age effects in speeded skill-related tasks should be more pronounced for amateurs, given that their skilled mechanisms were acquired to a much lower level and subsequently were not adequately maintained. In contrast, age-related differences in experts' skill-related performance should be considerably reduced. Contrasting the two types of tasks amounts to a three-way interaction involving type of task, expertise level, and age group. The selective maintenance account predicts that the degree of reduction in age-related decline in highly skilled performance will be a direct function of the amount of maintenance practice in which older experts engage.

In our earlier work (Ericsson et al., 1993), we developed the framework of the acquisition of expertise through deliberate practice and showed that the amount of deliberate practice accumulated during childhood and adolescence accounts for individual differences in expert performance in music and other fields. In the present research, we addressed a different issue, namely, the maintenance of skills in older expert pianists and the relation between normal aging and preserved expert performance. To facilitate the extension of our theoretical framework, we used the data on young pianists from one of our earlier studies (Ericsson et al., 1993) for age comparisons with the older pianists in Study 1.

Study 1

For our main study we recruited a group of older professional pianists. To control for age, we identified a group of amateur pianists of the same age who were proficient enough to perform all of the music-relevant tasks successfully. Two groups of young expert and young amateur pianists with an overall level of piano playing skill that matched that of their older counterparts completed the factorial design.

Method

Participants

Fifty-two pianists were originally recruited for the study. We recruited amateur pianists through newspaper and campus advertisements. We recruited expert pianists through contacts with two Berlin music academies that have international reputations. To make the levels of music skill comparable across groups, we specified that all participants had to specialize in classical music. One young amateur and 1 older expert who specialized in jazz were excluded according to this criterion. To ensure a uniform minimum standard of proficiency, we further specified that participants had to be able to play Prelude No. 1 from Bach's *Wohltemperiertes Clavier.* Two young and 1 older amateurs failed to meet this criterion, leaving a total of 48 participants, 12 in each group, for analyses. Skill groups were successfully equated for mean age (for the young pianists, M = 24.7 years, SD = 3.0, range = 20–31; for the older pianists, M = 60.3 years, SD = 4.1, range = 52–68). There were 4 women and 8 men in each of the two expert groups. The young amateur group consisted of 5 women and 7 men; the older amateur group included 7 women and 5 men. No differences emerged among the four groups with respect to self-rated health condition; all participants reported that they were in at least average health. All of the pianists were paid for their participation.

Participants' educational background. All of the young participants, except for 1 in each skill group, had completed the German Gymnasium; that is, they had completed 13 years of public schooling. On average, the older participants had completed 11.5 years of school, because of the conditions following World War II and a more recent change in the German school system that increased the minimum years of public schooling and the time required to attain a degree for each of the three school types by another year. The skill groups were similar in this respect ($p >$ .71); the main effect of age group was significant, $F(1, 44)$ = 15.95, MSE = 1.42, $p < .001$. Detailed consideration of the professional backgrounds of the older amateurs and the professional career plans of the young amateurs suggested a high degree of similarity between groups.[1] The secular trend toward an increased number of years of schooling was almost identical in the two skill groups and would, if anything, increase the observed differences in performance between young and old participants and thus work against our maintenance hypothesis.

Participants' musical background. The young expert pianists were students in advanced soloist classes. All of them had already performed in public concerts. The older experts were professional pianists who had graduated from a music academy at younger ages and had considerable experience as public performers and teachers. Almost all of them had made several recordings or had appeared on radio or TV. The majority were teaching soloist students in master courses at music academies with international reputations. The expert pianists had started practice at a much earlier age (M = 6.75 years, SD = 2.75) than the amateurs (M = 9.33 years, SD = 3.82), $F(1, 44)$ = 7.38, MSE = 10.9, $p < .01$, with no significant differences between young and older participants. The young amateurs had had 9.9 years (SD = 4.9) of formal instruction at the piano, compared with only 6.0 years (SD = 3.0) for the older amateurs. Naturally, the young experts (M = 19.1 years, SD = 3.2) and older experts (M = 15.3 years, SD = 4.0) reported more years of formal instruction than the amateurs did. Differences between skill groups, $F(1, 44)$ = 69.27, MSE = 14.9, $p < .001$, and also age groups, $F(1, 44)$ = 11.96, $p < .01$, were reliable. A more detailed analysis suggested that the age effects reflected cohort differences and that older participants may have had to start working at an earlier age in their youth.

Apparatus

We used an electronic keyboard (Yamaha CB-300 Clavinova) and a Macintosh II computer to monitor the experimental tasks and collect data. A MIDI-interface recorded the velocity (i.e., force), onset, and offset of single keystrokes, with keystroke timing measured to the nearest millisecond. Velocity was measured in integer values ranging from 1–127, according to the standards supported by all MIDI equipment. We administered the Digit-Symbol Substitution Test (original version, Wechsler, 1955) as a pencil-and-paper test.

Procedure

We collected data during two sessions separated by 7–12 days. Session 1 began with an extensive biographical interview on the pianists' musical development. After answering a standard set of questions related to musical life events, the participants estimated the average amount of weekly deliberate practice they had had each year of their lives since they started playing the piano. They then participated in Experiment 1, which required speeded performance of coordinated movements. The task was to play a series of

[1] Ten of the 12 young amateurs were students in academic or vocational training programs. Two had already started to work full-time in their professions. Four were participating in nonacademic training programs as foreign-language secretaries or social workers or had completed such a program by the time of our study. The other 8 participants in this group were students from the sciences, environmental planning, and medicine. One subject in this latter group was already working as a scientist in a doctoral program. The older amateurs were 7 women and 5 men, 3 of whom had retired from their professions by the time of the investigation. Five were still working full-time, and the remaining 4 were working on a half-time basis. Eight of the 12 subjects had received academic training and had later worked as engineers (2), teachers (2), medical doctor, architect, lawyer, or scientist. Four subjects had worked or were still working in nonacademic professions, including accounting, nursery, and housekeeping. The two amateur groups were similar in terms of years of academic training beyond high school, with a higher mean for the older subjects (M = 5.5 years) than for the young subjects (M = 3.4 years).

nine keystrokes either with one hand or with both hands simultaneously. Each finger was assigned to one of five adjacent white keys on the piano; no lateral movements were required. We manipulated the complexity of hand coordination by having participants play with a single hand (left or right), simultaneously play mirror-image movements for the hands, or simultaneously perform different movements for the hands. We presented the tasks as a sequence of nine numbers, each indicating which finger of a given hand was to be used at that point in the movement sequence. We used numbers instead of musical notation to ensure that all participants used the identical assignment of fingers to keys. A display with the relevant task information appeared on the computer screen and remained accessible to participants during performance. Motor demands for each hand were identical across complexity conditions: The same series were used for the left and right hands, and bimanual tasks were generated by requiring that two of the single-hand tasks be performed simultaneously. Thus, the single-hand condition consisted of two series of keystrokes for each hand, and the two bimanual conditions involved playing two different series each. We presented conditions in ascending order of complexity and instructed the pianists to play accurately and rapidly while maintaining a steady tempo. We provided warm-up trials for each task to make sure the participants were able to execute the proper sequence of strokes. The participants then performed three blocks of 6, 12, and again 6 trials, respectively. During the first block of trials, we gave feedback only on speed and errors; during the second block of trials, participants received graphic feedback on speed and steadiness. The final block of trials was identical to the first block.

After Experiment 2, we introduced the diary procedure. Participants wrote down all the activities they could remember from the previous day on forms dividing the 24-hr day into 96 slots of 15-min intervals. They coded each activity according to a presented list of definitions for 12 music-related activities and 10 everyday activities. Between Sessions 1 and 2, participants filled out forms for each of 7 successive days and mailed them to us on the following day. At the end of the diary week, using copies of their diaries, participants coded each activity for the diary week according to the categories of activities provided in the instructions.

We began Session 2 with a debriefing on the diary procedure, after which we administered the musical interpretation task: Participants gave three successive performances of Prelude No. 1 in C Major (*Wohltemperiertes Clavier*) by Bach. We instructed the pianists to reproduce the interpretation of their liking three times, being as consistent as possible across performances. As mentioned earlier, musicians consider this piece to be technically simple; at the same time, it leaves room for musical interpretation and has been recorded by famous pianists. All performances were given from a score that, consistent with Bach's original version, included no notations on tempo or expressive interpretation. All of the participants knew the piece or felt sufficiently comfortable with it after up to 15 min of warm-up. The computer recorded the force (i.e., velocity measured as integer values ranging from 1 to 127) and onset/offset times of single keystrokes. Performances were also recorded on a tape recorder (UHER 4200 Stereo, Germany) at 15 inches per second for later evaluation.

After performing the musical interpretation task, the pianists completed a pencil-and-paper version of the Digit Symbol Substitution Test. They then performed a two-choice reaction time task that required speeded responding. In this task, the participants pressed one of two assigned keys on the piano keyboard with their right or left forefinger in response to four different stimuli (the letters *r, R, l,* and *L*) displayed on the computer screen. The experiment consisted of 120 trials, the first 20 of which we considered a warm-up block and did not include in the later analyses. The time between a participant's response and the presentation of the next item was 1 s. We used the piano keyboard in this task to make the response component of this measure of general processing speed as similar as possible to the skill under investigation. We used three finger-tapping tasks as measures of simple motor efficiency. After an auditory start signal, participants had to tap as fast as they could for 15 s using their right, left, or alternate forefingers on assigned piano keys. The end of a trial was marked by another auditory signal.

Experiment 2 was similar to Experiment 1. To eliminate any effects from difficulties the participants might have had with mapping symbols (i.e., number) to movements, we had the participants complete an extra block of trials during which they had to memorize the sequences. In this regard, Experiment 2 approached the normal conditions of piano solo performance involving playing from memory. After warm-up and the first block of trials, the participants had to memorize the relevant movement sequence without emphasis on speed. They had to perform the movement sequence correctly on three consecutive trials to reach the testing phase, which consisted of a block of 12 trials with feedback on errors, steadiness, and speed, followed by a final block of 6 additional trials. After Experiment 2, the pianists rated the six experimental tasks on how well they reflected components of piano playing skills. Session 2 concluded with an interview and a general debriefing.

Results

In discussing the results, we focus first on the mean differences in experimental task performance between age groups and expertise levels. When we present the results for the two skill-related tasks designed to maximize the effects of age and expertise, we contrast age effects on performance with the pattern of results that emerged from our assessment of general processing speed. This analysis provides a straightforward test of the selective maintenance account. We then describe the differences between our groups in past and current levels of deliberate practice. Finally, we focus on the relation between performance and deliberate practice, which we analyzed through a hierarchical regression approach.

Before conducting the analyses, we gave finger-tapping rates and single interkeystroke intervals (IKIs) in the complex movement tasks log transformations to compensate for the skewness of IKI distributions and to be conservative with respect to proportional Age $\times$ Task Complexity interactions (Cerella, 1990). The significance level for all analyses of variance (ANOVAs) was set to .05. We performed three post hoc comparisons to test interactions involving group factors: young experts versus older experts, older experts versus young amateurs, and young amateurs versus older amateurs. The post hoc tests were t tests with two-tailed alpha levels adjusted according to Bonferroni's method.

Self-Paced Musical Interpretation

Ratings of recordings. Three expert raters evaluated each pianist's second performance of Bach's Prelude No. 1

on seven 10-point scales.[2] Recordings were arranged on a tape in a randomized order, and raters listened to each of them without knowing the participant's background. We averaged the seven scales for each of the three raters and transformed the mean into z scores to control for different anchor points between raters. A repeated measures ANOVA using rater as a within-subject factor showed that experts (M = .566, SD = .577) were systematically rated higher than amateurs (M = −.566, SD = .824), $F(1, 44) = 36.19$, $MSE = 1.27$, $p < .001$. On average, older pianists' performances (M = −.296, SD = .921) were rated worse than younger pianists' (M = .296, SD = .805), $F(1, 44) = 9.88$, $p < .01$. Although the interrater reliability based on the aggregated scores was reasonably high (Cronbach's α = .892), the interpretation was complicated by a reliable three-way interaction involving rater, skill level, and age group, $F(1, 44) = 3.43$, $MSE = .26$, $p < .05$. Post hoc t tests showed that all three raters agreed in their higher evaluation of experts compared with amateurs, all ts(46) > 4.03, all ps < .001. Our analysis of rated performances clearly validated the hypothesized differences in the performances of expert and amateur pianists. Strong conclusions about age-related differences are difficult to draw because of the lack of agreement among raters. There was at least an indication of differences between young and older amateurs, however.[3]

Consistency of phrasing. Bach's Prelude No. 1 contains 35 bars, of which the first 32 have an identical temporal structure and a similar melodic structure (broken chords). We included only these bars in the analyses, and they provided three series of 512 data points for each pianist. Figure 1 illustrates the musical structure and the logic of analysis for the first three bars of the piece.

The whole piece can be perceived as a harmonic progression of chords, which are arpeggiated (broken) during performance. A deadpan performance, using only the information provided by the score, would produce identical time intervals between onsets of consecutive notes and identical loudness values for each keystroke. The most pertinent structure is implied in the harmonic progression of chords: Each bar constitutes a small phrase. The overall phrasing of the piece is most effectively expressed by the organization of relative tempo or loudness of these bar phrases. Our analysis of consistency of musical phrasing thus focused on the mean duration and force (loudness) of each bar. Wrong notes and keystrokes immediately following an error were not included in the analyses, and only those bars in which at least 14 of the 16 notes were correct in all three performances were considered for the analyses of consistency. Summary statistics of these analyses are provided in Table 1.

Figure 1. Force applied to single keystrokes from the first three measures in three performances of Prelude No. 1 in Bach's *Wohltemperiertes Clavier.* The solid line indicates the individual mean. Data are from 1 older expert pianist.

Experts had a lower error rate than amateurs, $F(1, 44) = 7.04$, $MSE = 5.64$, $p < .05$, and also played faster than amateurs, $F(1, 44) = 5.56$, $MSE = 1{,}311$, $p < .05$. Overall, they applied more force than amateurs, $F(1, 44) = 12.11$, $MSE = 158$, $p < .005$, and produced more variability in this measure than amateurs did, $F(1, 44) = 5.48$, $MSE = 16.3$, $p < .05$. Older pianists produced less variability (M = 5.45, SD = 2.31) than did young pianists (M = 7.00, SD = 2.52), $F(1, 44) = 5.35$, $p < .05$, and this effect was less pronounced in the first interpretation than in the other two interpretations, $F(1, 44) = 3.49$, $MSE = .51$, $p < .05$.

We calculated three coefficients (Pearson's product–moment correlations) reflecting the correlations between the 32 bar means in the three performances and transformed them into Z scores before conducting further analysis. The reliability based on the standardized scores so derived was high (Cronbach's α = .910). A repeated measures ANOVA revealed that expert pianists were more systematic in their variation of loudness (force) than amateurs were, $F(1, 44) = 29.89$, $MSE = 1.54$, $p < .001$, and this effect did not depend on which of the three performances were compared. Differences between age groups ($p > .07$) and the interaction of the two group factors ($p > .54$) were not significant. No group differences in variability and consistency emerged when we analyzed timing at the level of bar means, although the related coefficients showed reasonable reliability and were clearly above chance.

It could be argued that it is easier to produce higher consistency across repeated performances when more extreme variations are made. To adjust the derived correlations for individual differences in the total amount of variation applied, we performed a repeated measures analysis of

[2] We are indebted to John Sloboda for his advice on designing the scales. The seven scales were 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–precision of rhythm. Reliability (Cronbach's α) was high across raters (α = .950) and also when raters were considered separately (α > .856).

[3] Two of the three raters evaluated older amateurs' performances as worse than young amateurs' and gave similar credit to the performances by the two expert groups. On the basis of these ratings, age effects in the amateur group were reliable, $t(22) = 2.78$, $p < .05$, corresponding to a large (f = .59) effect size. Age-related effects in the expert group were small (f = .21) and not significant, $t(22) = 1.01$, $p > .32$. The third rater showed the reverse pattern, evaluating older amateurs nearly as positively as young amateurs, $t(22) = 1.59$, $p > .12$, while at the same time reliably rating young experts as better than older experts, $t(22) = 2.59$, $p < .05$.

Table 1
Differences Between Skill Groups in the Musical Interpretation Task

Variable	Amateurs	Experts
% of errors		
M	1.16	.11
SD	1.88	.21
Mean force applied (onset velocity: 1–127)		
M	74.5	81.8
SD	6.29	8.64
Variability of force applied		
M	5.44	7.01
SD	2.20[a]	2.61[a]
Total playing time (s)		
M	128	104
SD	50	15
Consistency of force variation (*r*)		
M	.636	.842
SD	.173	.079
Consistency of force variation (*z*)		
M	−.565	.565
SD	.942	.423

[a] Standard deviations of bar means.

covariance (ANCOVA) introducing the averaged standard deviations for the three pairs of performances as covariates into the analysis described above. As could be expected from the reported group differences in terms of overall variability, the regression coefficient for the covariates was significant, $F(1, 43) = 5.16$, $MSE = 1.41$, $p < .05$. The differences in adjusted consistency between skill levels were still highly significant, $F(1, 43) = 21.51$, $p < .001$, but the differences between age groups were attenuated, $F(1, 43) = 1.15$, $p > .29$. Maxwell, Delaney, and Manheimer (1985) demonstrated that an ANOVA of residuals obtained after controlling the effect of covariates in a regression analysis leads to a more conservative test of group differences than does the described ANCOVA in cases like ours. When we conducted the appropriate analyses, we found that the main effect of expertise was still highly significant ($p < .001$), whereas the age effect was further diminished ($p > .60$).

General Processing Speed and Peripheral Motor Efficiency

General processing speed. ANOVAs of the two measures of general processing speed showed the expected strong effects of age group: Older participants had a lower score on the Digit Symbol task ($M = 50.8$, $SD = 10.9$) than did young participants ($M = 69.0$, $SD = 9.62$), $F(1, 44) = 36.67$, $MSE = 108$, $p < .001$. Similarly, older participants' response times on the choice reaction time task were longer ($M = 518$ ms, $SD = 68$) than those of young participants ($M = 422$ ms, $SD = 44$), $F(1, 44) = 32.07$, $MSE = 3{,}423$, $p < .001$. Main effects of skill level interactions in both tasks did not even approach significance, all *F*s, $(1, 44) < .54$, all *p*s $> .46$. Following a convention in cognitive aging research (e.g., Salthouse, 1993, 1994), we also analyzed performance on the two measures of general processing speed in terms of log time per item, which yielded the same pattern of results. The error rates for both tasks were low and did not differ between groups. Digit Symbol score and number of errors were basically uncorrelated, indicating that participants did not make trade-offs between speed and accuracy. Number of errors and choice reaction time were correlated ($r = -.38$, $p < .01$); however, a control analysis using error rate as a covariate did not alter the pattern of statistically reliable findings. In sum, these results are in line with numerous findings from the cognitive aging literature (see Salthouse, 1985b, for reviews) and demonstrate that our older sample was "normal" with respect to age-related decline in speed of general cognitive–motor processes. Most important, there was no specific advantage for the expert pianists in either age group.

Peripheral motor speed: Simple finger-tapping tasks. We analyzed performance in the three tapping tasks (right, left, and alternate index fingers) with a repeated measures ANOVA using finger as a within-subject factor. We specified two orthogonal contrasts comparing right and left finger tapping and the mean of these two single-finger tasks with alternate-finger tapping. Both contrasts were significant, indicating that participants tapped faster with their right fingers than their left fingers, $F(1, 44) = 40.47$, $MSE = .001$, $p < .001$, and that alternate-finger tapping was faster than single-finger tapping, $F(1, 44) = 767.69$, $MSE = .002$, $p < .001$. This pattern was confirmed in separate post hoc tests for all groups, all $ts(11) > 2.88$, *p*s $< .05$.

The interaction of the expertise factor with the contrast of single-finger and alternate-finger tasks was reliable, $F(1, 44) = 12.22$, $p < .001$. The tapping performances of experts and amateurs is shown in Figure 2. Expert pianists gained a larger advantage than amateurs from overlapping movements of the different hands. Their superior performance at the level of peripheral motor ability was confirmed for all three conditions, $F(1, 44) = 53.49$, $p < .001$, and the pattern of statistically reliable findings did not change when partic-

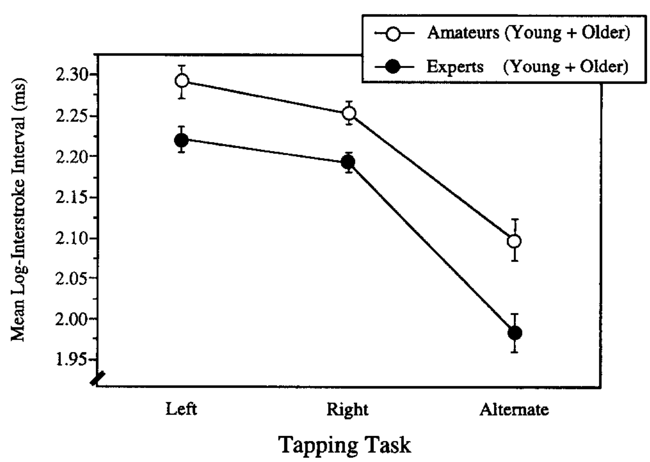

Figure 2. Mean log interstroke intervals for expert and amateur pianists in the three tapping tasks (left, right, and alternate index fingers). Bars indicate 95% confidence intervals.

ipants' handedness was taken into account. We found no reliable effects of aging on tapping performance for either expert or amateur pianists, and only in the alternate-finger tapping condition were age decrements suggested by the size of the effect. These findings were particularly surprising in the case of the amateur pianists, because of the consistent effects of aging on tapping performance that have been found in random samples of adults (Salthouse, 1985b), and were addressed in Study 2.

Performance in Complex Skill-Related Tasks

Experiment 1: Speeded movement coordination. Analyses of practice effects on performance indicated a strong overall speedup, which was similar for all groups; however, performance stabilized over the last two blocks. We analyzed log IKIs from the last block with a repeated measures ANOVA using level of coordination complexity as a within-subject factor.[4] The mean performance levels for all groups in the three conditions are shown in Figure 3.

To assess the effect of the experimental complexity manipulation, we defined two orthogonal contrasts comparing single-hand performance (the average of tasks performed with the right or left hand) with bimanual performance (the average of the mirror-image and different movements conditions) and the two bimanual conditions with each other. Bimanual performance was slower than performance in the single-hand condition, $F(1, 44) = 195.15$, $MSE = .002$, $p < .001$. Coordination of different movements in opposite hands impaired speed compared with the mirror-image movements condition, $F(1, 44) = 89.71$, $MSE = .007$, $p < .001$. Post hoc tests performed separately for each group confirmed that the experimental manipulation of task complexity was effective for all four groups of participants.

The effect of increased bimanual coordination complexity was more pronounced in experts than in amateurs. The skill factor interacted with the contrast between single-hand and bimanual tasks, $F(1, 44) = 9.00$, $p < .005$, and the interaction also emerged when the two bimanual conditions (the mirror-image and different movements conditions) were compared, $F(1, 44) = 6.31$, $p < .05$. Similarly, the difference in speed between bimanual and single-hand movements was larger for older pianists than for young pianists, $F(1, 44) = 8.46$, $p < .01$. Overall, the experts outperformed the amateurs, $F(1, 44) = 141.03$, $MSE = .02$, $p < .001$. This main effect was confirmed by conservative post hoc tests showing that older experts were superior to young amateurs in all conditions, all $ts(22) > 3.85$, all $ps < .001$. The older experts' performance was worse than the young experts' only in the most complex condition, $t(22) = 2.68$, $p < .05$; older amateurs were slower than young amateurs in all three conditions, all $ts(22) > 2.89$, all $ps < .01$.

Age groups and skill groups were similar in terms of error rates. Positive but mostly nonsignificant correlations indicated that pianists who had longer IKIs also made more errors, a finding that rules out speed–accuracy trade-offs. Task complexity was reflected in the overall error rates, which were higher in the bimanual tasks than in the single-hand tasks, $F(1, 44) = 9.16$, $MSE = 108$, $p < .005$, and also higher for the different movement condition than for the mirror-image movement condition, $F(1, 44) = 15.99$, $MSE = 136$, $p < .001$.

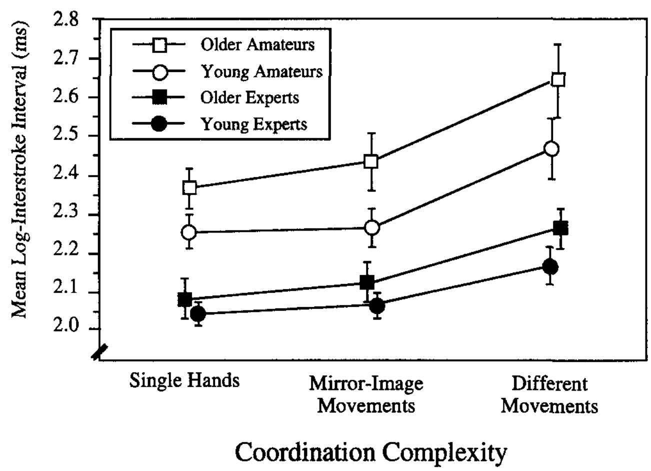

Figure 3. Mean log interstroke intervals for the three coordination complexity conditions in Experiment 1 for the four groups of pianists. Bars indicate 95% confidence intervals.

Experiment 2: Speeded movement coordination after memorization. We analyzed the data on speeded performance in Experiment 2 in the same manner as in Experiment 1. Practice effects across blocks were similar to those in Experiment 1 and justified the use of the last block of trials as a criterion measure. Mean performance levels are shown in Figure 4.[5]

The experimental manipulations of coordination complexity acted as predicted and were confirmed by separate post hoc tests for each group. Speed in the single-hand tasks was faster than in the bimanual tasks, $F(1, 44) = 184.04$, $MSE = .003$, $p < .001$. Different movements with opposite hands were reliably slower than mirror-image movements with opposite hands, $F(1, 44) = 101.56$, $MSE = .007$, $p < .001$. All of the main group differences found in Experiment 1 were replicated in Experiment 2. The dissociation between age and expertise level was more pronounced in Experiment 2 and emerged as a significant three-way interaction between age group and skill level when single-hand and bimanual movement conditions were compared, $F(1, 44) = 8.47$, $p < .01$. Post hoc comparisons revealed a straightfor-

[4] When we considered the movement sequences in each condition as single items, reliability coefficients were informative of the stability of participants' rankings across tasks. The single-hand condition included four sequences; the two bimanual conditions consisted of two sequences each. Cronbach's αs computed on the basis of these eight items were .972 (total sample), .925 (amateurs), .888 (experts), .973 (young pianists), .968 (older pianists), .921 (young amateurs), .824 (young experts), .857 (older amateurs), and .889 (older experts).

[5] Reliability coefficients for the three conditions in Experiment 2 were .959 (total sample), .892 (amateurs), .914 (experts), .956 (young pianists), .958 (older pianists), .893 (young amateurs), .807 (young experts), .838 (older amateurs), and .937 (older experts).

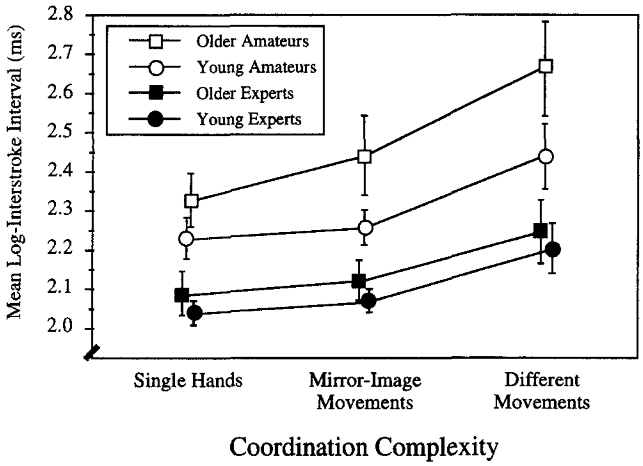

Figure 4. Mean log interstroke intervals for the three coordination complexity conditions in Experiment 2 for the four groups of pianists. Bars indicate 95% confidence intervals.

ward picture. None of the three comparisons between the two expert groups was reliable, all $ts(22) < 1.70$, all $ps > .10$. Older experts' performance was superior to that of young amateurs in all conditions, all $ts(22) > 3.37$, all $ps < .005$. and thus expert pianists generally outperformed amateurs, $F(1, 44) = 77.53$, $MSE = .033$, $p < .001$, even when this conservative standard with respect to age was adopted. Older amateurs were similar to young amateurs in the single-hand condition but reliably slower in both bimanual tasks, both $ts(22) > 3.32$, both $ps < .005$.

Expert pianists were less impaired by increased demands on coordination complexity when single-hand and bimanual movements were contrasted, $F(1, 44) = 15.29$, $p < .001$, and this was also true for the contrast of mirror-image and different bimanual movements, $F(1, 44) = 5.39$, $p < .05$. The main effect of age, $F(1, 44) = 13.23$, $p < .005$, was qualified by a reliable interaction between age group and expertise, $F(1, 44) = 4.15$, $p < .05$. Furthermore, the age effect interacted with the contrast between single-hand and bimanual tasks, $F(1, 44) = 7.68$, $p < .01$. Post hoc analyses confirmed larger performance decrements resulting from task complexity among the older amateurs than among the young amateurs.

Correlations between number of errors and IKI strongly suggested that slower pianists made more errors, a finding that rules out speed–accuracy trade-offs. The effects of task complexity and expertise reflected in the error rates were in line with the pattern of results for speed; no effects or interactions related to age were significant. The higher overall error rate in amateurs compared with experts, $F(1, 44) = 5.10$, $MSE = 412$, $p < .05$, was pronounced when we compared single-hand and bimanual movements, $F(1, 44) = 4.85$, $MSE = 64.4$, $p < .05$, and also when we compared mirror-image and different bimanual movements, $F(1, 44) = 8.16$, $MSE = 172$, $p < .01$.

In Experiment 2, participants had to memorize the movement sequences before taking the performance tests. The number of trials required for successful memorization was recorded, and the means and standard deviations for the number of trials to criterion are given in Table 2. Participants needed more trials to memorize sequences in the bimanual conditions than in the single-hand condition, $F(1, 44) = 14.36$, $MSE = 5.37$, $p < .001$. Memorization of sequences that required different movements with opposite hands was more difficult than memorization of sequences that required mirror-image movements, $F(1, 44) = 23.33$, $MSE = 9.85$, $p < .001$. Expert pianists took fewer trials than amateurs, $F(1, 44) = 5.25$, $MSE = 11.9$, $p < .05$. Neither the main effect of age group nor any interactions were significant. The memorization procedure was designed to provide the extra training necessary to permit later performance from memory and was not a test of memorization ability per se. Neither the amount of time participants spent with the task display after an error nor the method of memorization was under experimental control. The critical issue was whether observed differences during the memorization phase could limit the interpretability of the speed measures for performance from memory during testing. We calculated correlations between the number of trials required by each participant during the initial memorization phase on the one hand and error rates and IKIs during the final assessment for maximum speed on the other. The positive values obtained ruled out the possibility that interindividual differences in maximum speed could have been compensated for by benefits from extended memorization practice.

Comparison of General Processing Speed and Speeded Skilled Performance

Our findings show a large age-related decline in general processing speed for experts as well as amateurs. In con-

Table 2
Number of Trials to Criterion in the Memorization Phase of Experiment 2

Group	Single hand	Mirror-image movements with both hands	Different movement with each, simultaneously	Total (group)
Amateurs				
M	5.09	4.94	8.44	6.16
SD	2.17	2.63	4.74	3.08
Experts				
M	3.83	4.00	6.69	4.84
SD	1.07	1.48	4.05	1.61
Young pianists				
M	4.15	3.77	6.96	4.96
SD	1.90	1.22	4.37	2.12
Older pianists				
M	4.78	5.17	8.17	6.04
SD	1.69	2.66	4.54	1.99
Total (task)				
M	4.46	4.47	7.56	5.50
SD	1.81	2.17	4.45	2.11

Note. Minimum value = 3.

trast, the effects of age on experts' speed in skilled performance tested in Experiments 1 and 2 were small, and most failed to reach statistical significance. This pattern of results is inconsistent with the uniform age-related decline across tasks predicted by the general factor account. It was necessary, however, to demonstrate that the differential decline in the performance of experts predicted by the selective maintenance account was statistically reliable in a combined analysis of the performance on the two types of tasks. Log time per item was aggregated for the two measures of general processing speed (the Digit Symbol Substitution Test and the choice reaction time task) and compared with the mean log IKIs aggregated across the three conditions from Experiments 1 and 2. We conducted a repeated measures ANOVA with task type as an additional within-subject factor with two levels. Mean performances for the four groups in both types of tasks are shown in Figure 5.

The three-way interaction between age group, skill level, and type of task predicted by the selective maintenance account was indeed significant, $F(1, 44) = 5.84$, $MSE = .01$, $p < .05$, and is illustrated by the crossover of bold and dashed lines in Figure 5. Age-related effects for both general processing speed and skill-related tasks did not differ in the amateur group (the dashed line and the topmost line in Figure 5 are almost parallel). At the same time, differences between young and older experts were small in skill-related tasks but pronounced in measures of general processing speed. This impression was confirmed by a reliable interaction of skill level and type of task, $F(1, 44) = 93.95$, $p < .001$. Further confirmation came from subsequent ANOVAs conducted separately for skill levels using the same design: a reliable Age Group × Task Type interaction emerged in the expert group, $F(1, 22) = 4.67$, $MSE = .01$, $p < .05$; however, the interaction failed to reach significance in the amateur sample ($p > .15$).

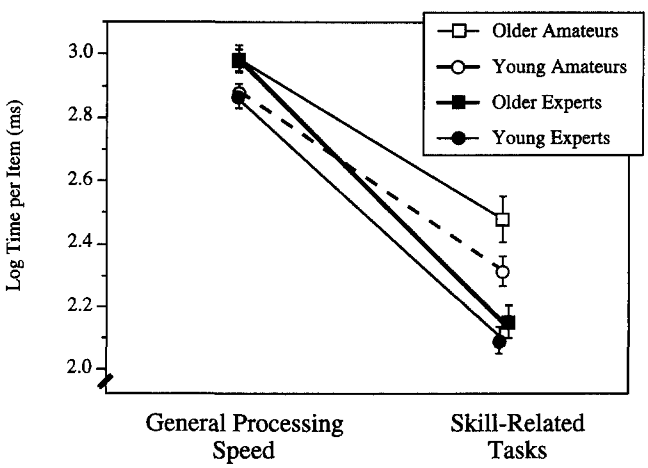

Figure 5. General processing speed and performance in representative skill-related tasks. Mean log time per item from the Digit Symbol Substitution Test and the choice reaction time task were averaged to measure general processing speed. Mean log interstroke intervals from Experiments 1 and 2 were averaged to measure performance in skill-related tasks. Bars indicate 95% confidence intervals.

In line with results reported earlier, post hoc tests revealed that age groups within and across both skill levels were reliably different from each other in aggregated measures of general processing speed, all $ts(22) > 4.22$, all $ps < .001$. Experts did not differ from amateurs, regardless of which of the two age groups was considered. Young amateurs performed better than older amateurs on skill-related tasks when measures were aggregated, $t(22) = 3.83$, $p < .001$; however, older experts clearly outperformed young amateurs, $t(22) = 4.65$, $p < .001$. Differences between young and older experts failed to reach significance by a slight margin when aggregated performance measures from skill-related tasks were compared, $t(22) = 1.89$, $p < .08$. Main effects of age and type of task in all analyses reported were reliable, as was the overall effect of skill level in the four-group design. No other main effects or interactions reached significance.

Power Analysis of Age Effects

A general problem for studies of expert performance is that only a small number of available participants meet the highly selective criteria for inclusion in the group of experts. Consequently, the statistical power in the post hoc comparisons involving experts is rather limited. This is especially problematic when measures are contrasted separately for single experimental conditions. A proper evaluation of the relative magnitude of age effects requires a power analysis.[6] Table 3 shows the estimated magnitudes (f) of the age effects in the ANOVAs reported for the total sample and separately for experts and amateurs. The critical N necessary on a priori grounds to have .80 power of detection is provided in those cases where the F test did not reach significance.

The musical interpretation task and measures of tapping speed did not reveal significant differences between age groups, but they did reveal clear effects of skill level. Note that the reported sizes of the effects for this task are conservative, because they do not take age-related differences in overall variability into account. Experiments 1 and 2 were designed to maximize the effects of age and expertise on speeded performance, and the production of complex movement sequences tested in these experiments was the only task condition that yielded reliable Age × Skill Level interactions.[7] The reported contrast of the performance in

[6] We computed power calculations as well as calculations for f and the critical N for attaining sufficient power with the program *G·Power* (Buchner, Faul, & Erdfelder, 1992), which uses the methods recommended by Cohen (1988) for our purposes. Effect sizes are given as f values and were always computed from η^2s calculated through the multivariate ANOVA routines in the *Statistical Package for the Social Sciences* (SPSS, Inc., 1988) to allow comparisons across analyses. Following Cohen's suggestions, effect sizes corresponding to fs of .10, .25, and .40 correspond to small, medium, and large effects, respectively.

[7] After log transformation, the data approached normal distribution, where the mean and the median coincide. The common procedure of analyzing the median of observed latencies would

Table 3
Effect Sizes (f) for Differences Related to Factor Age Group and Critical Ns

Task	Total sample		Experts		Amateurs	
	f	Critical *N*[a]	*f*	Critical *N*[b]	*f*	Critical *N*[b]
Musical interpretation task	.27	104	.32	78	.29	98
Tapping speed	.18	248	.12	518	.23	149
Right index finger	.12	555	.00	—	.23	149
Left index finger	.00	—	.05	2,607	.03	7,863
Alternate index fingers	.28	102	.29	95	.27	108
General processing speed	1.03	***	1.04	***	1.04	***
Digit Symbol Substitution Test score	.92	***	.92	***	.93	***
Choice reaction time	.88	***	.95	***	.81	***
Experiment 1	.69	***	.50	*	.84	***
Single hand	.50	**	.28	104	.71	**
Mirror-image movements with both hands	.64	***	.41	50	.82	**
Different movement with each hand	.58	***	.57	*	.62	**
Experiment 2	.55	***	.30	90	.73	**
Single hand	.41	**	.34	71	.47	*
Mirror-image movements with both hands	.56	**	.36	63	.71	**
Different movement with each hand	.49	**	.18	240	.72	**

Note. Critical *N* is the total sample size necessary for an a priori .80 power of detection at $\alpha = .05$. Values too large to be computed are denoted by a dash. For effects significant with the available sample size, asterisks denote alpha levels.
[a] $F(1, 46)$. [b] $F(1, 22)$.
* $p < .05$. ** $p < .01$. *** $p < .001$.

these two experiments with measures of general processing speed revealed different patterns of age-related decline for experts on the two types of speeded tasks, as predicted by the selective maintenance account. Consistent with this dissociation, a different pattern of effect sizes for amateurs and experts is shown in Table 3: Amateurs exhibited the pattern predicted by the general factor account, whereby the "normal" age-related decline observed for the measures of general processing speed matched the magnitudes observed for speeded performance in the complex, skill-related tasks. In contrast, the age effects observed in the same tasks for experts were much smaller than those found with measures of general processing speed. Nonetheless, the estimated age effects for the expert sample were medium to large in Experiments 1 and 2. On the basis of our power analyses, we cannot dismiss the claim that general age-related slowing may play some role even in experts' skilled performance; however, our results show that the detrimental effects of aging evident in the measures of general processing speed are somehow compensated for or moderated in older experts' performance on music-related tasks. The selective maintenance account predicts that the critical moderating factor involves active efforts directed at maintaining specific skills. To investigate this working hypothesis in more detail, we examined our data on deliberate practice.

Relation Between Performance on Music-Related Tasks and Deliberate Practice

In this section, we first examine mean differences among the four groups in current and past amounts of deliberate practice. Next, we report the results of hierarchical regression analyses we performed to explore the relation between performance in music-related tasks and deliberate practice. Our objective is to demonstrate that measures of deliberate practice can account not only for mean differences between age groups and skill levels, but also for interindividual differences within groups. We then show that maintenance practice is indeed critical to older experts' compensation for age-related decline in skilled tasks. Finally, we compare experts and amateurs with respect to the role of maintenance practice in moderating age-related decline in skilled performance. Returning to the issue of statistical power, we consider how much of the observed performance difference between the young and older pianists should be attributed to general aging and how much of it can it be explained by differences in deliberate practice.

Group differences in current and past amount of deliberate practice. As shown in earlier work (Ericsson et al., 1993), the activity of musicians that most closely matches our definition of deliberate practice is practicing alone. In the present study, the amount of time participants spent practicing at the time of investigation was determined from their diaries. Figure 6 shows the total amount of practice engaged in during the diary week by the four groups.

hence give similar results but entail somewhat less statistical power. Analyses based on medians gave the same results as found for Experiments 1 and 2 and the tapping tasks, with two noteworthy exceptions: First, the Age Group × Skill Level interaction in Experiment 1 was significant, $F(1,44) = 7.71$, $MSE = 55{,}499$, $p < .01$, and, second, the interaction between skill level and coordination complexity in the tapping tasks dropped below significance. Correlations between log values and medians in the three tasks ranged between .945 and .983, with a mean of .964.

An ANOVA revealed a significant interaction between age group and skill level, $F(1, 44) = 20.16$, $MSE = 34.4$, $p < .001$. Post hoc comparisons revealed that young expert pianists ($M = 26.7$ hr, $SD = 8.7$) practiced reliably more than older expert pianists ($M = 10.8$ hr, $SD = 7.6$), $t(22) = 3.74$, $p < .002$, who in turn invested more time in deliberate practice than young amateurs did ($M = 1.9$ hr, $SD = 1.9$), $t(22) = 4.04$, $p < .002$. The difference between the two amateur groups was not significant; older amateurs practiced for 1.2 hr ($SD = 1.3$) on average. The main effect of skill level, $F(1, 44) = 103.50$, $p < .001$, can thus be considered reliable.[8]

Consistent with earlier studies (Ericsson et al., 1993), we found our participants to be reasonably accurate in retrospectively estimating their past weekly amounts of practice. A comparison of diary measures and retrospective estimates for the last year showed a high correlation ($r = .88$, $p < .001$). Figure 7 shows the estimated weekly amount of solo practice as a function of participants' age.

To assess the long-term effects of practice, we summed up weekly estimates across years. We transformed amounts of accumulated practice into logs before analysis to equate variance across groups. Naturally, accumulated practice increased with age, $F(1, 44) = 36.34$, $MSE = .078$, $p < .001$, but it was also considerably higher among experts than among amateurs, $F(1, 44) = 135.86$, $p < .001$. Figure 8 shows the mean group differences for the untransformed values.

The need to distinguish between deliberate practice and mere experience, which inevitably increases with age (time of involvement), is best illustrated by a comparison of young expert pianists and older amateur pianists: At a mean age of 24, the young experts had accumulated more than twice as much practice as older amateurs had over an average of 60 years. This difference was reliable even after log transformation, $t(22) = 3.13$, $p < .01$.

The selective maintenance account posits that the role of practice goes beyond the initial acquisition phase. To separate the initial acquisition, peak engagement, and maintenance phases of skill development, we computed three measures of accumulated practice: practice accumulated until age 20, practice accumulated during a 20-year phase of maximal deliberate practice, and practice during the last 10 years before the year of the study. We should point out that these three variables captured overlapping time periods for the young participants but were likely to represent different time periods for older participants. We used log10 values for these three variables to equate variances across groups. Experts had accumulated more hours of deliberate practice during their first 20 years of life ($M = 4.02$, $SD = .241$) than had amateurs ($M = 3.07$, $SD = .808$), $F(1, 44) = 31.01$, $MSE = .347$, $p < .001$. When the 20 years of most intense engagement in deliberate practice were considered, reliable effects of skill level, $F(1, 44) = 140.83$, $MSE = .074$, $p < .001$, as well as age group, $F(1, 44) = 9.27$, $p < .005$, emerged. Amounts of practice during the last 10 years before the study were higher among experts ($M = 3.93$, $SD = .327$) than among amateurs ($M = 2.99$, $SD = .423$), $F(1, 44) = 77.74$, $MSE = .136$, $p < .001$.

The patterns of group means for current and past amounts of practice matched most of the differences we had found earlier in music-related performance for the four groups of pianists. However, a stronger test of the role of deliberate practice was whether the amount of practice predicted individual differences in performance beyond the design vari-

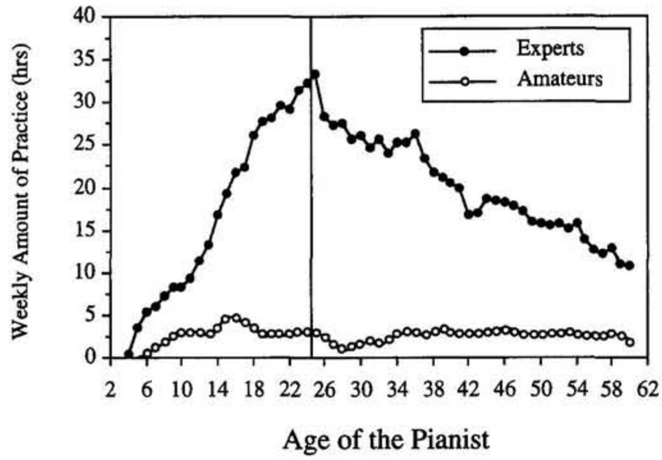

Figure 7. Pianists' retrospective estimates of their weekly practice as a function of age. Data in the left panel are aggregated for young and older pianists. Data points above the minimum ages (20 for the young pianists and 52 for the older pianists) include at least 50% of the participants in each group.

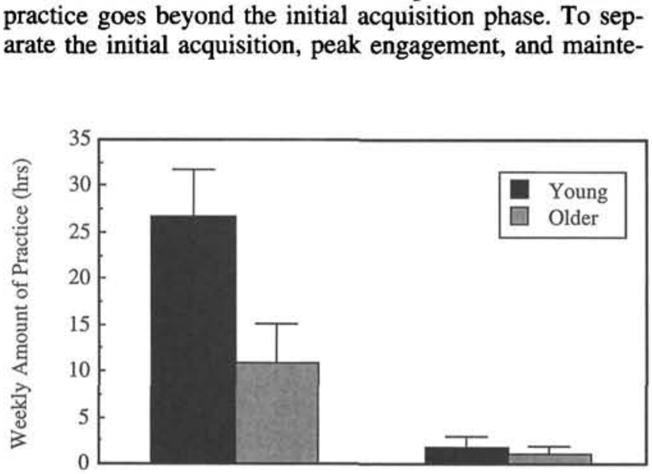

Figure 6. Weekly practice during the diary week for the four groups of pianists. Bars indicate 95% confidence intervals.

[8] The large differences between amateurs and experts, especially with respect to music-related activities, naturally affected the similarity of variances between cells. To conform with the statistical prerequisites of the ANOVA, we performed control analyses for all investigations of current activities. These analyses transformed the raw measures into $\log 10(x + 1)$ values (some participants had values less than 1 on these measures) whenever the equal variances assumption was violated. The pattern of results for these and later analyses was the same when we analyzed the transformed values.

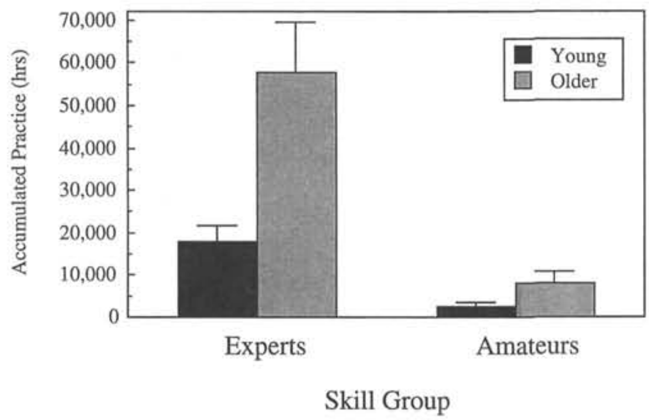

Figure 8. Estimated accumulated practice for the four groups of pianists. Bars indicate 95% confidence intervals.

ables of expertise and age group and their interaction. We present the results of this analysis in the next section.

Amount of deliberate practice as a predictor of music-related task performance. We performed hierarchical regression analyses to address two questions: (a) whether measures of deliberate practice predicted individual differences in task performance within groups and (b) how well a model based solely on measures of deliberate practice can predict the performance of experts and amateurs. Using the Statistical Package for the Social Sciences (SPSS, Inc., 1988), we successively implemented three sets of predictor variables, henceforth referred to as the *design factor model,* the *practice model,* and the *combined model.* The design factor model included the orthogonal design factors age group, skill level, and their interaction. The practice model included four measures of deliberate practice: amount of current practice based on the diaries and the three measures of accumulated practice reflecting engagement during different phases of skill development. The combined model consisted of all predictor variables, that is, the three design factors plus the four measures of deliberate practice mentioned above. Because of the presumed collinearity among different measures of practice intensity, on the one hand, and among practice variables and design factors, on the other hand, we performed the hierarchical regression analyses following an approach recommended by Cohen and Cohen (1975). We analyzed four sets of tasks: the consistency of dynamic force changes in successive interpretations of Bach's Prelude No. 1, the three tapping tasks, and the three conditions of Experiments 1 and 2. We used log-transformed IKIs as dependent measures in speeded tasks; the mean of the three z-standardized coefficients for consistency of force variation at the level of phrase (bar means), served as the dependent measure in the musical interpretation task.

There is consensus in the literature that the relation between amount of practice and acquired level of performance is nonlinear and is best described by a power function (Anderson, 1982; Newell & Rosenbloom, 1981). The theoretical motivation and empirical support for this assumption are weaker for phases beyond the initiation of training (i.e., the 20 years of most intense engagement and the last 10 years), however. Still, a monotonous log transformation for all three measures of accumulated practice appeared to be a reasonable first approach. The nonlinear relation of the power function can be converted into a linear form by log-transforming both the amount of practice and the performance. Although we used linear regression techniques, the underlying statistical model actually assumed a log–log relation between accumulated practice and raw measures of speeded performance.

The results of the hierarchical regression analysis are presented in Table 4. Consistent with the results from the ANOVAs, the amount of variance accounted for by the design factor model was significant in all tasks and conditions, all $Fs(3, 44) > 9.85$, all $ps < .001$. We determined the unique contributions for each design factor by separately removing single variables from the complete model. Given the orthogonal design, the unique variances added up to the total R^2 for the design factor model within the accuracy of rounding errors.

The combined model resulted from the simultaneous addition of the four practice variables to the design factor model. The associated incremental R^2s (see Table 4) allowed an evaluation of whether the account of individual differences could be improved over and above the group means by the consideration of deliberate practice. Reliably more variance was accounted for in the most complex condition of all speeded tasks, that is, for different movements by opposite hands in Experiment 1, $F_{\text{change}} = 4.49$, $p < .005$, as well as in Experiment 2, $F_{\text{change}}(4, 40) = 4.17$, $p < .01$, and in the alternate-finger tapping task, the $F_{\text{change}}(4, 40) = 3.04$, $p < .05$. The beta weights indicated that pianists who practiced more showed better task performance. Predictability of performance in these conditions can thus be improved when individual differences in amounts of deliberate practice within groups are taken into account.

The combined model accounted for systematic variance in all tasks and conditions, all $Fs(7, 40) > 4.40$, all $ps < .001$. Inspection of the unique variances for the factors of the combined model was interesting, because it provided information about the degree to which variance associated with the design factors was captured by the practice variables. The unique variances related to skill level were clearly reduced by the presence of practice variables; however, except for the musical interpretation task and the alternate tapping task, small yet reliable variance remained. The unique variances associated with the interaction term and the age group main effect were also reduced, but to a less extent than the variance related to the skill factor. The small amounts of unique variance associated with the four practice measures were not interpretable and reflected only the high collinearity among these variables.

The practice model was implemented through simultaneous removal of the three design variables from the combined model. The associated R^2s (see Table 4) reflected a loss in predictive power when individual differences were accounted for only in terms of the four practice variables.

Table 4
Hierarchial Regression Analyses Implementing Three Different Models

		Finger tapping			Experiment 1			Experiment 2		
Predictor variables	Musical interpretation	Right	Left	Alternate	Single hands	Mirror-image movements with both hands	Different movements with each hand, simultaneously	Single hands	Mirror-image movements with both hands	Different movements with each hand, simultaneously
Design factor model	.43***[a]	.46***[a]	.40***[a]	.52***[a]	.75***[a]	.72***[a]	.72***[a]	.62***[a]	.65***[a]	.63***[a]
Skill level	.38***[a]	.44***[a]	.40***[a]	.48***[a]	.67***[a]	.57***[a]	.61***[a]	.55***[a]	.51***[a]	.50***[a]
Age group	.04	.01	.00	.04	.06**[a]	.12***[a]	.10***[a]	.06**[a]	.11***[a]	.09**[a]
Age Group × Skill Level	.01	.01	.00	.00	.02	.03*[a]	.01	.01	.04*[a]	.04*[a]
Incremental R^2 for practice variables	.02	.01	.03	.11*[a]	.03	.02	.09**[a]	.07	.04	.11**[a]
Combined model	.46***[a]	.47***[a]	.44***[a]	.63***[a]	.79***[a]	.73***[a]	.80***[a]	.69***[a]	.69***[a]	.74***[a]
Skill level	.03	.07*[a]	.08*[a]	.02	.06**[a]	.05**[a]	.03*[a]	.06*[a]	.03*[a]	.04*[a]
Age group	.01	.00	.00	.00	.01	.03*[a]	.06***[a]	.01	.05*[a]	.02
Age Group × Skill Level	.01	.00	.00	.00	.03*[a]	.04*[a]	.01	.01	.04*[a]	.04*[a]
Practice until age 20	.00	.00	.00	.00	.01	.00	.03*[a]	.04*[a]	.03	.02
Practice during the peak 20 years	.00	.00	.00	.01	.00	.00	.00	.02	.00	.01
Practice during the last 10 years	.01	.01	.02	.07**[a]	.01	.00	.01	.02	.00	.07**[a]
Current practice	.00	.00	.02	.00	.00	.00	.00	.00	.00	.01
R^2 removed with design factors	.07	.10	.08	.03	.16***[a]	.20***[a]	.15***[a]	.13**[a]	.21***[a]	.16***[a]
Practice model	.38***[a]	.37***[a]	.35***[a]	.60***[a]	.63***[a]	.53***[a]	.65***[a]	.56***[a]	.49***[a]	.57***[a]
Practice until age 20	.00	.00	.00	.00	.00	.00	.02	.03	.01	.01
Practice during the peak 20 years	.00	.03	.03	.00	.01	.00	.00	.00	.00	.00
Practice during the last 10 years	.02	.01	.01	.08**[a]	.01	.01	.04*[a]	.03	.02	.11**[a]
Current practice	.03	.01	.00	.01	.05*[a]	.06*[a]	.01	.03	.03	.00

Note. Values are R^2s for variables and their combinations in the three models. For the design factor model, the partial R^2s for single variables add up to the R^2 for the model within rounding errors. Sums of partial R^2s in the other models are much lower than the model's R^2, reflecting collinearity among variables. Asterisks with partial R^2 values denote a significant, unique contribution for a single variable. Asterisks with R^2 values for models denote significance for complete model.
[a] R^2 value.
* $p < .05$. ** $p < .01$. *** $p < .001$.

This step led to a significant reduction in the total variance accounted for in all conditions of Experiment 1, all $F_{\text{changes}}(3, 40) > 9.70$, $p < .001$, and also in Experiment 2, all $F_{\text{changes}}(3, 40) = 5.50$, $p < .005$. Joint removal of the design factors did not result in a significant loss of total R^2 in the three tapping tasks or the musical interpretation task.

Overall, the practice model accounted for reliable variance in all tasks and conditions under consideration, all Fs(4, 43) > 5.80, all ps < .001. Unique variances for variables in the practice model were small, again reflecting the high collinearity among practice measures. Practice over the last 10 years was the only predictor that stood out, attracting reliable unique variance in each of the most complex conditions of the speeded tasks. Thirty-five of 40 standardized beta coefficients for the four variables in the speeded tasks were in the predicted direction, indicating that pianists who had practiced more performed better. The remaining 5 coefficients indicated slight overadjustment but were close to zero.

When we analyzed the residuals from the practice model based on the four different measures (see Krampe & Ericsson, 1995, for details), we found that, consistent with the selective maintenance account, age effects in the expert sample were further reduced after we controlled for the four measures of deliberate practice. The largest age-related decline was found in the most complex condition of Experiment 1, where we had observed reliable differences between young and older experts before controlling for differences in practice. However, after statistical control for the four practice measures, the residual age effect accounted for less than 0.1% of the variance ($p > .80$). Whereas virtually all of the age-related differences in experts' music-related performance could be accounted for by deliberate practice, a completely different pattern was observed for the performance of amateurs. After controlling for practice, we found that age-related decline in amateurs' residuals remained or was even amplified. Correlations between the two measures of general processing speed and the residuals from Experiments 1 and 2 were positive in the amateur group and reached significance in the more complex task conditions. The same correlations computed for the expert sample were all nonsignificant, and most were negative, indicating that the general marker variables would adjust predicted performance in the opposite direction than would be assumed on the basis of any reasonable theory.

In sum, the analyses of the four sets of performance data showed that most of the variance related to the skill factor in our design was equally well accounted for by differences in deliberate practice. To a less extent, this was also true for the age-related variance. However, reliable age-related variance remained even after differences in practice were controlled statistically. At the same time, measures of deliberate practice accounted for reliable unique variance in performance that was not captured by differences in age and skill level. We submitted the selective maintenance account to its final test by determining the phase of deliberate practice most critical for the maintenance of expert music performance.

The most critical phase of deliberate practice in maintaining expert performance. Our hierarchical regression analyses revealed high collinearity of measures in the practice model. Table 5 shows the correlations between the practice measures and performance in all tasks and conditions considered in the hierarchical regression analyses described so far. As may be seen, practice during the last 10 years before the study showed the strongest correlation with task performance in all but one condition. Overall, correlations were much stronger in the expert sample than in the amateur sample. To identify the best single predictor of individual differences in task performance, we conducted stepwise regression analyses with the four different measures of deliberate practice, applying a fixed entry criterion of $\alpha < .05$. The resulting picture was straightforward. With the single exception of left-hand finger-tapping speed, practice during the last 10 years was the predictor variable that accounted for the most variance in all analyses, all Fs(1, 46) > 23.00, all ps < .001, all R^2s > .33. Practice during the last 10 years was the first and only predictor for all dependent measures, satisfying the 5% entry criterion of the stepwise regression routine, except for Experiment 1, where current practice and practice during the first 20 years of life tended to add to the model. Correlations between practice variables and performance were always in the predicted direction. The left-hand finger-tapping task was the exception to the rule, given that practice during the 20 most intense years was the first and only variable entering the stepwise regression procedure, $F(1, 46) = 21.54$, $p < .001$. The amount of variance accounted for by this variable ($R^2 = .319$) differed from the reliable variance captured by practice during the last 10 years ($R^2 = .316$) by only a slight margin, however.

In further investigating whether the predominant effects of practice during the last 10 years indeed reflected efforts relevant to the maintenance of their skill on the part of the older experts, it was important to consider correlational patterns across tasks and conditions for single subgroups. In general, the three measures of accumulated practice correlated with improved performance in all groups, as predicted by the practice model, whereas coefficients for diary estimates for current practice tended to be less systematic and smaller. The relevance of practice during the last 10 years was most pronounced in the older expert group. Five of the six correlations in Experiments 1 and 2 were significant; no other practice variable showed reliable correlations with older experts' performance in these tasks. Maintenance practice was also significantly related to alternate-finger tapping performance in the older expert sample; however, this was also true for current amount of practice. Practice accumulated until the age of 20 showed stronger correlations with performance in the young expert group, but the pattern was not as pronounced as in older experts. Presumably, this finding reflects the large overlap between the three measures of accumulated practice. Correlations were lower, and no systematic patterns emerged for the two amateur groups.

In sum, the results provide a clear picture: Practice during the last 10 years before the study turned out to be the

Table 5
Correlations (r) Between Practice Variables and Task Performance

Group	Musical interpretation	Finger tapping			Experiment 1			Experiment 2		
		Right	Left	Alternate	Single hands	Mirror-image movements with both hands	Different movements with each hand, simultaneously	Single hands	Mirror-image movements with both hands	Different movements with each hand, simultaneously
Total sample (N = 48)										
Practice until age 20	.373**	−.392**	−.382**	−.472**	−.557**	−.459**	−.620**	−.570***	−.522**	−.521**
Practice during the peak 20 years	.509**	−.561**	−.565**	−.632**	−.678**	−.593**	−.711**	−.612**	−.590**	−.621**
Practice during the last 10 years	.595**	−.578**	−.562**	−.769**	−.747**	−.685**	−.781**	−.705**	−.659**	−.751**
Current practice	.544**	−.484**	−.415**	−.634**	−.696**	−.664**	−.642**	−.631**	−.601**	−.569**
Amateurs (n = 24)										
Practice until age 20	−.004	.145	.110	.012	−.081	.077	−.320	−.225	−.119	−.126
Practice during the peak 20 years	−.021	.109	.024	−.118	.088	.170	−.206	.065	.063	−.065
Practice during the last 10 years	.264	−.107	−.009	−.406*	−.086	−.045	−.373	−.116	−.071	−.387
Current practice	.279	−.071	.003	−.239	−.077	−.328	−.135	−.044	−.166	−.105
Experts (n = 24)										
Practice until age 20	−.224	−.312	−.276	−.349	−.143	−.195	.036	−.115	−.247	−.218
Practice during the peak 20 years	−.159	−.200	−.271	−.103	.038	.094	.096	.020	−.046	.000
Practice during the last 10 years	.121	−.139	−.329	−.638**	−.642**	−.626**	−.578**	−.638**	−.687**	−.578**
Current practice	.317	.028	.148	−.333	−.392	−.410*	−.288	−.330	−.335	−.169

* $p < .05$. ** $p < .01$. *** $p < .001$.

practice measure that correlated the most strongly with individual differences in performance. This relation was most pronounced in the older expert group, lending further support to our claim that it is the amount of deliberate practice invested during the later phase of life (during their 50s and 60s in our older sample) that accounts for the moderation of age-related decline in older experts. In our further discussion, we refer to this measure as older participants' *maintenance practice.* Analysis of residuals and correlations between practice measures and performance yielded different patterns of results for experts and amateurs. We concluded our analyses by investigating the degree to which maintenance practice moderated age-related decline in skilled performance, focusing on the differences between skill levels.

Experts' and amateurs' moderation of age-related decline through maintenance practice. To directly compare the degree to which age-related variance was moderated by maintenance practice in experts and amateurs, we computed the R^2 values for the total and the unique variances associated with each variable in Experiments 1 and 2 for which we had any indication of systematic residual age-related variance. Table 6 presents the related statistics for the total sample and for amateurs and experts separately. The total R^2 values for practice during the last 10 years correspond to the squared correlations reported in Table 5. In correspondence with our power calculations in Table 2, we consider separate and aggregated task conditions.

Table 6 shows the variance accounted for by deliberate practice during the last 10 years in the complete sample. Separate consideration of the two skill groups shows that practice in the last 10 years was more strongly related to individual differences in performance among the experts than among the amateurs. When total and unique variances for the age group factor are compared separately for the two skill levels, two different patterns emerge. Age effects are clearly reduced in the expert sample, whereas in the amateur sample they are left largely unaffected when practice during the last 10 years is taken into account.

How difficult would it now be to detect age effects in the expert group after the control for maintenance practice? In regression analyses, the partial R^2 is usually transformed into an f^2 index before power calculations. All partial R^2s related to the age-group factor after the control for maintenance practice in the amateur sample corresponded to medium or even large (f^2 of .35 or above) effects, as one would expect on the basis of the general factor account. Values for f^2 smaller than .07 (all comparisons in our expert group) are considered small by convention. The highest value for residual age-related variance in the expert group (including skill-related tasks not reported here) was in the different movements condition of Experiment 1 and would still require a sample of 114 expert pianists to have a reasonable chance of detection (.80 power) in a two-predictor regression model like the one we applied. Note that the residuals for this task showed no reliable correlation with Digit Symbol Substitution score or choice reaction time speed. By the same standards, to detect age effects for the other variables listed in Table 6, sample sizes of more than 400 expert pianists would be necessary.

In sum, older experts who maintained a sufficiently high level of deliberate practice throughout later adulthood did not show the same age-related decline in skilled music performance that they showed in measures of general processing speed. When we took into account the amount of maintenance practice, age-related declines in the expert group were reduced and corresponded to very small effect sizes. In contrast, age-related decline in speeded musical tasks for amateurs appeared to be largely independent of differences in deliberate practice.

Summary and Discussion

Regardless of their age, experts performed better than amateurs on all the music-related tasks. The advantage of expertise spanned many types of abilities, ranging from peripheral motor efficiency (simple tapping) to the systematic control of movement parameters in the context of a musical interpretation. Expert pianists demonstrated a specific advantage when speeded bimanual movements had to be coordinated, an effect that was documented even at the level of simple alternate-finger tapping.

The pattern of age-related decline also differed between experts and amateurs, as demonstrated by a reliable three-way interaction among skill level, age, and type of speed task. Older amateurs showed similar declines in general processing speed and speed of music-related performance, a pattern predicted by the extended general factor account. In contrast, whereas the decrements in older experts' general processing speed were indistinguishable from those of the older amateurs, their age-related decline in speed of music-related performance was reliably smaller than that of the amateurs. The only difference between young and older experts that reached significance was found for the most complex condition of Experiment 1. Even this difference could not be replicated with memorized movement sequences in Experiment 2, which pianists in all four groups rated as a more relevant condition for evaluating piano playing skills. However, a power analysis of performance in different tasks indicated consistent yet small age-related decline for experts' speeded music-related performance. Although the large difference in experts' rate of age-related decline in general capacity compared with music-related capacity would be viewed as atypical within the extended general factor account, the pattern of results is not in itself inconsistent. This account would, however, need to argue that expert music performance is only weakly related to general capacity and therefore a small age-related decline is observed. Before accepting that expert performance is virtually protected against adverse effects of aging, let us examine the crucial assumption that this reduced rate of decline is unrelated to individual differences in experience, particularly deliberate practice.

To assess the factors responsible for the selective maintenance of expert pianists' music-related performance, we analyzed current and past amounts of deliberate practice. As

Table 6
Total and Unique Variances Accounted for by Age Group and Practice During the Last 10 Years

Group	Experiment 1: Single hands	Experiment 1: Mirror-image movements with both hands	Experiment 1: Different movements with each hand, simultaneously	Experiment 1: Mean	Experiment 2: Single hands	Experiment 2: Mirror-image movements with both hands	Experiment 2: Different movements with each hand, simultaneously	Experiment 2: Mean
Total sample								
Total R^2 for practice during the last 10 years	.56***[a]	.47***[a]	.61***[a]	.60***[a]	.50***[a]	.43***[a]	.56***[a]	.55***[a]
Total R^2 for age group	.06	.12*[a]	.10*[a]	.10*[a]	.06	.11*[a]	.09*[a]	.10*[a]
Unique R^2 for practice during the last 10 years	.51***[a]	.41***[a]	.55***[a]	.54***[a]	.45***[a]	.38***[a]	.51***[a]	.49***[a]
Unique R^2 for age group	.02	.06*[a]	.04*[a]	.04*[a]	.02	.05*[a]	.03	.04*[a]
Amateurs								
Total R^2 for practice during the last 10 years	.01	.00	.14	.05	.01	.01	.15	.05
Total R^2 for age group	.33**[a]	.40***[a]	.28**[a]	.42***[a]	.18*[a]	.34**[a]	.34**[a]	.35**[a]
Unique R^2 for practice during the last 10 years	.00	.00	.11	.02	.01	.00	.11	.03
Unique R^2 for age group	.33**[a]	.40**[a]	.24**[a]	.39***[a]	.17*[a]	.33**[a]	.30**[a]	.32**[a]
Experts								
Total R^2 for practice during the last 10 years	.41***[a]	.39***[a]	.33**[a]	.49***[a]	.41***[a]	.47***[a]	.33**[a]	.48***[a]
Total R^2 for age group	.07	.14	.25*[a]	.20*[a]	.10	.12	.03	.09
Unique R^2 for practice during the last 10 years	.34**[a]	.26**[a]	.15*[a]	.31**[a]	.30**[a]	.36**[a]	.31**[a]	.40***[a]
Unique R^2 for age group	.00	.01	.07	.02	.00	.00	.01	.00

Note. Values are partial R^2s for variables in isolation or after control for the other factor.
[a] R^2 value.
* $p < .05$. ** $p < .01$. *** $p < .001$.

expected, experts had practiced much more both recently and in the past than amateurs had, and the amount of practice a participant had had was closely related to his or her performance on all music-related tasks. Consistent with the predictions of the selective maintenance account, the single best predictor based on practice data was the amount of practice participants had maintained during the last 10 years. Most important, maintained practice had a differential effect in accounting for age-related decline in music-related performance for both older experts and older amateurs. For older amateurs, age-related decline was unrelated to maintained practice, and statistical control for individual differences tended to amplify age-related variance. In contrast, for older experts maintained practice was related to performance and associated age-related variance, and statistical control for maintained practice reduced any residual age-related variance to a bare minimum. In sum, the selective maintenance account can accurately describe factors responsible for the selective maintenance of music-related performance of older experts.

The extended general factor account provides an accurate description of the age-related decline seen in older amateur pianists, with the exception of their performance on the finger-tapping and musical interpretation tasks, which showed no reliable decline. Given that the musical interpretation task was not speeded and measured primarily the control of expressive variations in performance, the predictions of the general factor model for effects of aging are less clear. However, the absence of a decline in finger-tapping speed for older amateurs is clearly inconsistent with predictions of the model as well as with earlier findings in representative populations of older participants. One potential explanation is that the age range examined in Study 1 was more limited than the age ranges in many studies that have documented decline with age. Longitudinal evidence (Hertzog & Schaie, 1986, 1988) suggests a marked transition from stability to change in intellectual functioning for most individuals between the ages of 55 and 70. As an alternative hypothesis, finger-tapping speed might be considered an integral skill in the context of piano playing; pianists must increase their peripheral motor efficiency and speed of tapping to a certain level to master the piano. Once they have attained a certain level of tapping speed, they may be able to preserve it merely by playing the piano and may not need further focused practice. A recent study of the cortical representation of the fingers of expert string players, such as expert violinists, showed systematic differences compared with those of nonmusicians that could be attributed to the experts' training and practice in music (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). More generally, a comprehensive recent review (Kaas, 1991) showed that cortical representations remain closely dependent on maintained levels of relevant stimulation for associated activity of the limbs, even into adulthood. From this perspective, we would predict that individual differences in performance, once attained, remain relatively stable across pianists' life spans, as long as they continue playing the piano.

We tentatively conclude from Study 1 that the general factor account, although failing to account for age-related changes in expert-level performance, can be extended toward skilled performance in amateurs with reasonable success. To investigate this hypothesis further, it was necessary to conduct a study of amateur pianists that addressed the aforementioned issues about tapping performance and musical interpretation, where our expectations of age-related decline were not met. This study also examined the stability of tapping performance in response to short-term practice over the course of repeated testing. Recruiting amateur pianists who were a decade older than those in Study 1 would allow a replication and more powerful test of the theoretically significant relation between general cognitive–motor ability and music-related performance documented for older amateurs in Study 1.

Study 2

The older amateurs recruited for Study 2 were more than a decade older, on average, than those in Study 1. We compared this group with a group of young amateurs similar in age to those tested in Study 1, assessing tapping speed in three different tasks (repetitive tapping with the right, left, and alternate index fingers) in the same manner as in Study 1. Unlike in Study 1, however, we tested participants repeatedly on the tapping tasks, so that we could assess reliability and short-term practice effects. We administered the same musical interpretation task used in Study 1, in order to contrast speeded performance in a simple task with performance in a more complex, nonspeeded task that required more musical skill. In addition, participants performed two rhythm production tasks not discussed in this article.

Method

Participants

Thirty-two pianists who had not participated in Study 1 were recruited for the study. Two older participants and 2 young participants did not complete the experiment and were excluded from the data set. Fourteen young (M = 23.8 years, SD = 3.47, range = 19–30) and 14 older (M = 71.4 years, SD = 6.8, range = 60–81 years) participants remained for the final analyses. There were 8 women and 6 men in the young group and 9 women and 5 men in the older group. All participants except for 1 member of the older group were right-handed. All participants labeled their health as at least average, and young and older were similar in their ratings. All persons were paid for their participation.

Participants' educational background. The mean number of years spent at public schools did not differ reliably between young (M = 12.6 years) and older (M = 11.6 years) participants and was consistent with the cohort effects observed in Study 1. The young and older groups were similar in terms of years spent at a university (M = 3.45 years). As in most similar age-comparative studies, the mean was slightly higher for older (M = 3.93 years) than for young (M = 2.96 years) participants, only a few of whom had completed their professional training by the time of the study. On average, the participants had decided on their professions at age 18.6 and had started related training at age 20. Examination of the data showed a high degree of similarity between the professional backgrounds of the older amateurs and the professional career plans of the young amateurs.[9]

Participants' musical background. On average, the participants had received 11.4 years (SD = 8.2, range = 3.5–37) of formal piano instruction from 2.6 (SD = 1.4) different instructors, and the age groups did not differ in this respect ($p > .50$). The age at which the first piano lesson had been taken (M = 9.1 years, SD = 1.8) and the age at which systematic practice had started (M = 9.0 years, SD = 1.7) coincided for most participants; group means did not differ significantly between the age groups ($p > .70$). Six young and 4 older pianists were receiving formal instruction at the time of the investigation.

Apparatus

The experimental setup in Study 2 was the same as in Study 1, except that the keyboard used in Study 2, a Yamaha CLP-124, is a newer version of the one used in Study 1. The quality of the sound produced by the two models is the main difference between them, while the keyboard mechanics are nearly identical, according to the manufacturer.

Procedure

We collected data during seven sessions, each lasting 1.5–2 hr. In Session 1 we first elicited biographical data and retrospective estimates of past amounts of deliberate practice and then administered the two-choice reaction time task and Digit Symbol Substitution Test. After completing these measures of general processing speed, participants performed the three tapping tasks (right, left, and alternate index fingers). They then performed the two rhythmic tasks, after which they repeated the tapping tasks. We assessed tapping speed in all three conditions twice during each of Sessions 1–6, at the start and the end of the session, with the two rhythmic tasks administered in between. The musical interpretation task was administered at the beginning of Session 3. The procedures for all tasks and measures were identical to those in Study 1.

Results

We first compare older and young pianists' performances on measures of general processing speed and on the two skill-related tasks, finger tapping and musical interpretation. We then examine the relation among age, deliberate practice, and general processing speed in combined samples from Studies 1 and 2.

Age Effects on Measures of General Processing Speed

In Study 2 as in Study 1, age had reliable effects on the measures of general processing speed. The mean score on the Digit Symbol Substitution Test was 48.4 (SD = 6.7) for older pianists, which was lower than the mean score for young pianists (M = 62.4, SD = 7.9), $F(1, 26) = 25.35$, $MSE = 54.1$, $p < .001$. Similarly, mean response time in the two-choice reaction time task was longer for older pianists (M = 535 ms, SD = 68) than for young pianists (M = 475 ms, SD = 37), $F(1, 26) = 8.23$, $MSE = 3{,}003$, $p < .01$. The same patterns of results emerged when log times per item were analyzed. Error rates in both tasks were low and did not systematically differ between age groups. There was no reliable evidence for speed–accuracy trade-offs, which could have influenced the reported findings.

Age Effects on Skill-Related Tasks

Tapping speed. As in Study 1, we converted the number of taps participants produced during the available time interval into log IKIs. We averaged the means from the two tapping tests given each session to increase reliability. To study complexity, we specified the same two orthogonal contrasts we had used in Study 1. These contrasts compared right with left single-finger tapping and single-finger tapping with alternate-finger tapping. We performed a repeated measures ANOVA with session (6) and task complexity as within-subject factors. The session factor was specified by two orthogonal contrasts. The first contrast assessed general speedup through practice by comparing performance during the first three sessions of testing with performance during the last three sessions. The second contrast evaluated the stability of tapping speed toward the end of testing by contrasting performance in Sessions 4 and 5 with performance in Session 6. Overall, right finger tapping was faster than left finger tapping, $F(1, 26) = 42.04$, $MSE = .003$, $p < .001$, and alternate-finger tapping was faster than single-finger tapping, $F(1, 26) = 1218.62$, $MSE = .002$, $p < .001$. The main effect of age, $F(1, 26) = 8.57$, $MSE = .02$, $p < .01$, was qualified by a reliable interaction with the contrast between single-finger and alternate-finger tapping, $F(1, 26) = 20.95$, $p < .001$, indicating that age-related performance decrements were pronounced in the alternate-finger tapping task.

Participants' performances significantly improved in the second half of testing, $F(1, 26) = 14.24$, $MSE = .001$, $p < .005$; however, older participants' performances improved more than young participants' did, as indicated by a reliable Session × Age Group interaction, $F(1, 26) = 4.36$, $p < .05$. Practice effects leveled off after the first half (i.e., Sessions 1–3) of the assessment. None of the effects involving the second contrast relating to the session factor was significant. The stability of participants' ranking across the last three sessions was reasonably high (Cronbach's $\alpha > .87$ within task conditions and age groups). Short-term practice during the first half of testing was sufficient to reduce older amateurs' initial disadvantage in the right finger tapping task in Study 2, $t(13) = 2.78$, $p < .05$, to nonsignificance in the

[9] Thirteen of the young participants were students enrolled in psychology, medicine, or other disciplines. One young participant was being trained in a nonacademic program. Twelve older amateurs had retired by the time of the investigation, 1 was a still-active veterinarian, and 1 was working in the household for her family. All older participants had formal professional educations. Eleven of the 14 older participants had academic training as high school teachers or in various disciplines such as medicine, law, architecture, natural sciences, and engineering. The other 3 had been trained as a foreign-language secretary, librarian, and assistant for medical practice.

second half of testing, $t(13) = 1.59$, $p > .12$. In the alternate-finger tapping condition, however, where older pianists improved to a similar degree as in the right finger tapping condition, age effects remained stable. However, these improvements in tapping speed with practice were relatively insignificant compared with the large differences in tapping speed between experts and amateurs in Study 1 (see Krampe & Ericsson, 1995, for further details).

To obtain the best estimate of stable differences in tapping speed, we aggregated the means for the last three testing sessions. A repeated measures ANOVA showed that right finger tapping was faster than left finger tapping, $F(1, 26) = 33.11$, $MSE = .001$, $p < .001$, and that alternate-finger tapping was faster than single-finger tapping, $F(1, 26) = 935.21$, $MSE = 001$, $p < .001$. The main effect of age group, $F(1, 26) = 5.94$, $MSE = .001$, $p < .05$, was qualified by an interaction with the contrast between single-finger and alternate-finger tapping tasks, $F(1, 26) = 16.26$, $p < .001$. Age effects in the single-finger tapping tasks failed to reach significance; replicating our earlier findings; however, unlike the differences found in Study 1, the differences between age groups in the alternate-finger tapping condition in Study 2 were significant, $t(26) = 3.70$, $p < .001$. Means aggregated across the last three sessions are shown in Figure 9.

Musical interpretation. We analyzed the consistency of force and tempo variation in exactly the same manner as in Study 1. Age groups and successive performances did not differ reliably in terms of error rates ($M = .79\%$, $SD = .98$), overall performance tempo (M [total playing time] = 123 s, $SD = 29$), or mean force applied ($M = 60.0$, $SD = 8.94$). As in Study 1, variability of force produced at the level of phrase means was lower for older pianists than for young pianists, but this difference failed to reach significance (total $M = 5.94$, SD = 2.79). Consistency of force variation was equally high in both age groups, both $Fs(1, 26) = .93$, $p > .34$. Note that the reliability for the three z-transformed

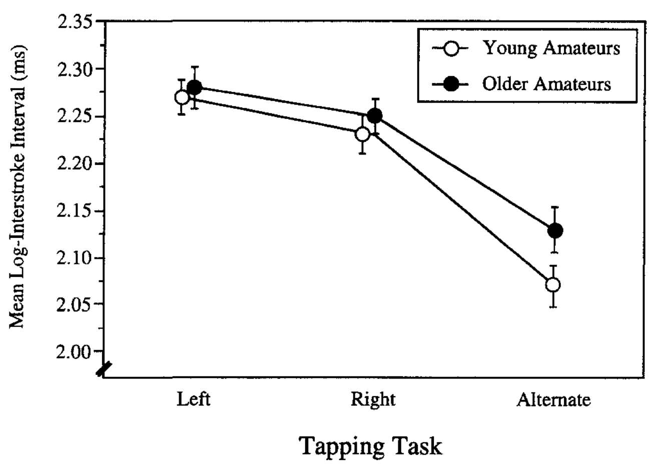

Figure 9. Mean log interstroke intervals in the three tapping tasks (left, right, and alternate index fingers) for the young and old amateur pianists in Study 2. Data are aggregated across the last three sessions. Bars indicate 95% confidence intervals.

correlation coefficients was high (Cronbach's $\alpha = .955$; αs > .94 in subgroups), and raw correlations ($M = .680$, $SD = .231$) were sufficiently above chance to guarantee that our method of analysis was indeed capturing systematic variation in participants' performances. As in Study 1, analyses of timing consistency revealed no systematic differences, and differences between age groups for both consistency measures were further reduced when overall variability was taken into account. These results replicated our findings from Study 1, suggesting small effects of age on amateurs' performance in this type of task even when the differences in participants' age were further increased.

Measures of Deliberate Practice as Predictors of Task Performance by Amateurs

To maximize the statistical power of our investigation of the relation between age, general factors, and deliberate practice on the one hand and performance in the tapping tasks and musical interpretation task on the other, we decided to pool our young and older amateur samples from Studies 1 and 2. The total number of these participants, whose ages ranged from 19 to 30 and 53 to 81, respectively, was 52, a number that yielded sufficient power (.78) to detect medium-sized ($f^2 = .15$) age effects in a multiple regression analysis. Table 7 shows the correlation between the predictor variables on the one hand and the three tapping measures and consistency of loudness variation in the musical interpretation task on the other. In Study 1 we measured tapping speed only once, and therefore we used only the first trial of tapping in Study 2 in this analysis.

Inspection of the correlation patterns revealed that alternate-finger tapping speed declined with age and correlated with individual differences in the two markers of general processing speed. At the same time, practice during the last 10 years before the study showed a reliable correlation with alternate-finger tapping performance, indicating that pianists who had practiced more during this period performed better. Age, general processing speed, and deliberate practice showed no pronounced relations with single-finger tapping speed. The coefficients indicated a small (right finger tapping) to negligible (left finger tapping) age-related decline in performance on these tasks. A new result emerged for the musical interpretation task, which showed a reliable correlation with general processing speed as reflected by the Digit Symbol Substitution Test score.

We conducted stepwise regression analyses with a fixed entry criterion of $\alpha < .05$ on age and the four practice variables. As we expected given the correlations, only in the case of alternate-finger tapping could reliable variance be accounted for. Age entered in the first step and accounted for 21% of the reliable variance, $F(1, 50) = 13.46$, $p < .001$. Practice during the most intense 20 years entered in the second step and accounted for an incremental variance of 8%, F_{change} (1, 49) = 5.60, $p < .05$. The regression model including both factors accounted for 29% of the variance, $F(2, 49) = 10.15$, $p < .001$. Beta weights indicated that tapping speed was negatively correlated with age,

Table 7
Correlations (r) Between Predictor Variables and Performance Measures in the Pooled Amateur Samples (N = 52)

Variable	Right finger tapping	Left finger tapping	Alternate finger tapping	Musical interpretation
Age	.208	.026	.461**	−.183
Digit Symbol Substitution Test score	−.100	.190	−.323*	.291*
Choice reaction time	.222	.020	.425**	−.122
Practice until age 20	.040	.008	−.101	.104
Practice during the peak 20 years	−.048	−.065	−.234	.067
Practice during the last 10 years	−.075	−.120	−.280*	−.026
Current practice	.038	−.015	−.049	.043

$^* p < .05$. $^{**} p < .01$.

with pianists who had practiced more performing better. When the age variable was removed, the regression model was no longer significant and its predictive power was reduced by 24%. Practice during the 20 most intense years had relatively small unique variance associated with it. In combination with age, however, it accounted for reliable individual differences that could not be captured by either of the two predictors alone.

Practice during the last 10 years before the study was the only practice variable that correlated reliably with performance in the alternate-finger tapping task. Once age was taken into account, however, the variance accounted for by this variable was only 2%. This contribution was not significant, $F_{\text{change}}(1, 49) = 1.21, p > .25$. Further examination showed that practice during the last 10 years systematically decreased with age ($r = -.324, p < .05$), reflecting the fact that several older amateurs reported that they had stopped practicing completely, in favor of just playing for fun.

Summary

Study 2 replicated the absence of a reliable age-related decline in single-finger tapping speed and performance in the musical interpretation task found in Study 1 with a sample of amateurs who were more than a decade older than those who participated in Study 1. At the same time, we were able to demonstrate a reliable age-related decline in alternate-finger tapping. These findings were elaborated when the data from the amateurs in Study 1 and 2 were pooled. Analysis of the pooled sample suggested that once the effects of age were statistically controlled, reliable effects of deliberate practice on alternate-finger tapping speed could be identified. Most interestingly, for amateurs' tapping performance the critical period of deliberate practice was the 20 most intense years of practice, our first evidence for the role of the amount of early practice without mediation by maintained practice. As further support of our proposition that the general factor account captures important aspects of subexpert performance, we found a reliable correlation between consistency in the musical interpretation task and performance on the Digit Symbol Substitution Test.

General Discussion

The most important finding of our studies is that the pattern of age-related decline across speeded music-related performance and psychometric measures of general processing speed differed for amateur and expert pianists. Only the pattern we observed for the amateurs is consistent with the uniform effects of aging predicted by the influential general factor account. Amateurs exhibited age-related performance decrements in speeded music-related tasks that corresponded to decrements in general processing speed. Furthermore, markers of age-related slowing in basic processing operations accounted for individual differences in music-related tasks. The fact that our amateur groups showed the pattern of "normal aging" observed in numerous studies is important because it validates our choice of amateur pianists as a representative age-matched control group for comparison with older expert pianists. The older expert pianists did not differ systematically from older amateur pianists in general processing speed, and these two groups showed similar amounts of age-related decline on these measures. In comparison, the age-related declines in speeded music-related performance for the older experts were quite small and failed to reach significance for individual tasks—except for the most complex task in Study 1. However, the small age-related declines were consistent across tasks and would have been difficult to detect with the available number of expert participants. The experts' pattern of differential effects of aging across types of speeded performance cannot be accounted for by the extended general factor account but is consistent with the selective maintenance account.

The selective maintenance account explains the different age-related reductions in speed in general psychometric tests and music-related performance by proposing that experts have acquired specific mechanisms that mediate their performance in their domain of expertise. These mechanisms enable them to circumvent the general processing limitations that inevitably increase with age (Salthouse, 1991b) and constrain other types of unskilled performance in the general population as well as in elite pianists. It is through deliberate practice that expert pianists initially acquire these mechanisms and subsequently maintain them.

Our results show that the role of deliberate practice in expert-level performance is not limited to the early acquisition phase, as one would expect on the basis of earlier findings on less skilled individuals (e.g., Bahrick, 1984; Bahrick & Hall, 1991). Rather, once elite levels of speeded performance are attained, they must be actively maintained.

On the basis of the selective maintenance account, we made predictions about the relation between current and past amounts of deliberate practice and current performance in young and old pianists. Our studies confirmed earlier findings (Ericsson et al., 1993) showing that experts accumulate a large amount of deliberate practice during the period in which they are working to attain expert performance. The amount of deliberate practice they accumulate is larger by an order of magnitude than that accumulated by amateurs during the corresponding period. Most important, older experts were found to maintain a reduced, but still high, level of deliberate practice throughout their careers. In contrast, the level of practice by amateurs remained low, and a few of the oldest amateurs had even completely stopped practicing.

Consistent with the predicted role of continued deliberate practice, the relation between amount of maintenance practice and performance differed for the older amateur pianists and older expert pianists. For the amateurs, with their low levels of deliberate practice, there was no systematic relation between current level of practice and performance. This is consistent with the general factor account, as well as training research (Ackerman, 1988). In contrast, individual differences in deliberate practice for experts were related to performance on speeded music-related tasks and could even explain most of the age-related differences in this type of performance for them as a group. Our findings thus suggest that the general factor account does not extend to the expert performance of older individuals who engage in regular deliberate practice to maintain their superior expert performance.

Before turning to the implications of these findings, we discuss evidence on experts that has been cited in support of the general factor account and the pattern of results on the different music-related tasks in our studies.

Evidence Supporting Preserved Differentiation and Compensation in Older Experts

According to the preserved differentiation account proposed by Salthouse et al. (1990), superior performance in older experts compared with age-matched controls reflects differences in stable, general abilities that already existed at a younger age. Age-related decline in speeded performance, according to this account, is caused by a deterioration of basic capacities, an inevitable process that experiential factors cannot modify. Salthouse et al. found no moderation of age effects through experience with spatial visualization, a measure that would correspond to all types of music-related activities, not just the deliberate practice we examined. In fact, these authors acknowledged the distinction between practice and experience (see also Salthouse, 1991a, 1991d). Our studies also showed the predicted age-related decline in measures of general processing speed, and we found no evidence for differences in performance on these measures between experts and amateurs in either the older or the young group. Even the amount of deliberate practice during the acquisition phase did not differ reliably between older and young experts. Hence, our results for expert pianists cannot be adequately explained by the preserved differentiation account, but the results for older amateur pianists are at least consistent with that account. Although the older amateurs engaged in very little deliberate practice, they spent almost an hour a day on music-related activities. Their level of involvement in music may thus have approached that of some of the previously studied groups of professional experts, who did not appear to invest much time in daily deliberate practice and engaged primarily in other domain-related activities. The suggestion that the general factor account provides reasonable predictions about the effects of aging on performance in the limiting case of no or minimal amounts of deliberate practice is consistent with the selective maintenance account.

A comparison of the characteristics of the different music-related tasks provides some theoretical grounds for specifying the locus of processing deficits in older amateurs and the specific advantages underlying expert performance. Speeded bimanual coordination was the critical aspect of performance that revealed specific advantages of expertise as well as pronounced age-related performance deficits in amateurs. This general finding was established even at the level of simple tapping tasks, in which the alternate-finger tapping condition magnified the effects of expertise and age. Experts' superior performance in these tasks must relate to the optimal overlap in the preparation of successive keystrokes permitted by advance preparation and coordination. By commanding these specific mechanisms, expert pianists can largely circumvent performance constraints that have been demonstrated earlier with different tasks for less skilled participants (Kelso et al., 1979; Klapp, 1979) and for older adults (Haaland et al., 1993; Light & Spirduoso, 1990; Stelmach et al., 1988).

The empirical analyses of the musical interpretation task focused on individual differences in systematic control of variability. This task differed from the others in our studies in its lack of explicit speed requirements. Furthermore, the prelude selected for this task may also be considered one of the simpler serious musical pieces in terms of bimanual coordination requirements. Earlier studies of control of variability (Palmer, 1989; Povel, 1977; Shaffer, 1976, 1981, 1982; Sloboda, 1983) were designed to demonstrate the correspondence between musically meaningful units and measurable behavior without focusing on individual differences. Although potentially missing some of the finer aspects of intentional control as they emerge from top-level interpretations, we were able to show that reliable performance differences between expert and amateur pianists can be identified even with a technically simple piece that is familiar to both types of musicians.

Unlike earlier approaches, our analyses distinguished individual differences in controlled variation from the overall variability in the musical interpretations. In spite of reliable differences in control of variability between experts and amateurs, we found no evidence for systematic decline with age. If we assume that the skill of controlling force and timing in expressive performance relies mainly on musical knowledge, our finding of relative age stability in the musical interpretation task is consistent with accounts proposing crystallized forms of intelligence (Horn, 1982) and encapsulation of knowledge (Rybash, Hoyer, & Roodin, 1986). However, several studies have shown that markers of fluid intelligence can also account quite well for individual differences in more crystallized tasks (e.g., Salthouse, 1993, 1994), which is consistent with the significant correlation we found between Digit Symbol Substitution Test scores and measures of consistency of performance in the interpretation of the Bach prelude in the extended amateur sample.

It was necessary to select a technically simple piece to compare the performance of the same composition by musicians with very different levels of skill. However, the lack of technical difficulties of the piece raises issues about generalizing our results to age-related decline in experts' performance of difficult pieces that would be a challenge even for our experts. Finding a single complex piece that all of the young and older expert pianists had already mastered was unfortunately impossible. Furthermore, given the very long period of practice and preparation professional pianists require to prepare a piece to the desired level of perfection, it would not be realistic to assign them a specific piece to learn just for our study. Although we can only speculate what would have happened under these circumstances, on the basis of our findings from the complex movement coordination tasks, we would expect that effects of age on the older expert pianists' performance would be detectable with sufficient sample sizes. However, by the same line of reasoning, we would also expect that older experts who maintained a high level of practice would show little, if any, age-related decline in this situation.

The compensation account that we described briefly at the beginning of this article argues that older experts have to acquire different mechanisms or the same skilled mechanisms to a higher degree than young experts to attain the same level of performance. Related findings (Charness, 1981a, 1981b; Salthouse, 1984) suggesting that older experts need a compensation for age-related decrements in general working memory capacity and speed to maintain a certain level of performance seem to offer solid evidence for inevitable decline due to aging. However, our comparison of age effects in expert pianists' performance on simple finger-tapping tasks and the more complex speeded tasks did not show support for such compensatory mechanisms. In fact, we found the opposite pattern of results: Age-related decrements for older experts increased at higher levels of complexity and cognitive mediation.

An alternative account for the original evidence for compensation in older typists (Salthouse, 1984) and older chess players (Charness, 1981a, 1981b) would focus on reduced levels of deliberate practice in older experts. Like the compensation account, this account would predict a decline in skilled performance with increasing age even for individuals who remain active in the domain. Hence, older experts who have considerably reduced their level of practice would have exhibited a higher level of performance when they were young and originally acquired all the associated skilled characteristics. We propose that reduction in practice has a differential impact on various skill components. We assume that skilled mechanisms such as eye–hand span for typists (Salthouse, 1984, 1991b) patterns and knowledge about chess playing (Charness, 1981a, 1981b) and musical knowledge relevant to interpretation are less affected by this change in maintained practice than are components relating to speeded movement coordination. For example, professional typists perform everyday typing at much slower speeds than their maximal speed, and it is likely that deliberate practice focusing on maximal speed might be necessary to maintain the speed. Unless older expert typists regularly engage in typing at their maximal speed, a decline in their tapping speed would be expected. This prediction is consistent with the age-related decline in tapping speed Salthouse (1984) observed in skilled typists. A similar account of the age independence of single-finger tapping would view increased tapping speed as a reflection of physiological adaptations of peripheral components needed to reach a certain level of piano playing skill. In contrast to rapid bimanual coordination, these adaptations can be maintained by the representative demands of normal piano playing, without further additional practice. The possibility of maintenance through regular demanding activity is consistent with the preserved response to exercise in very old age (Shephard, 1994) and the plasticity of the human body (see Ericsson, 1990, for an overview).

In line with our findings, Charness, Krampe, and Mayr's (1996) recent research on chess players' deliberate practice shows that the amount of deliberate practice decreases with age. Furthermore, these authors found that deliberate practice involves solitary study and analysis of chess games, which should benefit maintenance of memory and planning capacity—the aspects that were found to be most affected by aging (Charness, 1981a, 1981b). Finally, Charness et al. found that current levels of practice were more closely associated with chess skill in older chess experts than they were in younger chess players. In sum, the account of compensation in terms of age-related reductions of practice is consistent with the evidence, but only future longitudinal studies of the relation between the structure of expert performance and concurrent levels of deliberate practice will resolve this controversy.

Extension of the Framework for Expert Performance to Later Adulthood

In the framework proposed by Ericsson et al. (1993), the acquisition of expert performance is a process of continued adaptation to domain-specific and developmental constraints through which individuals try to maximize the outcome of their deliberate practice activities. In our study, the expert pianists had started practice at a much earlier age than the amateurs had and had spent increasing amounts of time on deliberate practice until their mid-20s. Ericsson et al. documented similar effects for a variety of domains and showed that the amount of deliberate practice accumulated during this developmental period was related to the attained level of performance. This framework could even be extended to world-class soloists, who were distinguished from expert pianists like those in our sample by the younger age at which they had started practice.

In this article, we have extended the framework to middle-age and older experts and argued that deliberate practice not only is essential for the original acquisition of expert performance but continues to be important in maintaining expert performance during adulthood. Our studies show that the amount of deliberate practice engaged in reaches its maximum around the end of formal training (mid-20s), after which it declines but remains substantial even for older expert pianists (in their 60s). In this section, we first discuss some potential causes for the initial decline in practice and then turn to additional factors emerging during the later adulthood.

Once they complete their formal education in their mid-20s, musicians must find a way to support themselves. Only the most outstanding among them are able to pursue a solo career that allows them to focus exclusively on developing their music performance until they reach their peak sometime during their 30s and early 40s (Lehman, 1953). The remaining expert musicians must accept other types of music-related jobs, such as playing in professional orchestras or teaching expert and amateur musicians. The change from being a full-time music student to being a professional musician has consequences for the availability of quality time for deliberate practice and is also associated with changes in motivation and long-term goals. In a recent study, Heizmann et al. (1993) found that after joining an orchestra, highly accomplished violinists reduced the amount of time they spent weekly on practice and changed their original aspirations for a solo career to a more predictable though less prestigious career. Independent of any age-related changes, these changes in responsibilities must require reductions in deliberate practice time. If full-time students in the music academy maximized the duration of their daily deliberate practice, then the time and effort demanded by professional duties of full time teachers or orchestra members must lead to a reduction of deliberate practice. In addition, or perhaps as a consequence of the reduced opportunity to practice, the aspirations of the expert musicians will change and further influence the amount of practice they engage in and their goals during continued practice. When young elite musicians and athletes retreat from competition yet remain active in the domain, they show even more dramatic declines in deliberate practice (Kaminski, Mayer, & Ruoff, 1984). Although professional musicians can adjust their aspirations, they must continue to give and participate in public concerts in which their performance skills are evaluated by the same criteria as those of young experts. The demand for frequent public exhibition of one's performance, where it is subject to evaluation by one's peers, is much greater for expert musicians than for most other types of experts, whose superiority of performance compared with nonexperts cannot even be validated in many cases (Ericsson & Lehmann, 1996). Even in domains with objective performance measurement, such as track, gymnastics, and swimming, older master coaches are not expected to be able to produce the elite performance they expect their young athletes to attain. Hence, we argue that older expert musicians are unusually motivated to maintain their performance.

Our analysis of the diary data support this claim. As we have described in more detail elsewhere (Krampe & Ericsson, 1995), the decrease in deliberate practice does not reflect a retreat from professional activities, but rather a shift in focus. Older expert pianists spent an average of 60 hr per week on music-related activities, which was even slightly more than young experts spent. Their professional requirements, such as teaching, simply leave less time for practice. Furthermore, older individuals spent more time on health and body care than younger adults did. At the same time, we found that older experts had less leisure time than individuals in the other three groups, a reduction presumably reflecting active efforts to make time for practice in spite of demanding professional requirements and responsibilities. In our framework, we interpret this behavior as evidence for the active negotiation of time constraints, motivated by the goal to maintain expert performance.

Within our theoretical framework, deliberate practice corresponds to activities designed to improve and maintain specific aspects of performance. Assuming that older expert pianists' goals for their current and future performance differ from those of young experts, we would expect that the content and goals of specific practice activities also differ. Furthermore, the reduced availability of quality time for practice should lead older expert pianists to develop the ability to monitor their activities so that their goals for the maintenance of their performance are efficiently achieved. This implies that among older expert pianists the aspects of music performance that closely match the representative demands on the performance will show the least age-related decrement. This implication is consistent with the pattern of age-related decline across tasks that we observed. Hence, maintenance of expert performance requires specific practice activities similar to those required for the original acquisition of performance. However, the amount of practice required to maintain an already acquired characteristic of expert performance appears to be reduced, and at least some aspects (cf. finger tapping speed) may be maintained simply by continued active engagement in representative music-related activities. A deeper understanding of the maintenance and age-related decline of the performance of experts and professionals requires a detailed analysis of their current performance goals and their daily activities of work and deliberate practice.

The present research did not address the limits of deliberate practice for maintenance of elite performance especially for expert performers who are even older than our participants. However, the domain specificity of deliberate practice precludes the possibility of maintaining all types of performance in every domain at the same time, a point supported by the age-related declines we observed in performance on unfamiliar tasks, such as the psychometric tests of general cognitive–motor capacity. In addition, it is generally assumed that increased age leads to a diminished pool of resources, which forces elderly persons to be selective in its allocation if they are to preserve their level of functioning in a given domain (Baltes & Baltes, 1990). Furthermore, research on master athletes (Hagberg et al., 1985) suggests that some physiological characteristics that limit performance, such as maximum heart rate, show an inevitable decline that cannot be modified by practice. More important, it has also been shown that the amount and intensity of deliberate practice that individuals can maintain with complete recovery on a daily basis decrease as function of age (Ericsson, 1990). It remains for future research to determine whether the availability of resources for sustained effort is a primary source of the age-related decline in productivity observed even for highly motivated individuals at the highest level of achievement (Lehman, 1953; Simonton, 1988).

In conclusion, our studies do not support the traditional view that high levels of performance in older experts reflect superior general capacities that are subject to inevitable age-related decline. Furthermore, they show that maintenance of expert-level performance is not an automatic consequence of expert skill acquired during early adulthood, even when the individuals remain active in the domain. Rather, experts deliberately maintain a level of performance in music by engaging in solitary practice activities designed to improve and preserve specific aspects of their domain-specific performance. Once we accept that most characteristics of human performance are not fixed but are influenced by essentially continuous adaptations made necessary by daily activity and training, individuals' active role in the maintenance of their performance during adulthood becomes apparent. Maintaining a high level of acquired skill and adaptation appears to require a continued level of focused effortful practice, and because of the age-related decline in their general resources older experts have to become increasingly selective regarding which skills they actively maintain. We believe that the study of the content and structure of the practice activities of experts, especially older experts, will provide insights into how motivated individuals should be able to effectively improve and preserve high levels of performance in specific types of activities into late adulthood. The prospect of accumulating and distributing this knowledge about training methods and deliberate practice to the general public would provide a concrete alternative to the common fateful belief that the observed typical age-related declines in skilled performance are inevitable.

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