

# Timing, Sequencing, and Executive Control in Repetitive Movement Production

Ralf Th. Krampe  
University of Potsdam

Ulrich Mayr  
University of Oregon

Reinhold Kliegl  
University of Potsdam

The authors demonstrate that the timing and sequencing of target durations require low-level timing and executive control. Sixteen young ( $M_{\text{age}} = 19$  years) and 16 older ( $M_{\text{age}} = 70$  years) adults participated in 2 experiments. In Experiment 1, individual mean-variance functions for low-level timing (isochronous tapping) and the sequencing of multiple targets (rhythm production) revealed (a) a dissociation of low-level timing and sequencing in both age groups, (b) negligible age differences for low-level timing, and (c) large age differences for sequencing. Experiment 2 supported the distinction between low-level timing and executive functions: Selection against a dominant rhythm and switching between rhythms impaired performances in both age groups and induced pronounced perseveration of the dominant pattern in older adults.

Complex rhythm production requires the precise timing of intervals, such that their absolute and relative durations as well as their adequate sequencing are respected. Theories of action control (e.g., Jordan & Rosenbaum, 1989; MacKay, 1987) refer to these performance constraints as the problems of *timing* and *serial order control*. Many theorists would agree that this distinction corresponds to dissociable mechanisms (e.g., MacKay, 1987; Vorberg & Wing, 1996). Indeed, there exists a large body of work on the neural bases of simple timing processes (e.g., Hazeltine, Helmuth, & Ivry, 1997; Ivry, 1997; Wing, 2002) as well as on the psychological (Collard & Povel, 1982; Rosenbaum, Hindroff, & Munro, 1987; Rosenbaum, Inhoff, & Gordon, 1984) and neurologic bases of sequential processing (e.g., Grafton, Hazeltine, & Ivry, 1998; Hazeltine, Grafton, & Ivry, 1997). However, empirical evidence from within one experimental paradigm that involves both a systematic variation of timing and sequencing complexity is missing so far.

---

Ralf Th. Krampe and Reinhold Kliegl, Department of Psychology, University of Potsdam, Potsdam, Germany; Ulrich Mayr, Department of Psychology, University of Oregon.

The project was funded by the Grant INK 12 (Project B1) of the German Research Foundation. Parts of this research were also supported by National Institute on Aging Grant R01 AG19296-01A1 awarded to Ulrich Mayr. This research was part of the interdisciplinary project "Formal Models of Cognitive Complexity" conducted at the Center for Cognitive Studies, University of Potsdam, Potsdam, Germany.

Comments by Asher Cohen, Richard Ivry, Steven Keele, and Dirk Vorberg at early stages of the project are gratefully acknowledged. We thank Petra Gruettner, Andrea Kliewe, and Antje Fuchs for their invaluable help with data collection.

Correspondence concerning this article should be addressed to Ralf Th. Krampe, who is now at the Department of Psychology, Katholieke Universiteit Leuven, Tiensestraat 102, B-3000, Leuven, Belgium. E-mail: ralf.krampe@psy.kuleuven.ac.be

Our basic assumption is that a critical component of the serial order control problem consists of the adequate selection of action plans that specify parameters for the hierarchical programming of the low-level timing mechanism while countering the interference from competing plans. So conceived, the serial order control problem during the production of temporal sequences is just one type of a more general class of executive control problems. We also assume that the low-level timing mechanism can function in relative independence of executive control mechanisms in tasks with low representational demands on target durations and their sequencing. We call this set of assumptions the *executive control hypothesis of timing*.

We test this hypothesis with two methods. First, we determine for individual participants the most salient characteristic of timing processes, the systematic increase in variability with produced interval duration (*mean-variance functions*) for a number of experimental conditions. These conditions comprised the repeated production of identical target intervals (isochronous tapping) as well as the sequencing of multiple target intervals into rhythmic patterns. The most general prediction of our model is that slopes of mean-variance functions in complex rhythm tasks should be steeper than slopes for low-level timing obtained from isochronous tapping. At a more detailed level, the executive control hypothesis predicts specific mean-variance patterns for the different target intervals within a rhythmic sequence, which identify hierarchical control over and above low-level timing.

Our second approach to dissociate low-level timing and sequencing mechanisms capitalizes on the observation that low-level timing remains functional until older adulthood (e.g., Duchek, Balota, & Ferraro, 1994; Greene & Williams, 1993), whereas specific aspects of sequential processing exhibit marked age-related decline (Kramer, Hahn, & Gopher, 1999; Mayr, 2001). In sum, we aimed to demonstrate task-specific and age-specific dissociations between low-level timing and executive control.

### Low-Level Timing

To account for participants' repetitive productions of single-interval durations in simple tapping tasks, Wing and Kristofferson (1973a, 1973b) proposed a two-level timing model, composed of a central clock mechanism and separate, effector-specific motor systems. According to this model, the *central timer* generates pulses at certain intervals that trigger the relevant effector; implementation is then achieved with a certain *motor delay*. The strongest support for the putative two-stage process comes from studies demonstrating that the variance associated with the central timing mechanism increased systematically with longer interval durations while motor delay variances remained constant across target intervals (Wing, 1980; Wing & Kristofferson, 1973a, 1973b). The two-level model has generally received support from studies in which participants repeatedly tapped out a certain target interval with a single finger or foot (e.g., Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985), and it has since been extended in several ways (Krampe, Engbert, & Kliegl, 2002; Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Vorberg & Wing, 1996).

Important for the present investigation is that extant models of cognitive aging (e.g., Salthouse, 1985, 1996) postulate a general age-related slowing of cognitive processes, including internal clock mechanisms (Salthouse, Wright, & Ellis, 1979; see Drake, Jones, & Baruch, 2000, for similar claims related to oscillator slowing in rhythmic attending). Age-comparative studies with simple tapping tasks provided a mixed picture of outcomes. Woodruff-Pak and Jaeger (1998) found age-related increases in central clock variability, whereas researchers in other studies (Duchek et al., 1994; Greene & Williams, 1993) observed similar variabilities in young and older participants, who repeatedly tapped a target interval of 550 ms (the same in all three studies). In Experiment 1 of this study, we use slope estimates derived from individual mean-variance functions for a large range of target intervals to investigate age-related changes in low-level timing, that is, a potential slowing of the internal clock.

### Rhythmic Timing: Hierarchical Representations and Executive Control

The proposal that the sequencing of complex movements relies on hierarchical representations rather than on successions of local response transitions dates back to Lashley's (1951) seminal work. Rhythmic patterns typically consist of two or more intervals differing in their target (i.e., their ideal) durations, which are organized into larger, recurring groups (rhythmic *cycles*). Thus, rhythm production presumably imposes constraints that go beyond those imposed by the simple tapping tasks used to investigate low-level timing. We view these constraints in rhythm tasks as a special case of the serial order control problem that has been linked to hierarchical representations. For the most part, hierarchical control models have been proposed in the context of speech production and the sequencing of keystrokes with multiple fingers (MacKay, 1987; Povel & Collard, 1982; Rosenbaum et al., 1987; Rosenbaum, Kenny, & Derr, 1983). More recently, Vorberg and Wing (1996) proposed a hierarchical control model for rhythmic timing, the *rhythm program hypothesis*.

At the core of the rhythm program hypothesis is the distinction between a *parameter specification* process and the actual

execution of intervals specified within a pattern by another process called *timekeeper execution*. Timekeepers are temporary representations of certain interval durations. Parameter specification refers to the programming of target durations for the different timekeepers as specified by the underlying *rhythm program*. Similar to the concept of a motor program, a rhythm program is an abstract representation of the serial order of events in an action sequence that translates into a hierarchy of adjustable timekeepers at the time of its implementation. Hierarchical parameter specification and timekeeper execution both contribute to the variance of observed interresponse intervals. Frequent updating processes during performance permit the flexibility typical of human movement timing: The overall tempo (the cycle period) can be changed without the rhythm program becoming obsolete.

The process of updating the rhythm program has many features in common with the process of selecting between competing mental sets or task sets, a problem vigorously studied in research on executive task management using the task-switching paradigm (e.g., Monsell, 2003). A general finding from this research is that adequate selection and maintenance of a mental set can be hampered by interference through mental sets that are currently irrelevant but that could be applied in principle. This type of interference is increased when competing mental sets share representational features (e.g., use the same response keys; Mayr, 2001; Yeung & Monsell, 2003). A second, slightly different type of mental set interference can arise even in the absence of an explicit set-selection situation, namely, when the instructed set needs to be maintained in the face of a set that is in some manner dominant. An example is the Stroop task, where interference from the dominant word-reading task set needs to be counteracted to successfully name the color of each word. In the present context, it is particularly important that both types of interference have been found to increase with adult age (e.g., Mayr, 2001; West & Baylis, 1998).

Our executive control hypothesis of timing maintains that rhythm programs are mental sets that specify the overall duration of an action, the number and sequence of its behavioral components (i.e., keystrokes or taps), and the relative (with respect to the overall duration) time intervals between single responses. Executive demands of selecting between competing rhythm programs can be particularly large (a) because they usually consist of overlapping elements (e.g., recombinations of identical action durations) and (b) because there are often dominant rhythmic programs that interfere with the currently relevant program. It is exactly when either one or both of these two types of interference occur that we predict large adult age effects in rhythmic performance.

Within the Vorberg and Wing (1996) framework, difficulties during the selection or maintenance of the adequate rhythm program affect timing variability through downward propagation of target-specification problems. In Experiment 1, we looked at the manner in which timing variability of specific intervals is affected when the intervals are embedded within complex rhythms that should require executive selection of rhythm programs. We expected that older adults' timing abilities should be not much different from those of young adults for simple, repetitive production of the same durations (indicating an intact low-level timer).

However, they should be severely affected by the rhythm complexity manipulation.<sup>1</sup>

### Outline of Experiment 1

Figure 1 depicts the three conditions in Experiment 1: isochronous tapping, a simple rhythm, and a complex rhythm. Isochronous tapping (Figure 1A) was used to establish a low-level timing baseline. Repetitive tapping of a single interval does not involve sequencing operations for multiple targets. Consequently, differences in performance because of age effects should be small or negligible. In the two rhythm tasks (Figures 1B and 1C), participants produced the illustrated patterns for a fixed number of *cycles*. A cycle comprises one execution of the illustrated sequence of intervals. The simple rhythm (Figure 1B) consisted of two target durations, a long and a short duration forming a simple 2:1 ratio. Sequencing demands are low in this condition compared with the complex rhythm (Figure 1C). This condition consisted of three different target durations for a total of six intervals, and all local transitions between successive intervals were ambiguous (i.e., each target interval has two potential successors across repeated productions of a cycle). High sequencing demands should yield large differences between the two age groups.

Systematic variations of induced performance tempos allowed the estimation of individual mean-variance functions for each condition or for specific target durations within the same condition. For a first test of the executive control hypothesis of timing, we predicted steeper mean-variance slopes in those tasks that require executive functions (the rhythm tasks) as compared with the low-level timing condition (isochronous tapping), and this prediction equally applied for both age groups. Furthermore, the executive control hypothesis of timing posits that complex rhythm production is controlled by hierarchical timing and sequencing operations, processes susceptible to age-graded declines in efficiency. Hierarchical control processes can be identified by comparing mean-variance functions for different target durations within the same task. In the following, we detail these predictions using the rhythm program framework proposed by Vorberg and Wing (1996).

Figure 2 provides a schematic sketch of the hypothetical rhythm programming process for the complex rhythm task depicted in Figure 1C. During the first programming stage, timekeepers controlling constituent target durations are specified from the overall rate (i.e., the momentary representation of the overall tempo or the cycle period). In complex rhythms, timekeepers specified at the top level (typically controlling longer intervals) are used at a second stage to program subordinate timekeepers, which in turn control shorter target durations in the same cycle. In our example, four timekeepers with target durations of one-fourth cycle period are specified at the first hierarchy stage. Two of them represent target durations for the two long intervals at the beginning and the end of each cycle; the other two timekeepers propagate their target durations down to subordinate timekeepers controlling short and medium intervals, respectively. Other control hierarchies are possible for this rhythm (Jagacinski, Marshburn, Klapp, & Jones, 1988). The final stage in the rhythm programming process is the sequencing of programmed timekeepers. According to Vorberg and Wing (1996), subsequent timekeeper execution is accom-

plished by a general-purpose mechanisms (or central timer), a device that we refer to as the *low-level timing mechanism*.

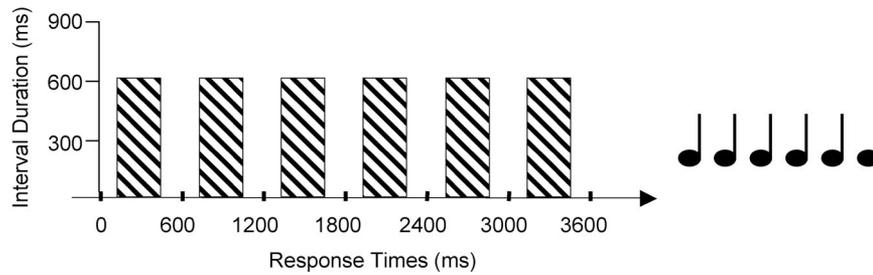
Two sources of variability characterize parameter specification, namely *rate fluctuation* and *error propagation*. Rate fluctuation refers to the assumption that participants' representations of the cycle period (the overall tempo) are not perfectly stable but fluctuate during successive performances of multiple cycles. Error propagation denotes the assumption that target specifications at any level in the hierarchy will be less than perfect (e.g., as a result of unsuccessful updating of the relevant set) and that these duration specification errors are propagated down from top-level timekeepers to their subordinates.

Hierarchical control, most notably the effects of rate fluctuation and error propagation, reveals itself through distinct patterns of mean-variance relations for different intervals within the same task (Vorberg & Wing, 1996; for empirical tests of the model, see Krampe, Engbert, & Kliegl, 2001; Krampe et al., 2000). Target specification for top-level timekeepers as proportions of the momentary rate (Stage 1 in Figure 3) implies that timekeepers inherit rate fluctuation, which is proportional to their relative duration within the cycle. If multiple overall performance tempos (induced cycle periods) are compared, rate fluctuation can be expected to increase as a direct function of cycle period. As a consequence, longer target durations (e.g., the first and the last interval in Figure 2) should show steeper mean-variance functions compared with those with smaller proportional durations (the other intervals in Figure 2). If parameter updating is next to perfect (as we argue is more likely for young adults), rate fluctuation remains as the main factor determining observed variabilities of interresponse intervals. Under these conditions, the slopes of mean-variance functions for intervals in the complex rhythm task are expected to differ according to their target duration ratios (e.g., 3:1 for long vs. short durations).

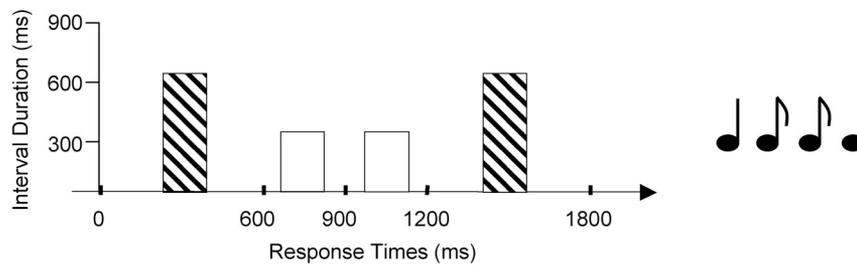
Specification errors and their propagation alter the described pattern. Failures to update the parameter set induce specification errors for top-level timekeepers that are propagated down the hierarchy. As a result, specification errors will have a more pronounced effect on those durations controlled by subordinate timekeepers (i.e., short and medium intervals in Figure 2), thereby altering the pattern induced by rate fluctuation alone. Considering the complex rhythm condition, a higher rate fluctuation in older

<sup>1</sup> We assume that the level of difficulty for low-level timing relates to the number of pulses that must be accumulated by a clock-counter mechanism to delineate certain target durations. Krampe, Engbert, and Kliegl (2001, Appendix) have shown that under the assumption of a clock-counter mechanism with scalar (i.e., Weber) properties, observed variances must be a direct function of internal clock speed and the square of the target interval. We operationalize low-level timing difficulty by contrasting observed variabilities for different, isochronous target intervals realized across blocks of trials. In contrast, differential challenges for sequencing and executive control arise from combinations of different target intervals into a rhythmic pattern within a certain trial. Our model predicts that observed variances for a specific interval from a rhythmic pattern depends on its target duration (particularly its proportion of the target cycle period) and the interval's position within the programming hierarchy.

## A. Isochronous Tapping



## B. Simple Rhythm



## C. Complex Rhythm

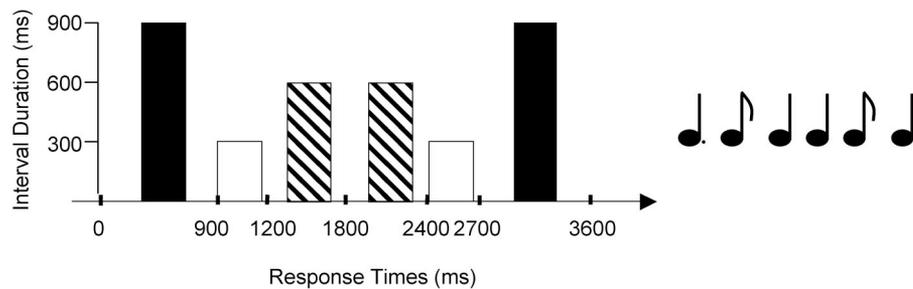


Figure 1. Conditions in Experiment 1. *Isochronous tapping* (A) was assessed at nine target durations (200–2,000 ms) and constituted the low-level timing baseline. One cycle of the *simple rhythm condition* (B) consisted of four intervals with two (short and long) target durations. The *complex rhythm condition* (C) had six intervals in each cycle with three different target durations (short, medium, long). Column heights indicate target durations; column colors and patterns refer to identical target durations within and across conditions.

adults must affect the slopes for all three target durations. Age-related increases in specification errors will yield more pronounced slope differences between young and older adults for shorter and medium intervals. This prediction is opposite to the assumption of an age-related slowing of the internal clock, which predicts larger differences in performance between the age groups for long durations.

In sum, our goal in Experiment 1 was to dissociate low-level timing and executive control in both young and older adults' performances of tasks differing in sequence complexities. A critical provision to this end is the demonstration of hierarchical control in complex rhythm production. In Experiment 2, we provide direct evidence for set selection processes by contrasting productions of a dominant pattern, a nondominant pattern, and a sequence that involves alternating

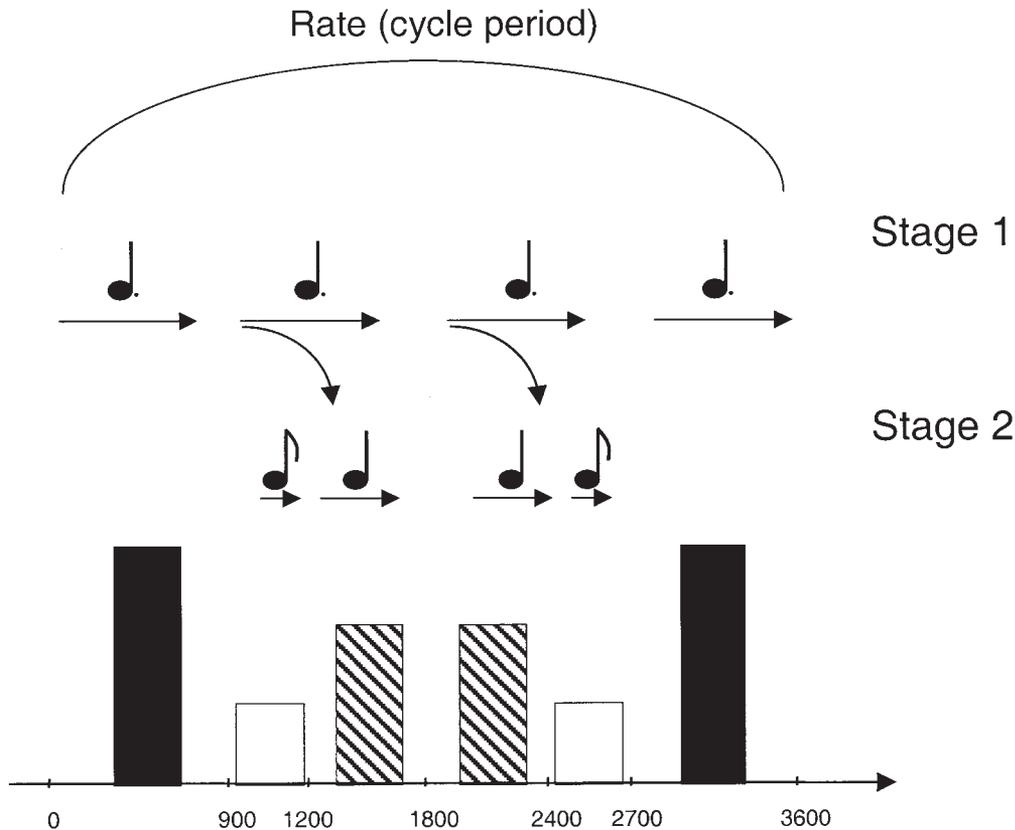


Figure 2. Schematic illustration of the hypothetical target-specification process (rhythm programming) providing the input for low-level timing in the complex rhythm condition. At Stage 1, target durations for superordinate timekeepers (controlling long intervals) are specified as proportions of the cycle period. At Stage 2, target values are propagated to subordinate timekeepers controlling short and medium intervals. Column heights indicate target durations; column colors and patterns refer to identical target durations within and across conditions.

(switching) between two patterns. In this context, we demonstrate that executive control demands do not arise from the number of elements (target durations) in a sequence alone. Furthermore, in Experiment 2, we further elucidate the capacities and limitations of the low-level timing mechanism by investigating how it handles local transitions in strict alternations of intervals differing in their duration ratios. We return to these issues after our presentation of the findings from Experiment 1.

## Experiment 1

### Method

**Participants.** Sixteen young ( $M_{\text{age}} = 19.06$  years,  $SD = 1.18$  years; 8 female) and 16 older participants ( $M_{\text{age}} = 70.00$  years,  $SD = 4.15$  years; 8 female) participated in 12 experimental sessions. As is typical of age-comparative studies (Salthouse, 1985), young adults ( $M = 63.38$ ,  $SD = 11.01$ ) had a higher score on the Digit-Symbol Substitution Test from the Wechsler Adult Intelligence Scale (Wechsler, 1955) than did older adults ( $M = 48.13$ ,  $SD = 8.73$ ),  $F(1, 30) = 18.85$ ,  $MSE = 98.72$ ,  $p < .001$ . We recruited participants with limited musical training: None of the young participants had ever learned to play a musical instrument, and only 2

participants in the older sample reported taking instrument lessons in their youth for less than a year. All participants were self-reported right-handers.

**Apparatus.** Participants, while seated on height-adjustable chairs, produced interval sequences with standard drumsticks on electronic drum equipment. They were instructed to hold the drumsticks with a tight but relaxed grip (in their right hands for unimanual conditions), with their thumbs on the upper sides. Taps caused deformations of piezo-ceramic sensors in the MIDI drumpads (KAT, Alternate Mode Inc., Chicopee, MA). An Alesis DM5 drum synthesizer with a 48 MHz processor (Alesis Inc., Cumberland, RI) sampled these signals and triggered drum sounds. Signals were transmitted by a MIDI TimePiece II (Mark of the Unicorn, Cambridge, MA) digitizer to the serial port of a Macintosh PowerPC (7100/66) that time stamped events to the nearest millisecond. Trial presentation, the generation of pacing beats (500-Hz sine wave, 30-ms duration), and feedback display were computerized. Drum sounds and pacing signals were displayed through external speakers.

**Procedure.** The 12 sessions lasted between 1 hr (isochronous tapping task) and 1.5 hr (rhythm tasks), including breaks as participants desired them. In Session 1, participants completed a personal questionnaire and the Digit-Symbol Substitution Test (Wechsler, 1955), and they were then introduced to the apparatus and the handling of the drumsticks. Maximum tapping rates for right, left, and alternate hand(s) were assessed at the

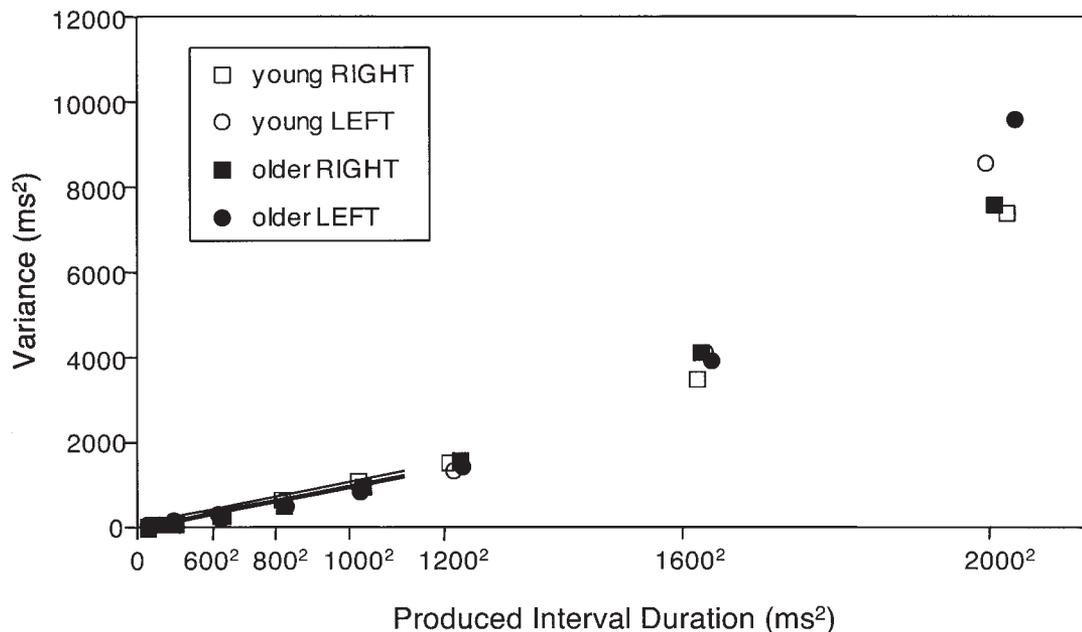


Figure 3. Variances as a function of produced interval durations (squared) for left- and right-hand isochronous tapping (Experiment 1). Curve fits are based on mean individual regression coefficients for left- and right-hand productions at five target durations ranging from 300–1,000 ms.

beginning of this and each following session. Participants performed the isochronous tapping in Sessions 1–6. The simple rhythm condition (Figure 1B) was administered in Sessions 7–9, the complex rhythm condition (Figure 1C) in Sessions 10–12. Conditions were administered in ascending order of complexity, which turned out to be more beneficial for older adults, as intended (see the *Results* section).

Nine conditions of required target intervals (200 ms, 300 ms, 400 ms, 600 ms, 800 ms, 1,000 ms, 1,200 ms, 1,600 ms, and 2,000 ms) were administered for isochronous tapping. The simple rhythm was performed at six cycle periods (1,200 ms, 1,800 ms, 2,400 ms, 3,600 ms, 4,800 ms, and 6,000 ms) and the complex rhythm at five cycle periods (2,400 ms, 3,000 ms, 3,600 ms, 4,800 ms, and 6,000 ms). In the isochronous tapping condition, we assessed right- and left-hand unimanual as well as alternate tapping. Participants performed the rhythm tasks unimanually (right hand) and with alternating hands. The order of target interval and hand condition in each task was counterbalanced across participants and across sessions. During each block, participants had to produce five valid trials; trials containing alternation errors or timing outliers (intervals deviating by more than 25% from the mean produced interval) were immediately repeated up to a maximum of eight trials per block.<sup>2</sup>

We used the continuation paradigm (Wing & Kristofferson, 1973a). That is, after listening to the pacing beat as long as they wanted, participants played along with the computer sound (synchronization phase). After a fixed number of synchronization taps, the pacing signal was discontinued and participants performed the task without external pacing (continuation phase). Beginnings of rhythmic cycles in the simple and complex rhythm tasks were not specially marked in the pacing signal. For isochronous tapping, synchronization phases comprised 10 taps followed by 32 continuation taps. Five synchronization cycles and 10 continuation cycles were required in the two rhythm tasks. Detailed feedback was provided at the end of each trial, indicating the realized duration of single intervals as bar diagrams along with horizontal reference lines for target durations of single intervals. In addition, values for mean realized cycle periods (rhythm conditions), mean realized durations for single

target intervals, and number of outliers were displayed. At the onset of each of the three task conditions, participants received warm-up blocks at target intervals that were not used in later testing.

## Results

We restrict data presentation to the unimanual conditions to reduce the complexity of the article. The main dependent variable of interest was the increase of variabilities as a function of produced interval durations in different experimental conditions. For these analyses, we aggregated mean interval durations and associated standard deviations across trials and determined individual linear regression coefficients for variances (squared averaged standard deviations) as a function of squared interval durations (Ivry & Hazeltine, 1995).

*Characteristics of the low-level timing mechanism.* We considered the initial blocks of trials for each of the nine target durations (Sessions 1–3) to be practice. Participants' performance improved from the first to the second phase (Sessions 4–6), and age groups were similar in that respect. Overall, participants produced an average of 95 trials during that second testing phase. Prior to aggregation and the computation of regression coefficients, we screened trials according to (a) premature terminations

<sup>2</sup> During warm-up for the complex rhythm, it became evident that the 25% single-interval outlier criterion was too strong for this condition. For reasons of compatibility across conditions, it was maintained during actual testing. Instructional training proceeded until participants accomplished three trials in a row with proper sequencing of target intervals at the prescribed overall tempo. Nonetheless, all but one older but only one young participant required an extra instructional session for the complex rhythm.

of interval production or very long pauses, (b) violations of overall tempo, and (c) single-interval outliers.<sup>3</sup> In this process, 5.17% of the trials were discarded, with similar means for young and older adults.

For maximum comparability with the earlier study by Ivry and Hazeltine (1995), we restricted our estimate of individual mean-variance functions to a range of 300- to 1,000-ms target durations. Individual mean-variance functions were fitted using data from both unimanual conditions.<sup>4</sup> Figure 3 shows the variances for right- and left-hand tapping as a function of produced interval durations (squared). The fit lines in Figure 3 are based on averaged regression coefficients for each group. Individual fits were satisfactory in young (median  $R^2 = .859$ ) and older participants (median  $R^2 = .845$ ). Mean slopes for older adults ( $M = 0.000913$ ,  $SD = 0.000422$ ) were similar to those of young adults ( $M = 0.000972$ ,  $SD = 0.000413$ ),  $F(1, 30) = 0.20$ ,  $p > .66$ . The same was true for intercepts (older adults,  $M = -1$ ,  $SD = 98$ ; young adults,  $M = 42$ ,  $SD = 125$ ),  $F(1, 30) = 1.00$ ,  $p > .32$ . Our estimates for slopes were an almost exact replication of the values reported by Ivry and Hazeltine (1995, Experiment 1).

Age differences in slopes of mean-variance functions did not depend on the range of target intervals considered. A mixed-design analysis of variance (ANOVA) on variances with age group as the between-subjects factor and target duration (1,200 ms, 1,600 ms, and 2,000 ms) as the within-subjects factor revealed a continued variance increase at even longer target intervals: For linear contrast,  $F(1, 30) = 39.42$ ,  $p < .001$ . There were no significant differences between the hands, and main effects of age group or interactions with age group were far from significant, all  $F_s < 0.20$ ,  $p_s > .7$ . Inclusion of the 1,200-ms and 1,600-ms target durations into the individual curve fitting led to negative intercepts but, again, replicated the pattern of comparable slopes and intercepts for the two age groups. In sum, our data demonstrated the usual increase in variability with interval duration and age invariance in this low-level timing capacity across a large range of target intervals. These results do not support the assumption of internal clock slowing in later adulthood.

*Comparison of mean-variance functions across conditions.* According to our executive control hypothesis, the low-level timing mechanism is recruited or programmed by other mechanisms during complex rhythm production. Additional costs arising from executive functions should reveal themselves in steeper slopes in the rhythm tasks relative to the low-level timing baseline. Differences in mean-variance relations between target intervals for the same rhythmic sequence could be used as evidence for hierarchical target-specification processes. In a first step, we estimated a single slope for each rhythm condition using all the target intervals that it comprises. To maximize the number of identical target durations across conditions, we restricted our range of induced target intervals to those that include target durations between 200 ms and 1,600 ms. Thus, we excluded the longest cycle period in the simple rhythm condition, because it generates long target durations (2,000 ms) that have no counterparts in the complex rhythm condition. Given that rhythms were performed with the right hand only, we used right-hand isochronous tapping performance at eight target durations between 200 ms and 1,600 ms as a baseline. Five cycle periods (1,200 ms, 1,800 ms, 2,400 ms, 3,600 ms, 4,800 ms) with four target durations (two long and two short intervals) provided

the data from the simple rhythm condition. Data for the complex rhythm condition were six target durations (two long, two short, two medium), each produced at five cycle periods (2,400 ms, 3,000 ms, 3,600 ms, 4,800 ms, 6,000 ms).

The same screening criteria for trial screening as before (premature trial termination and long pauses, violation of target intervals or target cycle periods, single-interval outliers) were applied. To meet a criterion for sequencing accuracy in the two rhythm conditions, we discarded trials with cycles in which the produced rank order for short-, long-, and medium-interval target durations was violated. The number of acceptable trials increased significantly after the first testing session in both rhythm conditions,  $F_s(1, 30) > 4.60$ ,  $p_s < .05$ , but had stabilized for the remaining two sessions. Related improvements were similar for young and older adults in the simple rhythm condition; however, older adults improved more after the first session with the complex rhythm condition,  $F(1, 30) > 4.34$ ,  $p < .05$ . Thus, data from the first sessions in each rhythm task were considered practice and not included in further analyses. The number of trials with errors was higher in the complex rhythm condition ( $M = 20.50$ ,  $SD = 20.85$ ) than in the simple rhythm condition ( $M = 4.09$ ,  $SD = 4.30$ ),  $F(1, 30) > 29.52$ ,  $p < .001$ . This effect was reliable in both age groups but more pronounced in older adults,  $F(1, 30) > 11.73$ ,  $p < .005$ . Older adults were similar to young adults in the simple rhythm condition,  $t(30) = 0.78$ ,  $p > .4$ ; however, in the complex rhythm condition, they produced more trials with errors ( $M = 31.44$ ,  $SD = 23.81$ ) than young adults did ( $M = 9.56$ ,  $SD = 8.74$ ),  $t(30) = 3.45$ ,  $p < .005$ . The vast majority of trials with errors in both rhythm conditions were sequence violations, and age groups were similar in that respect. The error pattern indicates a specific age difference in the complex rhythm condition, in line with our assumption of the involvement of executive control processes.

Only correct trials were used for individual curve fitting. Two older adults failed to master a sufficient number of target cycle period conditions in the complex rhythm task. A third older participant produced slopes that were clear outliers in the same task. These participants were excluded from this and the following analyses in Experiment 1. Figure 4 shows variances as a function of squared target intervals in the three conditions for young (top panel) and older adults (bottom panel). Regression lines are based on means of individual regression coefficients. Table 1 shows the Age  $\times$  Condition regression statistics.

<sup>3</sup> Premature termination or extremely long pauses were defined as being twice the target duration, and an average of only 0.84 ( $SD = 2.51$ ) trials per participant were discarded for that reason. We excluded 3.05 trials ( $SD = 2.86$ ) per participant because of violations in the overall tempo (defined in terms of nonoverlapping windows around adjacent target durations). After the application of these screening criteria, only very few trials ( $M = 0.28$ ,  $SD = 0.92$ ) had to be discarded because they contained single-interval outliers (defined as more than 50% deviation from the produced mean).

<sup>4</sup> Initial curve fits conducted separately for the hands revealed marginally significant differences in intercept (with higher means for the left hand) but no hand effects for slope. More important, there was no indication of age effects or interactions. Linear trends were similar for age groups, and analyses of regression coefficients led to the same pattern of results when based on detrended data. The same was true when trials with single-interval outliers were included.

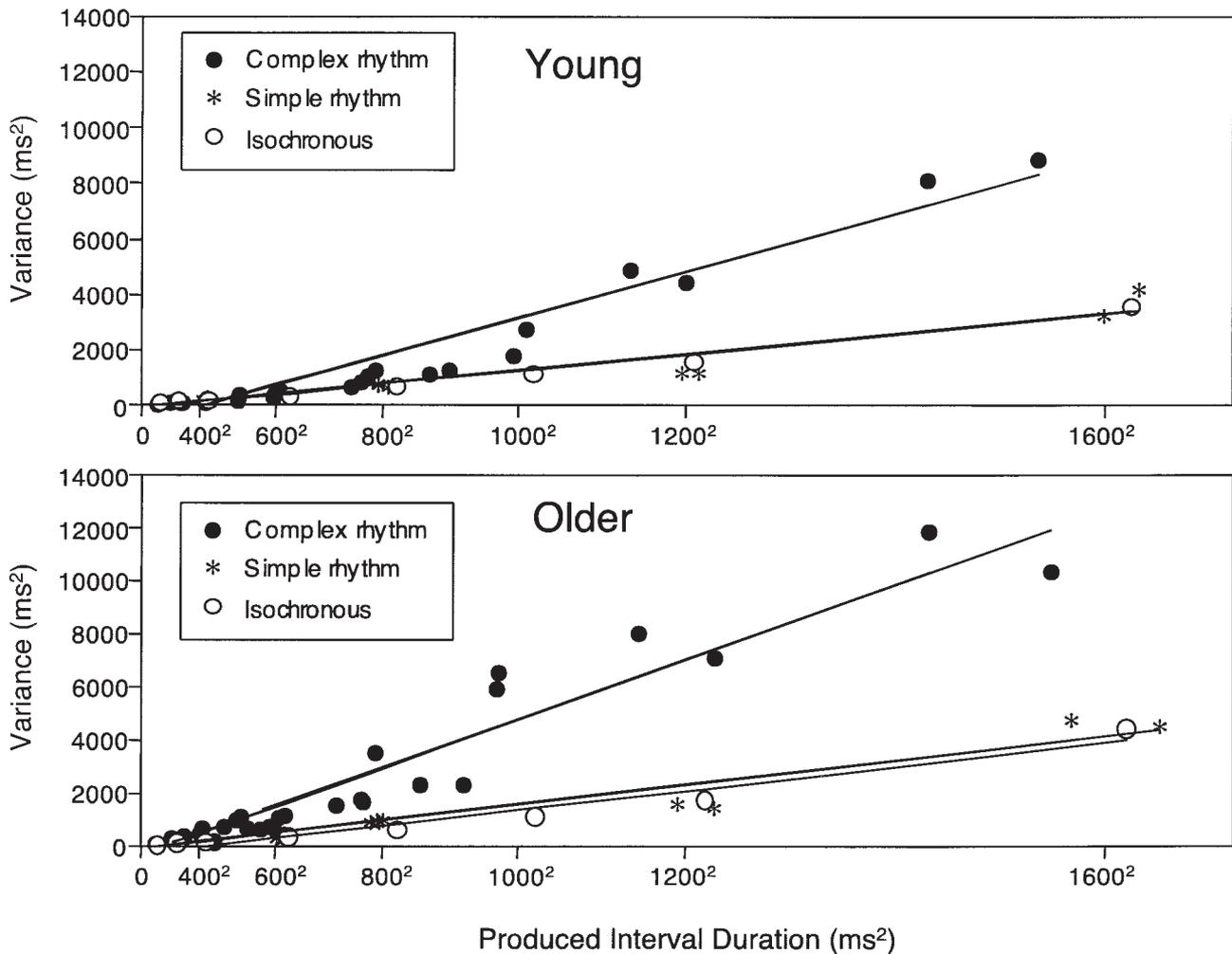


Figure 4. Variances as a function of produced interval durations (squared) for the three conditions in Experiment 1 (isochronous tapping, simple rhythm, complex rhythm). Curve fits are based on mean individual regression coefficients for all target durations in each condition (cf. Table 1).

We conducted mixed-design ANOVAs on intercepts and slopes, with age group as the between-subjects factor and condition (isochronous, simple rhythm, complex rhythm) as the within-subjects factor. Differences in intercepts across conditions failed to reach significance by a slight margin,  $F(2, 54) = 3.04, p < .06$ . The main effect of age group and the Age Group  $\times$  Condition interaction were not significant. The critical analysis of slopes yielded a main effect of condition,  $F(2, 54) = 21.25, p < .001$ , supporting our main prediction that timing for rhythmic sequencing differs from low-level timing. Again, main effects of age group and the Age Group  $\times$  Condition interaction,  $F(2, 54) = 0.62, p > .5$ , were not reliable. Post hoc  $t$  tests showed that slopes for the complex rhythm were significantly higher compared with slopes in the simple rhythm condition,  $t(28) = 4.58, p < .001$ , or isochronous tapping,  $t(28) = 4.94, p < .001$ . Separate  $t$  tests for the age groups corroborated these findings for both young,  $t(15) > 4.2, p < .001$ , and older adults,  $t(12) > 2.79, ps < .017$ . Slopes for isochronous tapping and the simple rhythm condition did not differ reliably

( $p > .99$ ), pointing to the possibility that low-level timing is sufficient to generate patterns comprising only two target durations.<sup>5</sup>

*Mean-variance relations in hierarchical timing and the effects of age.* The steeper slopes for the complex rhythm condition suggested that performance required more than low-level timing.

<sup>5</sup> We conducted additional analyses with even the longest target intervals (2,000 ms) in the isochronous tapping and the simple rhythm conditions included. The pattern of results was exactly the same as the pattern reported for the restricted range of target durations. A mixed-design ANOVA on slopes with condition as a within-subjects factor yielded the critical effect of condition,  $F(2, 54) = 14.86, p < .001$ , and no other effects were significant. Slopes in the complex rhythm condition ( $M = 0.0043, SD = 0.0036$ ) were reliably steeper than in isochronous tapping ( $M = 0.0018, SD = 0.0012$ ) or the simple rhythm condition ( $M = 0.0022, SD = 0.0013$ ),  $t(28) > 3.60, ps < .001$ . The latter two slopes did not differ reliably ( $p > .16$ ). As before, this pattern and, hence, the dissociation we claim held at the level of single age groups.

Table 1  
*Mean Linear Regression Coefficients and Model Fits for Mean-Variance Relations Estimated for All Target Durations Within Each Condition in Experiment 1*

Condition and group	Intercept (ms <sup>2</sup> )		Slope		Median <i>R</i> <sup>2</sup>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Isochronous					
Young adults	−99	257	0.00134	0.00083	.939
Older adults	−243	407	0.00163	0.00120	.909
Simple rhythm					
Young adults	−48	240	0.00131	0.00084	.858
Older adults	−71	309	0.00166	0.00138	.860
Complex rhythm					
Young adults	−597	602	0.00375	0.00225	.837
Older adults	−286	1,466	0.00507	0.00475	.798

However, although numerically in the predicted direction (see Table 1), the Age Group × Condition interaction was not significant. Fortunately, the executive control hypothesis makes strong assumptions about the characteristics of the mechanisms that must operate prior to invoking low-level timing in complex rhythm production. Specifically, we can compare mean-variance functions for different target durations within the same rhythmic sequence. Focusing on the complex rhythm condition, we also provide model-based tests of age differences in executive control.

According to our model, programming of the low-level timing mechanism must reflect two additional sources of variability, namely (a) the effects of rate fluctuation during the specification of proportional target durations from the overall rate and (b) the effects of propagation of specification errors to subordinate timekeepers. We predicted that hierarchical timing in young adults should mostly reflect rate fluctuation, that is, a systematic ordering of mean-variance slopes according to relative target duration. In contrast, specification errors and their propagation in older adults should lead to steeper slopes for durations controlled by subordinate timekeepers, that is, short and medium durations.

Figure 5 shows variances as a function of squared produced durations, with long, medium, and short durations for young (top panel) and older adults (bottom panel) presented separately. Fit lines in Figure 5 are based on means of individual regression coefficients. Table 2 lists the corresponding regression statistics. Results of a mixed-design ANOVA on slopes with age group as the between-subjects factor and target durations as the within-subjects factor were consistent with predictions related to the effects of hierarchical timing and age. On average, mean-variance slopes were steeper in older adults compared with young participants,  $F(1, 27) = 10.78, p < .005$ . The main effect of target duration was significant,  $F(2, 54) = 4.70, p < .05$ , as was the predicted interaction between age group and target duration,  $F(2, 54) = 3.46, p < .05$ .

As predicted, young adults' mean-variance slopes showed a systematic ordering with respect to long, medium, and short target durations,  $t_s(15) > 2.20, p_s < .05$ . Ratios of mean slope estimates corresponded closely to the proportions for long–short (3:1) and long–medium (1.5:1) target durations, yielding values of 2.97 and 1.57, respectively. This outcome points to rate fluctuation as the

dominant factor in young participants' timing variability, while the effects of propagating target values to subordinate timekeepers were small.

In contrast, older adults' mean-variance functions showed the predicted effects of specification errors and their propagation to subordinate timekeepers over and above the effects of rate fluctuation. Functions for medium target durations intersected those for long intervals, whereas slope differences between long and short targets were small and nonsignificant,  $t(12) = 0.61, p > .5$ . At the same time, slopes for medium targets were significantly higher than those for short targets,  $t(12) = 2.39, p < .05$ . In line with the assumption of an age-related increase in specification errors, we found that slopes for short and medium target durations were significantly higher in older adults than in young adults,  $t_s(27) > 3.10, p_s < .005$ . Slopes for long targets, that is, for those durations presumably specified at higher levels in the programming hierarchy, did not differ reliably between age groups,  $t(27) = 0.57, p > .5$ .<sup>6</sup>

### Discussion

According to the executive control hypothesis of timing, low-level timing and executive control processes can be dissociated by their mean-variance signatures. Experiment 1 provided strong support for this prediction: Slopes of individual mean-variance functions were steeper in the complex rhythm condition than in the isochronous tapping condition, the low-level timing baseline. This dissociation was demonstrated for both young and older adults. In addition, we obtained independent evidence for hierarchical control in the complex rhythm task for both age groups: Mean-variance relations in different intervals produced within this task showed a distinct

<sup>6</sup> Analyses of intercepts corroborated the findings related to slopes. We obtained a main effect of target duration,  $F(2, 54) = 11.12, p < .001$ , and a reliable Age Group × Duration interaction,  $F(2, 54) = 4.17, p < .05$ . In young adults, the size of negative intercepts reflected the steepness of slopes. This pattern was violated in older adults, for whom the intercept for medium durations had the most negative value, which differed reliably from the estimates obtained for young participants,  $t(27) = 2.80, p < .01$ .

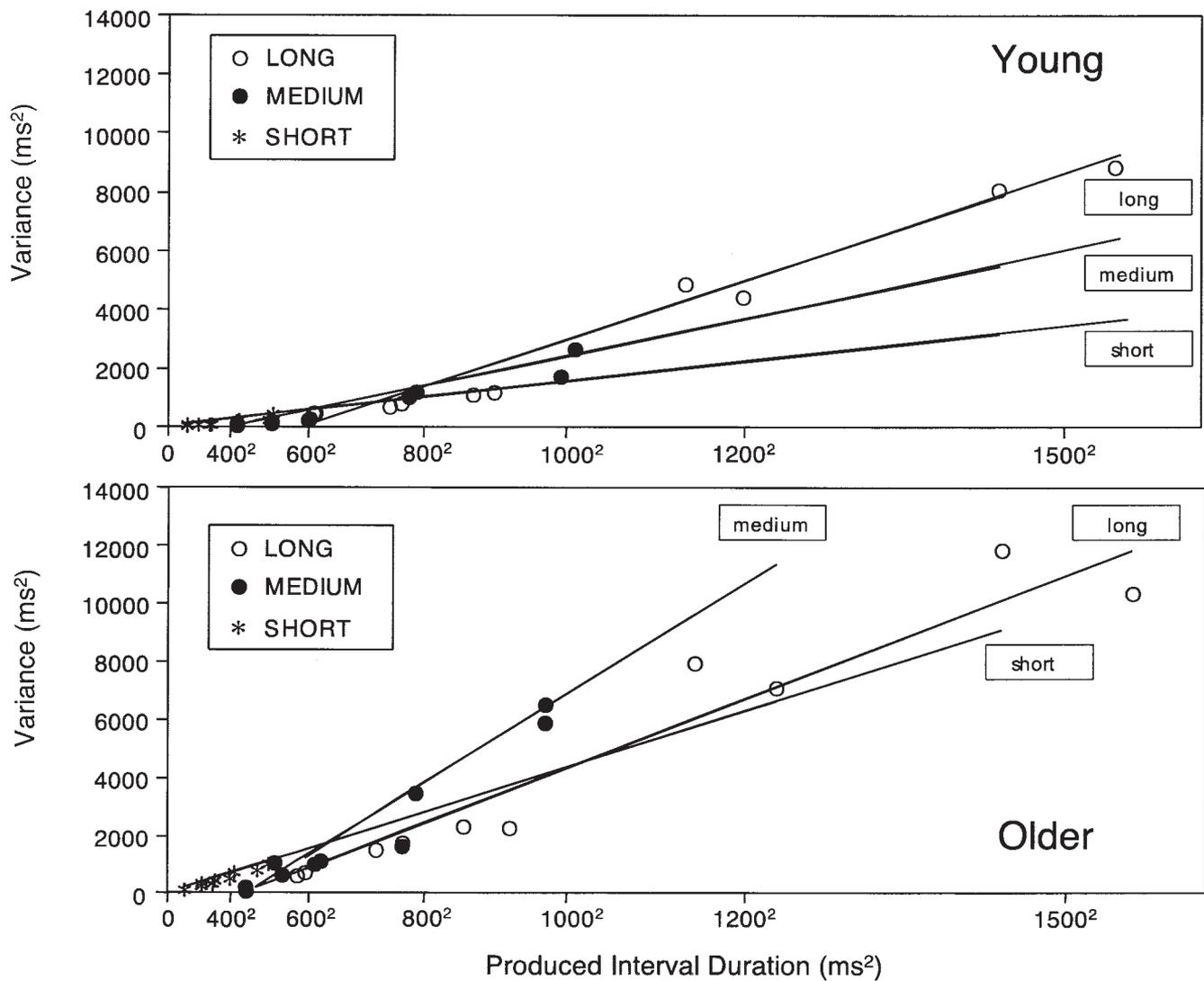


Figure 5. Variances as a function of produced interval durations (squared) for short, medium, and long intervals in the complex rhythm condition (Experiment 1). Data for young adults are shown in the top panel, older adults' data are presented in the lower panel. Curve fits are based on mean individual regression coefficients (cf. Table 2).

pattern, which we had predicted from the rhythm-programming hypothesis (Vorberg & Wing, 1996). These findings are at odds with the predictions of a central clock model, although they support our claim that models of that class fail to account for complex rhythm production without assuming additional mechanisms.

Additional analyses provided evidence for specific decrements at the level of target-specification errors and their propagation in older adults. The finding that in older adults, variances of shorter durations are more affected by hierarchical control than are longer durations coming from the same cycles contradicts predictions from models of age-related clock slowing. We attribute older adults' target-specification problems to their less efficient selection, maintenance, and updating of the

task-relevant sets. Conversely, the relative age-graded stability of isochronous tapping performance across a large range of target intervals (i.e., task difficulties) supports our claim that low-level timing can largely operate without the intervention of executive control processes in the absence of complex sequencing demands.

The findings from the simple rhythm condition were unexpected because, following Cohen et al. (1990), we had assumed that the local ambiguity in this sequence would encourage participants to form abstract, hierarchical representations and rely on executive control the same way they did in the complex rhythm condition. However, mean-variance slopes in this condition were similar to those obtained for the low-level timing baseline. Moreover, older adults were able to produce the simple rhythm at a considerable

Table 2  
*Mean Linear Regression Coefficients and Model Fits for Mean-Variance Relations Estimated for Three Target Durations in the Complex Rhythm Condition (Experiment 1)*

Interval	Intercept (ms <sup>2</sup> )		Slope		Median <i>R</i> <sup>2</sup>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Long					
Young	-1,467	1,306	0.00444	0.00280	.870
Older	-998	1,640	0.00530	0.00517	.889
Medium					
Young	-404	736	0.00283	0.00238	.786
Older	-1,702	1,670	0.00855	0.00685	.831
Short					
Young	80	95	0.00150	0.00081	.695
Older	10	342	0.00432	0.00298	.634

range of cycle periods with variabilities similar to those of young adults.<sup>7</sup>

Evidence suggests that under minimal sequencing demands, like alternating between two target durations, low-level timing can support the production of two different intervals by producing concatenations of a single base duration (e.g., Collier & Wright, 1995; Semjen & Ivry, 2001). A dominant finding in related experiments (e.g., Essens & Povel, 1985; Povel, 1981) was that participants were most accurate in tasks where intervals formed 1:1 or 2:1 duration ratios, that is, exactly those duration ratios constituting the simple rhythm in Experiment 1. More complex target ratios tended to be distorted in the direction of these simpler ratios. As an example, participants' actual productions of 1.4:1 ratios showed a strong bias toward 2:1 (Summers et al., 1989). Thus, performance constraints in the simple rhythm condition might have fallen into the capability range of low-level timing, where sequencing proceeded without the intervention of executive control functions.<sup>8</sup>

If we restrict our contrast to the low-level timing baseline and the complex rhythm condition, the results of Experiment 1 were in full accordance with the rhythm program hypothesis. However, they did not provide direct evidence for the operation of set-selection processes as maintained by the executive control hypothesis. Although it could be argued that complex rhythm production amounts to overcoming a dominant tendency toward isochronous timing (e.g., Krampe et al., 2001), participants in our study had no obvious alternative sets to choose from. A conservative interpretation of Experiment 1 should be restricted to the maintenance and updating of the same task set, processes that are, arguably, instances of executive control. A much simpler account could emphasize the number of different target intervals as the key factor in determining variances in the three conditions. For example, one (isochronous tapping) or two targets (simple rhythm) might be below participants' representational thresholds, whereas three target intervals (complex rhythm) could have exceeded their capacities, specifically those of older adults. More direct evidence for executive control would require experimental manipulations of the frequencies and the difficulty of set-selection processes independent of sequence length and the number of target durations. These problems relate to processes of set selection, selection against a dominant set, and set switching, and we aimed Experiment 2 specifically at their investigation.

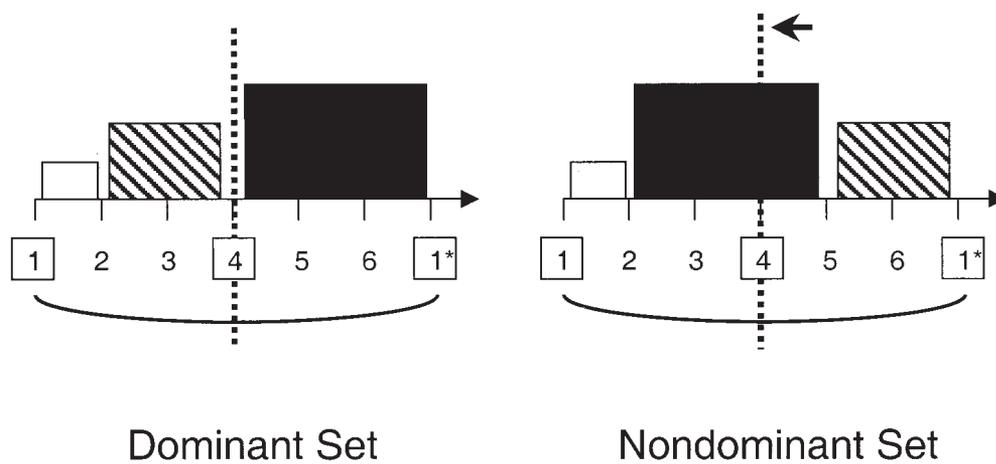
A second alternative account that does not necessarily imply executive control functions relates to potential problems at the level of local transitions among successive intervals: Adjacent intervals in isochronous tapping or the simple rhythm condition formed 1:1 or 2:1 duration ratios (cf. Figure 1), whereas the complex rhythm included additional local transitions with 3:1 duration ratios. If the latter transitions pose specific difficulties, the higher variances observed in the complex rhythm condition could be partly explained at the level of local transitions. There are two theoretical possibilities in this regard. First, changing a temporal interval in a way that does not obey the laws of simple (i.e., 1:1, 2:1) ratios could imply an executive control problem in the sense of reprogramming a target setting. The preceding interval specification may perseverate and therefore influence computation of the next interval. If this is the case, older adults should have larger problems with producing higher order integer or complex ratios than young adults do. Second, the finding that successive intervals cannot be selected arbitrarily may reflect not so much an executive control problem but rather the fact that local transitions in tasks with minimal sequencing demands (i.e., two alternating intervals) are implemented through or at least in close interaction with the low-level timing mechanism. We addressed these issues in Experiment 2.

## Experiment 2

Figure 6 illustrates the problems of set selection, selection against a dominant set, and set switching for the rhythmic patterns used in Experiment 2. The dominant set (left panel) was similar to the complex rhythm in Experiment 1 in that it encouraged the

<sup>7</sup> A comparison of slope estimates for long and short target durations in the simple rhythm condition did not yield reliable differences between durations ( $p > .05$ ). Age differences and the Age Group  $\times$  Target (long vs. short) interaction were not significant ( $ps > .4$ ).

<sup>8</sup> A related account focusing the issue of ambiguity of transitions has been proposed by Cohen et al. (1990). The authors pointed out that repetitions of the same element in a sequence are frequently treated as a single element. Thus, in the simple rhythm task, participants may have solved the sequencing problem at the level of local, unambiguous transitions among interval categories by treating the immediate repetitions of long and short intervals, respectively, as single elements (cf. Figure 1).



*Figure 6.* Schematic illustration of set dominance. Numbers on axes refer to the underlying metrum (subdivision) into six beats with preferred positions 1 and 4. In the dominant set (left panel), short and medium intervals form one half of the total cycle such that the third interval (long) can be initiated at a preferred beat (4). In the nondominant set condition, participants must counteract a tendency to prematurely initiate the third interval. Failure to do so (arrow) results in relative shortening of the long and lengthening of the medium interval and a bias toward 1:1 ratios for medium and long intervals in nondominant sets. Column heights indicate target durations; column colors and patterns refer to identical target durations within and across conditions.

hierarchical parsing in two symmetric half cycles: Short and medium intervals sum up to the same duration as the long target interval. Symmetric subdivision is a key aspect of rhythm in Western music, and beats evenly subdividing cycles receive special attention even in musically untrained listeners (e.g., Jones, 1984). In the dominant set, the privileged fourth beat coincided with interval boundaries for medium and long targets. In contrast, this boundary is on the fifth beat in the nondominant set, preventing symmetric subdivision and preferred hierarchical parsing. To the degree to which participants are not able to prevent intrusion of this dominant but incorrect response (i.e., placing a tap at the fourth beat), the second interval in the nondominant pattern would be shortened while the remaining interval would be longer than its ideal cycle proportion. As a result (i.e., a failure to select against the dominant set), the long–medium duration ratio would be distorted toward 1:1 and the probability of sequence errors (i.e., Interval 3 being longer than Interval 2) in the nondominant set increases, turning it, in fact, into the dominant set.

In the set-switching condition, participants alternated between the dominant and nondominant sets. Thus, identical target intervals were arranged into two different sequences within the same trial. Note that this was already the case for the complex rhythm condition in Experiment 1; however, symmetric parsing was possible in both half cycles. In contrast, switching between dominant and nondominant sets required replacing the currently active set operations, which are subject to failure. The asymmetry between the two sets described above should lead to perseveration problems; that is, participants should maintain or default to the dominant pattern instead of switching to the nondominant pattern. Failures to switch back to the dominant set are possible, although presumably less frequent. As a result, performance of both patterns in the switching task should be worse than if produced in isolation.

Experiment 2 comprised three conditions that we illustrate in Figure 7. We refer to these conditions as Experiment 2A (local transitions between alternating target durations), Experiment 2B (set selection and selection against a dominant set), and Experiment 2C (set switching). In Experiment 2A, participants produced strict alternations of two target intervals with simple (2:1, medium–short), lower order integer (3:1, long–short), and complex duration ratios (1.5:1, medium–long). To control for the effects of different duration ratios, we used the same local transitions to construct the three-interval sequences in Experiments 2B and 2C. In Experiment 2B, participants performed separate blocks of trials for the dominant and the nondominant sets, respectively. In the set-switching condition (Experiment 2C), dominant and nondominant sets had to be carried out in alternation within a given trial.

From our theoretical perspective, the most critical difference between the three conditions was that the tasks in Experiment 2A could, at least in principle, be handled by low-level timing, whereas the tasks in Experiments 2B and 2C required executive control. The executive control hypothesis predicted two task-related process dissociations. First, low-level timing in the alternating-intervals condition (Experiment 2A) should reveal itself through systematic distortions of complex (1.5:1) and lower order integer (3:1) ratios toward 2:1 ratios (Summers et al., 1989). In contrast, the executive control hypothesis of timing predicted biases toward 1:1 ratios for adjacent pairs with complex ratios in nondominant patterns, that is, in the opposite direction (see our discussion at the beginning of this section related to Figure 6). Second, as a replication of our findings in Experiment 1, we predicted higher variabilities in the dominant sequence in Experiment 2B compared with Experiment 2A, signifying the involvement of executive control processes in the set-selection but not in the alternating-intervals conditions. In addition, Experiments 2B

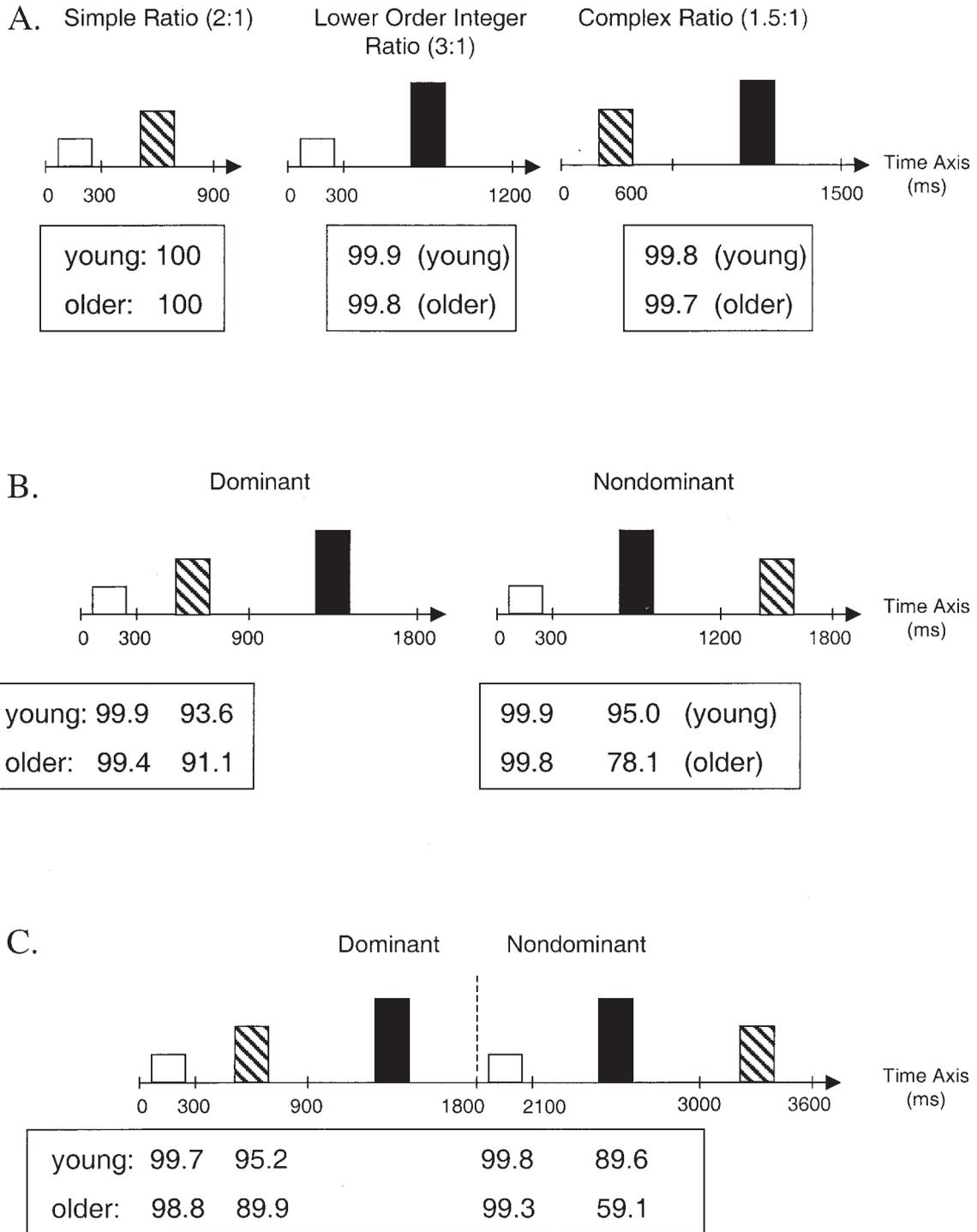


Figure 7. Conditions in Experiment 2. Column heights and horizontal spacing indicate target durations for short (300 ms, open columns), medium (600 ms, striped columns), and long intervals (900 ms, dark columns). A: In Experiment 2A, participants produced alternations between two target durations with simple (2:1), lower order integer (3:1), or complex ratios (1.5:1). B: In Experiment 2B, participants performed separate blocks of dominant (set selection, left panel) and nondominant (selection against dominant set, right panel) sets. C: In the set-switching condition (Experiment 2C), participants alternated between dominant and nondominant sets within trials. Values in boxes refer to the percentages of cycles in which the proper sequence of target durations was realized. In Experiments 2B and 2C, values for the second interval in each set are conditional on the proper realization of the first (short) interval. The latter values are identical with the percentages correct for properly sequencing the full cycle.

and 2C had variations in their hypothesized executive control demands independent of sequence length and constituent target durations. Set dominance should make failures to activate the nondominant pattern more likely, leading to performance decrements in the nondominant relative to the dominant set conditions. Moreover, performance of both patterns in the switching task should be worse than if produced in isolation.

Assuming that the low-level timing mechanism maintains its functionality until later adulthood, we should find that older adults produce local transitions between two alternating intervals as well as young adults do, irrespective of whether simple or complex ratios are required. From our findings in Experiment 1, we expected negative age effects, however, even for the dominant set in the set-selection condition (Experiment 2B). Executive control problems are more aggravated in older adults when there is a dominant or modal schema that needs to be overcome by an internal plan (selection against a dominant set), especially when competing response schemas share critical elements (Mayr, 2001; West & Baylis, 1998). From this, we expected the magnitude of negative age effects in Experiments 2B and 2C to increase with higher executive control demands.

### Method

The complexity of Experiment 2 required participants with experience in the conditions of Experiment 1. Therefore, we asked the same individuals to return for Experiment 2. One older participant was no longer available, leaving 16 young and 15 older participants for continued testing in Experiment 2. Apparatus and overall procedure including pacing stimuli and feedback format were the same as described earlier. Data were collected in the course of two sessions of approximately 1.5-hr duration, including breaks. Session 1 was a practice session with the same procedure as described for Session 2 below; however, the pacing signal continued throughout all trials in Session 1.

Participants performed all tasks unimanually with their right hands. To control for possible transfer among conditions, we administered three blocks of the set-switching condition (Experiment 2C) at the beginning, the middle, and the end of each session, with Experiments 2A and 2B inserted after the first or the second block for Experiment 2C. Order of occurrence for Experiments 2A and 2B and the order of tasks within conditions were counterbalanced across participants. So that we could obtain a comparable number of trials (i.e., 12) in each of the three conditions (2A, 2B, and 2C), each block required a minimum of four trials in Experiment 2A, six trials in Experiment 2B, and four trials in Experiment 2C. Trials in all tasks comprised the same number of taps, namely, 12 during synchronization and 60 during the continuation phase. Error trials and trials containing outliers were immediately repeated up to a maximum of two repetitions per block.

### Results

After we discarded 12 trials in which participants prematurely terminated interval production, 1,506 trials collected in Session 2 remained for analyses. Only data from the continuation phases were analyzed.

*Sequence errors.* Sequence errors were calculated as the probability of correct transitions within rhythmic cycles. Related values are provided in the boxes below the bars in Figure 7. Because of

the minimal sequencing demands imposed by the alternation between two target intervals, participants' performance was perfect or close to perfect in Experiment 2A. The left figure in each box related to Experiments 2B and 2C is the probability of properly initiating cycles with the shortest of three intervals; the following figures give the conditional probabilities of producing the proper interval at the second position (which is identical to the probability of proper sequencing for all three target intervals). In line with our claim that sequencing in the four conditions of Experiments 2B and 2C was controlled at the level of sets rather than at the level of local transitions, participants were next to perfect in terms of initiating each set with the shortest of three intervals (the identical element in both sets).

The probabilities of correctly sequencing medium or long intervals in set-selection and set-switching conditions reflected the predicted effects of executive control demands and their age sensitivity. We performed a mixed-design ANOVA on these probabilities using age group as the between-subjects factor and set (dominant vs. nondominant) and condition (set selection vs. set switching) as within-subjects factors. Main effects of condition,  $F(1, 29) = 9.84, p < .005$ , and set,  $F(1, 29) = 6.59, p < .05$ , were reliable, and older adults' overall accuracies ( $M = 78.0\%$ ,  $SD = 8.34$ ) were significantly below those of young adults ( $M = 93.4\%$ ,  $SD = 6.65$ ),  $F(1, 29) = 32.21, p < .001$ . Negative age effects were more pronounced in the switching conditions (Experiment 2C) relative to the set-selection conditions (Experiment 2B),  $F(1, 29) = 5.40, p < .05$ , and differences between age groups were larger for nondominant sets compared with dominant sets,  $F(1, 29) = 4.21, p < .05$ . Neither the Task  $\times$  Set interaction ( $p > .09$ ) nor the three-way interaction was reliable ( $p > .6$ ).

*Produced duration ratios.* We first analyzed produced ratios in the alternating durations task (Experiment 2A). A mixed-design ANOVA on produced duration ratios with age group as between-subjects and target ratio as within-subjects factors yielded a main effect of target ratio,  $F(2, 56) = 95.64, p < .001$ . Neither the main effect of age group nor the Age Group  $\times$  Target Ratio interaction were significant ( $ps > .08$ ). Mean ratios in the age groups were almost identical for 3:1 and 1.5:1 conditions and, if anything, closer to target in older adults in the 2:1 condition. Overall, participants were close to the ideal ratio in the 2:1 condition ( $M = 1.95, SD = 0.20$ ). Produced ratios in the lower order condition ( $M = 2.59, SD = 0.29$ ) were 7 standard error units below the 3:1 target ratio, that is, biased toward 2:1 ratios. A similar but even stronger bias emerged in the complex ratio (1.5:1) condition ( $M = 1.91, SD = 0.17$ ), in which produced ratios were 12 standard error units above the target and actually closer to the 2:1 than to the 1.5:1 target ratio (see the leftmost panel in Figure 8). Thus, results in Experiment 2A were fully in line with earlier studies (Semjen & Ivry, 2001; Summers et al., 1989) and generalized to older adults' performances. The observed biases toward 2:1 ratios suggested that both young and older adults relied on low-level timing when producing alternations between two target durations.

The critical test for the executive control hypothesis involved a comparison of ratios for adjacent intervals with 1.5:1 target ratios

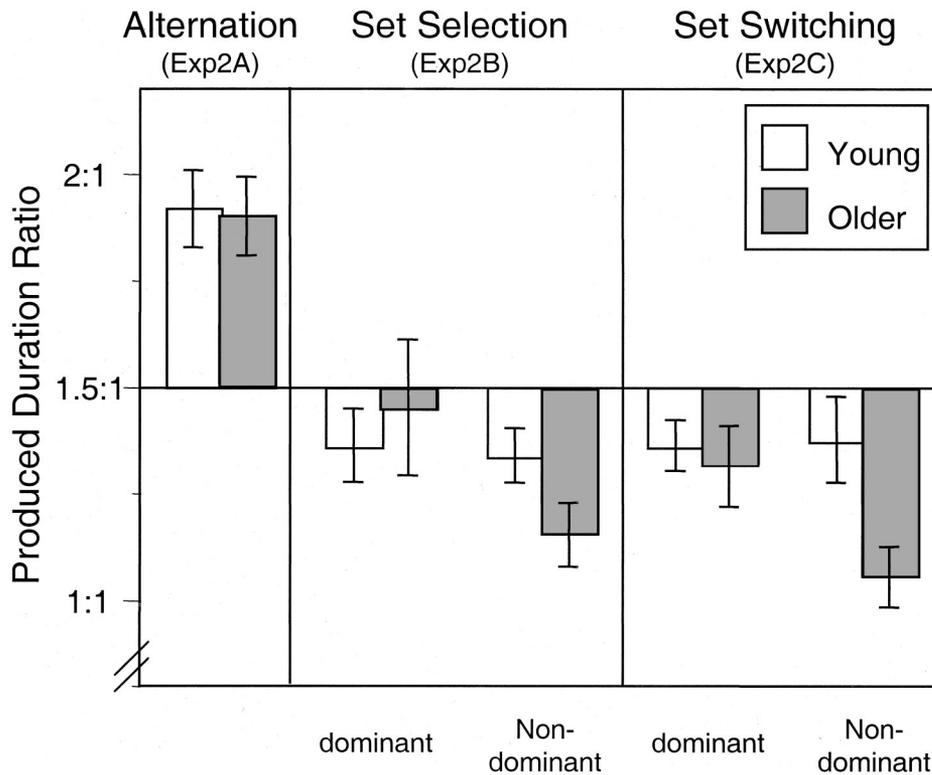


Figure 8. Produced ratios for adjacent intervals with 1.5:1 target ratios in Experiment 2. The leftmost panel shows produced ratios for alternating durations (Experiment 2A [Exp2A], complex ratio); data in the middle panel are from separate blocks for selection of dominant versus nondominant sets (Experiment 2B [Exp2B]); the rightmost panel refers to Experiment 2C (Exp2C), in which participants switched between dominant and nondominant sets within trials. Error bars indicate 95% confidence intervals for age groups.

across the conditions of Experiment 2.<sup>9</sup> The leftmost panel in Figure 8 illustrates the strong bias toward 2:1 ratios in Experiment 2A reported above. In contrast, ratios in set-selection and set-switching tasks were close to the ideal ratio or in the opposite (1:1) direction in nondominant set conditions as predicted. The dissociation was reliable at the level of contrasting any of the four conditions in Experiments 2B and 2C with the alternating-intervals condition (Experiment 2A), and this was equally true for young,  $t(15) > 8.00$ ,  $ps < .001$ , as well as older participants,  $t(13) > 5.00$ ,  $ps < .001$ .

A comparison of ratio biases in set-selection and set-switching conditions supported our predictions regarding negative age differences in executive control. A mixed-design ANOVA on produced medium-long ratios in Experiments 2B and 2C with age group as the between-subjects and set (dominant vs. nondominant) and switching condition (set selection vs. set switching) as within-subject factors yielded a main effect of set,  $F(1, 28) = 15.03$ ,  $p < .001$ , whereas the main effect of switching failed to reach significance by a slight margin ( $p < .07$ ). More important, we obtained the predicted negative main effect of age group,  $F(1, 28) = 7.73$ ,  $p < .01$ , and reliable interactions of age group with set,  $F(1, 28) = 13.80$ ,  $p < .001$ , as well as switching condition,  $F(1, 28) = 6.73$ ,  $p < .05$ . Produced ratios for dominant sets (averaged across switching and nonswitching conditions) were similar for age

groups ( $M = 1.38$ ,  $SD = 0.16$ ),  $t(13) < 0.40$ ,  $p > .69$ ; however, when producing nondominant sets, older adults ( $M = 1.11$ ,  $SD = 0.11$ ) showed stronger biases toward 1:1 ratios than young adults did ( $M = 1.36$ ,  $SD = 0.15$ ),  $t(28) = 5.02$ ,  $p < .001$ . Likewise, age differences were not significant for averaged set selection tasks in Experiment 2B ( $M = 1.33$ ,  $SD = 0.13$ ),  $t < 1$ ,  $p > .37$ , while set switching induced more biased ratios in older ( $M = 1.19$ ,  $SD = 0.12$ ) than in young adults ( $M = 1.37$ ,  $SD = 0.13$ ),  $t(28) = 3.85$ ,  $p < .001$ . The three-way interaction was not significant.

In sum, biases for complex duration ratios were in opposite directions depending on whether interval pairs were produced in alternation (Experiment 2A) or in set selection and switching contexts. This was equally true for both age groups. As predicted,

<sup>9</sup> For reasons of comparability across conditions, we used only those trials from Experiments 2B and 2C in which participants had properly produced the short interval at the first position within each cycle (more than 99% on average; see Figure 6). This means that the confusions between medium and long intervals were included. One older participant produced extreme values for sequence errors (more than 2.5 standard deviations off the mean) by perseverating the nondominant set in the switching condition. To reduce variability within groups, we excluded her data from this and all following analyses, a precaution that was not critical for the overall pattern of results.

increased executive control demands due to selection against the dominant set or set switching induced stronger biases toward 1:1 ratios in older adults.

*Variabilities of produced intervals.* The measure from Experiment 1 was used, namely, variances standardized by squared produced durations. We conducted a mixed-design ANOVA on the variation coefficients in the alternation task (Table 3) with age group as the between-subjects and the three alternation tasks (simple, lower order, complex ratios) and target duration as within-subjects factors. The main effect of target duration was significant,  $F(1, 28) = 12.61, p < .005$ . In line with our prediction that low-level timing prevails in the alternation condition, young and older adults produced similar variation coefficients ( $p > .6$ ). No other effect or interaction reached significance. To directly replicate our findings from Experiment 1, we conducted an analysis on variation coefficients in the dominant set condition in Experiment 2B (Table 4). This condition was most informative because it encouraged a similar symmetrical subdivision and hierarchical parsing in which short and medium durations were controlled by subordinate timekeepers. A mixed-design ANOVA with age group as the between-subjects factor and target duration (planned contrast: long vs. short and medium) as the within-subjects factor yielded a main effect of target duration,  $F(1, 28) = 14.54, p < .005$ . Overall, older adults were more variable in their performances than were young adults,  $F(1, 28) = 5.40, p < .05$ , and this effect was qualified by an interaction with the duration contrast,  $F(1, 28) = 6.82, p < .05$ . In line with our findings in Experiment 1, age differences were not significant for longer intervals ( $M = 0.00263, SD = 0.00153, t(28) = 0.76, p > .45$ , whereas older adults ( $M = 0.00484, SD = 0.00224$ ) were more variable than young adults ( $M = 0.00280, SD = 0.00133$ ) when producing short and medium durations,  $t(28) = 3.08, p < .005$ . Coefficients of variation for the short and medium durations in the dominant set condition were reliably higher than those observed when participants produced the same targets in alternation (Experiment 2A, simple ratios),  $F(1, 28) = 36.68, p < .001$ , and this effect was more pronounced in older adults,  $F(1, 28) = 9.77, p < .005$ . Thus, Experiment 2 provided a full replication of Experiment 1 with hierarchical timing in the dominant set leading to increases in variance over and above low-level timing and pronounced negative age differences.

As reported earlier (cf. Figure 7), increased executive control demands (i.e., selection against dominant set and switching) affected the number of sequence errors in older adults. In young adults, sequencing accuracies were close to ceiling; however, increased executive control demands revealed themselves in the

variability of produced intervals (Table 4 shows coefficients for single intervals). Variation coefficients (averaged across durations) were higher in the set-switching condition (Experiment 2C,  $M = 0.00386, SD = 0.00144$ ) compared with the set-selection condition (Experiment 2B,  $M = 0.00234, SD = 0.00081$ ),  $F(1, 15) = 14.01, p < .005$ . This increase was more pronounced for the nondominant set than for the dominant set,  $F(1, 15) = 18.73, p < .001$ .

## General Discussion

Our executive control hypothesis of timing started out from the assumption that timing and sequencing in paced movement production reflect the workings of two distinct processes: a low-level timing mechanism and a higher level sequencing mechanism operating within the larger system of executive control. During production of multitarget interval sequences, executive functions program the low-level timing mechanism: They control the endogenous provision of abstract (i.e., nonexecutable) sequence representations, that is, their updating, maintenance, and, if required by the task, their replacement by different action plans.

Our empirical approach in Experiment 1 aimed at task-specific and age-specific dissociations of the two hypothetical mechanisms on the basis of mean-variance functions estimated at the level of individual performances. We successfully separated two classes of movement production tasks. When participants generated patterns consisting of three different target durations arranged in a sequence of locally ambiguous transitions, we observed increases in variabilities over and above the low-level timing baseline obtained from isochronous tapping. These variance increases could be traced to participants' use of hierarchical representations in both age groups. It is important to note that these effects were more pronounced in older adults because of their decreased efficiencies in target-specification processes. In contrast, low-level timing of repeated intervals with constant target durations (i.e., isochronous intervals) was virtually unaffected by adult aging.

Age invariance in a simple rhythm condition with two alternating target durations motivated a further investigation of the representational capacity of the low-level timing mechanism and its potential to support primitive sequencing operations. Experiment 2 proved informative in this respect: The observed biases toward 2:1 duration ratios and the small variabilities in Experiment 2A (relative to set-selection and set-switching conditions) suggested that low-level timing can indeed produce two target durations. Alternations between two target intervals were presumably generated by a low-level timing mechanism that is equally efficient in young and older adults by concatenating single target representations, a

Table 3  
Variation Coefficients in Different Task Conditions in Experiment 2A (Alternation)

Group	Simple ratio (2:1)				Lower order ratio (3:1)				Complex ratio (1.5:1)			
	Short		Medium		Short		Long		Medium		Long	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Young	.0022	.0009	.0020	.0009	.0027	.0012	.0025	.0012	.0032	.0024	.0025	.0021
Older	.0027	.0013	.0022	.0008	.0033	.0013	.0024	.0014	.0029	.0014	.0025	.0017

Table 4  
*Variation Coefficients in Different Task Conditions in Experiment 2B (Set Selection) and Experiment 2C (Set Switching)*

Conditions and group	Dominant set						Nondominant set					
	Short		Medium		Long		Short		Long		Medium	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Set selection												
Young	.0022	.0011	.0034	.0020	.0024	.0014	.0020	.0005	.0024	.0012	.0016	.0006
Older	.0037	.0026	.0060	.0035	.0029	.0017	.0059	.0042	.0066	.0117	.0062	.0031
Set switching												
Young	.0023	.0015	.0039	.0019	.0036	.0020	.0017	.0004	.0046	.0026	.0071	.0042
Older	.0069	.0038	.0119	.0069	.0045	.0020	.0048	.0029	.0103	.0100	.0142	.0098

Note. The order of intervals corresponds to the order in task.

capacity that keeps variabilities small (relative to rhythm programming) but produces biased duration ratios. In contrast, repetitive rhythm production encourages abstract, hierarchical representations (e.g., metrical-grid strategies musicians use while practicing rhythms), which provides accurate durations but comes at the cost of increased variabilities.

Experiment 2 also provided further evidence for the dissociation of low-level timing and executive control mechanisms by demonstrating that problems with nontrivial sequencing demands do not arise from the mere number of intervals to be represented but rather from executive control demands. Set-selection and set-switching requirements in Experiments 2B and 2C led to a pattern of duration ratios markedly distinct from what we observed in both age groups when the same intervals were generated by the low-level timing mechanism. We replicated our findings from Experiment 1 with a demonstration of increased variabilities over and above the alternating-intervals task even in the simplest set-selection condition, in which sequencing errors were minimal in both age groups (the dominant pattern). As in Experiment 1 (the complex rhythm condition), variance increases were more pronounced in older adults than in young adults. Note also that all target intervals in Experiment 2 were below 1,000 ms, ruling out the possibility that the dissociation of low-level timing and executive control depends on the inclusion of long target durations.

Experiment 2 realized two conditions typical for situations with high executive control demands, namely, selection against dominant action plans and frequent selection among potentially possible plans (e.g., Mayr, 2001; Rogers & Monsell, 1995). Older adults had more problems suppressing the dominant representation, and frequent selection between different rhythm programs in the switching condition brought older adults' performances of the nondominant pattern close to chance level (59.1%; arbitrary selection of any of the two sets or perseveration of one set should yield values of 50% correct), whereas young adults maintained relatively high accuracies (89.6%). Notwithstanding their high accuracies, at the level of sequence errors, young adults' interval production was more variable in the set-switching condition than in the set-selection condition, in which they had produced the patterns in isolation.

### Related Theoretical Accounts

Our concept of low-level timing shares many similarities with the notion of a multipurpose device resembling a central timer espoused in the two-level timing model by Wing and Kristofferson (1973a, 1973b). In several other respects, most notably the assumption of separate timing and sequencing processes, the executive control hypothesis of timing is but an elaboration of the rhythm program framework developed by Vorberg and Wing (1996). Another approach that is related to our assumptions is the *cerebellar timing hypothesis* (Ivry, 1993, 1997). This model assumes that the cerebellum can provide effector- or duration-specific representations that are distributed across a set of neural elements within its larger structure. The recruitment of specific elements is task dependent and cerebellar output is gated prior to motor implementation. Recruitment and gating processes presumably involve neural structures outside the cerebellum (Hazeltine, Helmuth, & Ivry, 1997; Ivry & Richardson, 2002). The cerebellar timing hypothesis has received support from animal lesion and patient studies (Ivry, 1996); however, it awaits further experimental evidence for a dissociation between low-level timing and higher level processes informing its task-dependent recruitment. Ivry (1996) argued that such evidence must be based on common tasks and measures on the hypothesized processes. Our study provides evidence exactly along these lines.

As to the specific neural substrates of low-level timing, our findings cannot disambiguate between the cerebellar timing hypothesis and models, which posit a critical role for the basal ganglia in central timing operations (Harrington & Haaland, 1998; Harrington, Haaland, & Hermanowicz, 1998; Meck, 1996). However, both types of models and also recent neuropsychological evidence (Grafton, Hazeltine, & Ivry, 1998; Lewis, Wing, Pope, Praamstra, & Miall, 2004) suggest a specific involvement of higher cortical regions whenever rhythmic sequencing or the implementation of movement plans are required—a proposition that is clearly supported by our results.

### Alternative Accounts

Our finding of age-graded stability in isochronous tapping is in line with two earlier studies (Duchek et al., 1994; Greene &

Williams, 1993); however, negative age effects were reported by Woodruff-Pak and Jaeger (1998). It is interesting that these three earlier studies used the same single target duration (550 ms). In contrast, we based our interpretations on a method assessing accuracy for a large range of durations. In extension of previous work (Gibbon, 1977; Ivry & Corcos, 1993; Ivry & Hazeltine, 1995), we found that young and older adults had perfectly similar slopes in that range. In their meta-analytic review, Block, Zakay, and Hancock (1998) found no evidence for negative age effects in duration judgment or movement production task in any study that provided participants with feedback and at least some experimental practice, conditions that were both met in our study. Likewise, Salthouse, Wright, and Ellis (1979) observed similar performances in a duration judgment task using a psychophysical approach. These findings substantiate our claim regarding relative age-graded stability for low-level timing, at least in healthy, mentally fit adults (see also Duchek et al., 1994). Different from the majority of age-differential findings in the literature (for critical discussions, see Cerella, 1985; Salthouse, 1996), our dissociation argument entails the demonstration of age-graded stability across multiple levels of difficulty in one domain of functioning (i.e., low-level timing for a large range of target durations in isochronous tapping in Experiment 1 and multiple target ratios in Experiment 2A) along with differential negative age effects in the other (i.e., executive control in the complex rhythm condition in Experiment 1 and set selection and switching in Experiments 2B and 2C).

### Conclusion and Outlook

We argue that our conceptual linkage of timing and sequencing in repetitive movement production with extant models of executive control has demonstrated its explanatory potential by putting the empirical dissociation of low-level timing and higher level sequencing processes into the larger context of action control. This conceptual approach opens up to the investigation of long-standing issues in complex motor behavior, like the interplay between the sequencing of different effectors (fingers or hands) and the sequencing of target durations for different actions. For example, in piano music, complex rhythmic patterns are frequently assigned to simple, regular finger sequences—a measure that could enhance the cooperation of timing and sequencing processes by ameliorating the set-selection processes arising from convergence on identical motor actions (Mayr, 2001; Yeung & Monsell, 2003). We believe that consideration of executive control demands holds promise for addressing extant and intriguing problems of real-life movement timing in future studies.

### References

- Block, R. A., Zakay, D., & Hancock, P. A. (1998). Human aging and duration judgments: A meta-analytic review. *Psychology and Aging, 13*, 584–596.
- Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin, 98*, 67–83.
- Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*, 17–30.
- Collard, R., & Povel, D.-J. (1982). Theory of serial pattern production: Tree traversals. *Psychological Review, 89*, 693–707.
- Collier, G. L., & Wright, C. E. (1995). Temporal rescaling of simple and complex ratios in rhythmic tapping. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 602–627.
- Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: Attunement, referent period, focal attending. *Cognition, 77*, 251–288.
- Duchek, J. M., Balota, D. A., & Ferraro, F. R. (1994). Component analysis of a rhythmic finger tapping task in individuals with senile dementia of the Alzheimer's type and in individuals with Parkinson's disease. *Neuropsychology, 8*, 218–226.
- Essens, P. J., & Povel, D.-J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception & Psychophysics, 37*, 1–7.
- Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review, 84*, 279–325.
- Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1998). Abstract and effector-specific representations of motor sequences identified with PET. *Journal of Neuroscience, 18*, 9420–9428.
- Greene, L. S., & Williams, H. G. (1993). Age-related differences in timing control of repetitive movement: Application of the Wing–Kristofferson model. *Research Quarterly for Exercise and Sport, 64*, 32–38.
- Harrington, D. L., & Haaland, K. Y. (1998). Sequencing and timing operations of the basal ganglia. In D. A. Rosenbaum & C. E. Collyer (Eds.), *Timing of behavior: Neural, psychological, and computational perspectives* (pp. 35–61). Cambridge, MA: MIT Press.
- Harrington, D. L., Haaland, K. Y., & Hermanowicz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology, 12*, 3–12.
- Hazeltine, E., Grafton, S. T., & Ivry, R. B. (1997). Attention and stimulus characteristics determine the locus of motor-sequence encoding: A PET study. *Brain, 120*, 123–140.
- Hazeltine, E., Helmuth, L. L., & Ivry, R. B. (1997). Neural mechanisms of timing. *Trends in Cognitive Science, 1*, 163–169.
- Ivry, R. (1993). Cerebellar involvement in the explicit representation of temporal information. In P. Tallal, A. M. Galaburda, R. R. Llinas, & L. von Euler (Eds.), *Annals of the New York Academy of Sciences: Vol. 682. Temporal information processing in the nervous system: Special references to dyslexia and dysphasia* (pp. 214–230). New York: New York Academy of Sciences.
- Ivry, R. B. (1996). The representation of temporal information in perception and motor control. *Current Opinions in Neurobiology, 6*, 851–857.
- Ivry, R. (1997). Cerebellar timing systems. *International Review of Neurobiology, 11*, 555–573.
- Ivry, R., & Corcos, D. M. (1993). Slicing the variability pie: Component analysis of coordination and motor dysfunction. In K. Newell & D. M. Corcos (Eds.), *Variability and motor control* (pp. 415–447). Champaign, IL: Human Kinetics.
- Ivry, R. B., & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 3–18.
- Ivry, R. B., & Richardson, T. C. (2002). Temporal control and coordination: The multiple timer model. *Brain and Cognition, 48*, 117–132.
- Jagacinski, R. J., Marshburn, E., Klapp, S. T., & Jones, M. R. (1988). Tests of parallel versus integrated structure in polyrhythmic tapping. *Journal of Motor Behavior, 20*, 416–442.
- Jones, M. R. (1984). The patterning of time and its effects on perceiving. In J. Gibbon & L. Allan (Eds.), *Annals of the New York Academy of Sciences: Vol. 423. Timing and time perception* (pp. 158–167). New York: New York Academy of Sciences.
- Jordan, M. I., & Rosenbaum, D. A. (1989). Action. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 727–767). Cambridge, MA: MIT Press.

- Keele, S. W., & Hawkins, H. L. (1982). Explorations of individual differences relevant to high level skill. *Journal of Motor Behavior, 14*, 3–23.
- Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta Psychologica, 60*, 173–191.
- Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica, 101*, 339–378.
- Krampe, R. T., Engbert, R., & Kliegl, R. (2001). Age-specific problems in rhythmic timing. *Psychology and Aging, 16*, 12–30.
- Krampe, R. T., Engbert, R., & Kliegl, R. (2002). Representational models and nonlinear dynamics: Irreconcilable approaches to human movement timing and coordination or two sides of the same coin? *Brain and Cognition, 48*, 1–6.
- Krampe, R. T., Kliegl, R., Mayr, U., Engbert, R., & Vorberg, D. (2000). The fast and the slow of skilled bimanual rhythm production: Parallel versus integrated timing. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 206–233.
- Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: Wiley.
- Lewis, P. A., Wing, A. M., Pope, P. A., Praamstra, P., & Miall, R. C. (2004). Brain activity correlates differentially with increasing temporal complexity of rhythms during initialisation, synchronisation, and continuation phases of paced finger tapping. *Neuropsychologia, 42*, 1301–1312.
- MacKay, D. G. (1987). *The organization of perception and action: A theory for language and other cognitive skills*. New York: Springer-Verlag.
- Mayr, U. (2001). Age differences in the selection of mental sets: The role of inhibition, stimulus ambiguity, and response set overlap. *Psychology and Aging, 16*, 96–109.
- Meck, W. H. (1996). Neuropharmacology of timing and time perception. *Cognitive Brain Research, 3*, 227–242.
- Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*, 134–140.
- Povel, D.-J. (1981). Internal representations of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 3–18.
- Povel, D.-J., & Collard, R. (1982). Structural factors in patterned finger tapping. *Acta Psychologica, 52*, 107–123.
- Rogers, R. D., & Monsell, S. (1995). The cost of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207–231.
- Rosenbaum, D. A., Hindroff, V., & Munro, E. M. (1987). Scheduling and programming of rapid finger sequences: Tests and elaborations of the hierarchical editor model. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 193–203.
- Rosenbaum, D. A., Inhoff, A. W., & Gordon, A. M. (1984). Choosing between movement sequences: A hierarchical editor model. *Journal of Experimental Psychology: General, 113*, 372–393.
- Rosenbaum, D. A., Kenny, S., & Derr, M. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 86–102.
- Salthouse, T. A. (1985). *A theory of cognitive aging*. Amsterdam: North-Holland Press.
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.
- Salthouse, T. A., Wright, R., & Ellis, C. L. (1979). Adult age and the rate of an internal clock. *Journal of Gerontology, 34*, 53–57.
- Semjen, A., & Ivry, R. B. (2001). The coupled oscillator model of between-hand coordination in alternate-hand tapping: A reappraisal. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 251–265.
- Summers, J. J., Bell, R., & Burns, B. D. (1989). Perceptual and motor factors in the imitation of simple temporal patterns. *Psychological Research, 50*, 23–27.
- Vorberg, D., & Wing, A. M. (1996). Modelling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action: Vol. 3. Motor skills* (pp. 181–261). London: Academic Press.
- Wechsler, D. (1955). *Manual for the Wechsler Adult Intelligence Scale*. New York: Psychological Corporation.
- West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging, 13*, 206–217.
- Wing, A. M. (1980). The long and the short of timing in response sequences. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 469–486). Amsterdam: North-Holland.
- Wing, A. M. (2002). Voluntary timing and brain function: An information processing approach. *Brain and Cognition, 48*, 7–30.
- Wing, A. M., & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*, 5–12.
- Wing, A. M., & Kristofferson, A. B. (1973b). The timing of interresponse intervals. *Perception & Psychophysics, 13*, 455–460.
- Woodruff-Pak, D. S., & Jaeger, M. E. (1998). Predictors of eyeblink classical conditioning over the adult age span. *Psychology and Aging, 13*, 193–205.
- Yeung, N., & Monsell, S. (2003). Switching between tasks of unequal familiarity: The role of stimulus-attribute and response-set selection. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 455–469.

Received March 5, 2002

Revision received September 13, 2004

Accepted September 17, 2004 ■