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The Costs of Taking It Slowly: Fast and Slow Movement Timing in Older Age

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We investigated adult age-differences in timing control of fast vs. slow repetitive movements using a dual-task approach. Twenty-two young (M = 24.23 yr) and 22 older adults (M = 66.64 yr) performed three cognitive tasks differing in working memory load and response production demands and they tapped series of 550-ms or 2100-ms target intervals. Single-task timing was comparable in both groups. Dual-task timing was characterized by shortening of produced intervals and increases in drift and variability. Dual-task costs for both cognitive and timing performances were pronounced at slower tapping tempos, an effect exacerbated in older adults. Our findings implicate attention and working memory processes as critical components of slow movement timing and sources of specific challenges thereof for older adults.

Keywords: dual-task, finger tapping, variability, attention, working memory

A prevailing view on human performance is that “faster is better” or that rapid performance requires higher levels of skill. When navigating vehicles, playing computer games, or participating in team sports speeded performance is of obvious advantage. In certain domains like expressive performances in music, acting, dance, or martial arts, accurate timing of slow movement is considered a special skill. Given the ubiquity of age-related slowing in cognitive and motor processes (Salthouse, 1985) slow movements seem like a natural realm for older adults to display impressive levels of performance. Indeed, in musicians youth is frequently associated with breathtaking tempo and dramatic effects, whereas deep expression and musicality (sometimes in the absence of originality and virtuosity) remain privileges of matured artists and composers (e.g., Simonton, 1989). In the present study we use a dual-task approach to investigate young and older adults’ timing of fast and slow repetitive movements. We demonstrate that timing slow movements presents a particular challenge to older adults due to the involvement of age-sensitive higher cognitive processes, notably attention and working memory. Furthermore, we show that older age comes with decreases of dual-task performance at the level of these higher cognitive processes over and above the challenges of parallel response production.

Repetitive Movement Timing: Assessment, Age-Related Changes, and Accounts

Studies of repetitive movement timing frequently make use of the continuation paradigm (Wing & Kristofferson, 1973a, 1973b). At the onset of a trial, participants listen to a periodic pacing signal providing the target duration. Starting to tap along marks the beginning of the synchronization phase, a period comprising a limited number of taps after which the pacing signal stops leaving participants continue tapping for a further period without external pacing. Three task constraints to be mastered can be distinguished: first, the proper target duration(s) must be adopted during synchronization. At the onset of a trial, participants listen to a periodic pacing signal providing the target duration. Starting to tap along marks the beginning of the synchronization phase, a period comprising a limited number of taps after which the pacing signal stops leaving participants continue tapping for a further period without external pacing. Second, participants must avoid drift, that is, speeding up or slowing down within a trial. Finally, fluctuations of produced intervals (variability) must be kept at a minimum.

In tasks comprising but one target duration (isochronous tapping) participants have little problems to match the target interval and maintain it throughout trials if convenient tempos (typically target durations of 400-600 ms) are required. Researchers’ prime variable of interest in related studies has been timing variability. However, when larger tempo ranges are considered, deviations of mean produced intervals from target durations and drift become more critical (Collier & Ogden, 2004; Madison, 2001). In general, tapping variability increases systematically as a function of produced mean intervals (Wing, 1980). Timing control improves from childhood to young adulthood (Greene & Williams, 1993), but remains stable until older age, at least as far as isochronous timing
is concerned and if participants in good physical and mental health are considered (Duchek, Balota, & Ferraro, 1994; Greene & Williams, 1993; Krampe, Engbert, & Kliegl, 2001; Krampe, Mayr, & Kliegl, 2005).

The classic approach to repetitive movement timing uses the two-level model (Wing & Kristofferson, 1973a, 1973b), which distinguishes a central timer level and a motor implementation level. The central timer is conceived of as a universal, clock-like device, which during movement production delineates time intervals after which a signal is issued that triggers a movement after a certain motor delay. According to the model timing variability is the sum of two stochastically independent sources (linear combination of central timer and motor delay variances) and it occurs without error correction (open-loop). In contrast, coupled oscillator models, the second class of accounts, emphasize non-linear aspects of movement stabilization and error correction. These aspects feature prominently in bimanual coordination and multi-limb movements. Such models consider timing as a property emerging from biomechanical constraints (Schöner, 2002) without assuming explicit cognitive representations for target durations. The third group of timing models, pacemaker-accumulator or clock-counter systems, originate from research on duration judgment or single-interval reproduction tasks. According to the classic versions of these models (Creeelman, 1962; Treisman, 1963) the pacemaker or the clock emits pulses, which are registered and accumulated in the counter. The number of accumulated pulses after an event or interval have passed constitutes the basis for a duration judgment. During (re)production the number of accumulated pulses is compared with a memory representation of the target duration and a response is triggered after this criterion value is passed.

Higher Cognitive Functions’ Involvements in Short and Long Interval Timing

In their original versions neither the two-level model nor oscillator models foresee a role for attention and working memory processes in timing control. Their potential impact has been discussed, however, in extensions to more complex timing tasks, error-correction in synchronization, and stabilizing performance against drift. Krampe and colleagues found increased variability in rhythmic over isochronous timing and age-related declines for rhythmic timing in older novices (Krampe et al., 2005) and even older amateur musicians (Krampe et al., 2001). According to the authors these findings reflect the age-sensitivity of cognitive functions operating on abstract rhythm programs (Vorberg & Hambuch, 1984; Vorberg & Wing, 1996). In contrast, isochronous timing was as accurate in older as in young adults, pointing to “low-level timing,” a control mode that can largely function without attentional or working memory processes and that does not undergo much age-related decline.

Vorberg and colleagues proposed a model of error correction in synchronization tasks (i.e., tapping along with an external metronome), which assumes that the two last taps produced are being used for phase-corrections during the production of the current tap (Schulze & Vorberg, 2002; Sembjen, Schulze, & Vorberg, 2000; Vorberg & Wing, 1996). It seems plausible to assume that detection of synchronization errors requires attention and that working memory plays a role in maintaining recently produced intervals and information about the target duration. Repp (2001) observed seemingly automatic correction of small or subliminal perturbations in skilled participants’ synchronization tapping, that is, participants were frequently unaware of the perturbations and their adjustments. These findings from simple, isochronous tapping performed at convenient tempos do not explain how participants stabilize their performance in the absence of a pacing signal and at slower tempos. For example, in continuation tapping drift occurs inevitably in longer trials and it increases at longer target durations (Collier & Ogden, 2004; Madison, 2001) leading researchers to assume some sort of error-correction for continuation tapping as well. Arguably, detection of drift is more difficult at slower tempos, because the Weber-properties of duration judgment make deviations among longer intervals harder to detect (Gibbon, Church, & Meck, 1984). From this perspective attention and working memory should play a larger role for error correction at slow tempos.

Within the field of duration judgment tasks and animal learning clock-counter models have been widely applied (for reviews, see Church, 1997; Matell & Meck, 2000). Such models assume memory representations of target durations, a clock that emits pulses, a counter, and comparison mechanisms that evaluate counted pulses against the stored target duration. For example, both the influence of memory (Gibbon et al., 1984) and attention (Meck, 1984) on animals’ timing of delayed responses have been investigated within the framework of Scalar Expectancy Theory (SET). Based on this approach, Zakay and Block (1997) argued that level of attention moderates the accuracy of counting pacemaker pulses in human duration judgment. As another influence on timing accuracy, Treisman and colleagues (Treisman, Faulkner, Naish, & Brogan, 1990) have argued that the rate of the pacemaker is subject to physiological factors like body temperature or arousal: higher arousal would speed up the clock such that perceived duration would be relatively shortened due to faster accumulation towards a reference value compared with boring, less arousing activities. From their meta-analytic review of adult-age differences in duration judgments Block, Zakay, and Hancock (1998) concluded that age-effects were mostly limited to absolute verbal estimates or individual interval productions, but the exception for reproduction and psychophysical slope estimates. The authors speculated that older adults’ limitations in dividing attention between temporal and nontemporal processing might be a cause for these effects.

Several authors proposed that the role of higher cognitive processes in timing depends on target duration suggesting that brief durations—around 500 ms—appear to be beyond cognitive control, but rather rely on processes the neural substrates of which are presumably located subcortically (Mitrani, Shekerdjiiski, Goure-vitch, & Yanev, 1977; Rammsayer, 1992, 1994). In contrast, processing of longer intervals relies on cognitive processing (Michon, 1985; Zakay, 1990), with studies suggesting that duration judgments for intervals in the multi-seconds range rely on memory processes unlike judgments on the sub-second level (Rammsayer & Lima, 1991). Grondin, Meilleur-Wells, and Lachance (1999) argued that individuals rely on different mechanisms to evaluate short and long intervals with certain strategies like explicit, internal counting becoming useful for target durations longer than 1.18 seconds. Lewis and Miall (2003a; 2003b) argued for a dichotomy between temporal processing in short and long intervals. From their neuroimaging studies on temporal discrimination they identified two
networks of brain areas, an automatic (motor) timing system measuring intervals at the sub-second range and a more cognitive system measuring supra-second intervals. Studies that systematically looked at whether short and long target durations pose different challenges for young and older adults are missing from the literature.

In sum, attention and working memory are candidate processes relevant to temporal information accumulation and error correction. There is growing agreement in the literature that long interval timing in ranges well above one second, entails different cognitive processes and neural mechanisms than short interval timing in the sub-second range. Tempo ranges or transitions points and the nature of the processes underlying timing in either tempo region remain subjects of debate.

Timing Control and Dual-Task Performance

An approach to more directly assess the contribution of attention and working memory to motor timing is to study performance under dual-task conditions. The basic rationale is that timing accuracy suffers if a concurrent cognitive task competes for attention and working memory resources, particularly at slower tempos and for older adults. The general picture emerging from age-comparative dual-task studies shows pronounced dual-task costs in older adults not only for combinations of two cognitive tasks (for an overview, see Li, Krampe, & Bondar, 2005), but also for combinations of cognitive and sensorimotor tasks such as grip-force control (Voelcker-Rehage & Alberts, 2007), walking (Lindenberger, Marsiske, & Baltes, 2000), or posture control (Doumas, Rapp, & Krampe, 2009; Doumas, Smolder, & Krampe, 2008; Rapp, Krampe, & Baltes, 2006; Woollacott & Shumway-Cook, 2002). Hartley and colleagues (Hartley & Little, 1999) have challenged the assumption that these studies demonstrated specific dual-tasking deficits in the elderly. They argued that the observed disadvantages in older adults emerged from parallel response production, that is, output interference among concurrent tasks. Indeed, Hartley (2001) found higher costs in older participants only if responses to both tasks had to be given manually, but not in a condition where one task required vocal and the other manual responses.

Previous studies applying the dual-task approach to timing have for the most part investigated duration judgments or the reproduction of single intervals. Brown (1997) had participants perform pursuit rotor tracking, mental arithmetic, or visual search tasks while they tried to reproduce target intervals of 2 or 5s. Brown attributed the observed timing interference in terms of shared executive resources. In a later study by Brown and Merchant (2007) participants reproduced 5-s target intervals while performing sequence perception tasks. The authors interpreted the observed bidirectional dual-task interference as evidence for a common set of attentional resources in time and sequence perception. In a series of duration judgment studies Fortin and colleagues (Fortin & Breton, 1995; Fortin & Massé, 2000) found a systematic lengthening of intervals, if participants reproduced them under dual-task conditions after single-task learning. Following a pacemaker-counter model proposed by Zakay and Block (1997) they argued that reduction of attention given to the temporal task in a dual-task setting leads to a “narrowing” of the attentional-gate mechanisms. As a result, participants “missed” pacemaker pulses while attending to the secondary task and thus prolonged their intervals until they reached their original target criteria set during duration encoding. No study has as yet applied the dual-task paradigm to motor timing in older adults and systematically varied target durations in ranges typical for repetitive movement production.

Study Outline

In this study, we asked whether particular costs are associated with slow, accurate motor performance and whether these costs are higher for older than for young adults. Our working assumption was that attention and working memory play a critical role in repetitive movement timing at slower, more than at faster tempos. Their key roles are comparing momentary tempo (interval duration) with target durations and preventing drift through correcting errors (deviations), processes particularly challenging at slow tempos. To put our assumptions to a test we used a dual-task approach, in which young and older participants tapped at fast (target 550 ms) or slow (target 2100 ms) tempos while they performed one of three cognitive tasks differing in demands on working memory and parallel response production. Based on age-related reductions in working memory capacity (Engle, 2002; Salhouse, 1991), we predicted that dual-task challenges of attention and working memory processes under dual-task conditions affect older adults’ timing more than young adults’ timing, an effect that should be pronounced at slower tempos considering the role for attention and working memory in timing outlined above. While parallel response production will increase dual-task costs and related age differences, we expected such effects to emerge even in those dual-task timing conditions, which did not require parallel responses.

We will evaluate dual-task decrements in timing using the three task constraints outlined in the beginning: mean produced interval, stability (drift), and variability. The pattern of interference will also speak to the roles of attention and working memory as implied by the theoretical approaches reviewed. From the assumption of a central clock, which is tied to physiological arousal (Treisman et al., 1990), we would expect a systematic shortening of produced intervals if participants get more excited when they have to work on two tasks at the same time. In contrast, the assumption of an attentional gate that is narrowed through concurrent task demands (Zakay & Block, 1997), leads to the prediction of systematic prolongation of intervals under dual-task conditions, because participants compensate for those clock pulses they miss while attending to the concurrent task. Interference with error correction to stabilize performance will lead to more drift along with systematic distortions of mean produced durations and increased variability.

Methods

Participants

We recruited 22 young (M = 24.23 years old, SD = 1.44) and 22 older adults (M = 66.64 years old, SD = 3.61) through advertisements in local newspapers and on two Berlin University campuses. There were 12 women and 10 men in the young group and 13 women and 9 men in the elderly sample. All participants were self-reported right-handers and had no background of playing a musical instrument. Participants reported to be of average or
good health. Mini-Mental (Folstein, Folstein, & McHugh, 1975) scores were 28 or higher ruling out cases of dementia. Through medical interviews it was determined that none of the participants had a history of dementia, polyneuropathy, Parkinson’s disease, epilepsy, stroke, systemic CNS disorders, or major psychiatric disorders. As is typical of alike adult samples (e.g., Verhaeghen & Salthouse, 1997) older and young adults were similar (M = 25.36, SD = 3.37) in vocabulary knowledge (spot-a-word, adapted from Lehrl, 1977), while higher scores were observed in young compared with older adults, Myoung = 25.52, SD = 4.71; Mold = 15.91, SD = 4.93; t(42) = 6.54, p < .001, for reasoning (Raven, 1962) and two marker tests from the WAIS (Wechsler, 1981), digit-symbol-substitution, Myoung = 65.59, SD = 9.30; Mold = 50.00, SD = 7.68; t(42) = 6.07, p < .001, and digit-span, Myoung = 6.68, SD = .84; Mold = 5.95, SD = 1.02; t(42) = 2.56, p < .05. Subjects were paid for their participation. The study was approved by the Ethics Committee of Free University Berlin, Medical School.

Apparatus and Tasks

Task arrangement in different sessions is shown in Table 1. Participants performed all finger-tapping tasks on Morse-keys (Joseph Junker Elektroapparatebau GmbH, Bad Honnef, Germany) using the index finger of their preferred hand. Tap onsets were assessed to the nearest millisecond using a NB-MIO 16 Instrument Card (National Instruments Corp., Austin, Texas) that was connected to a Macintosh PowerPC for data storage and task presentation. The computer was equipped with a pair of external loudspeakers that were used to produce pacing tones (400 Hz sine wave of 100 ms duration). Volume of the speakers was set comfortably for each participant. In a continuation trial participants could listen to the pacing signal for as long as they wanted. After starting to tap, they synchronized for five taps after which the pacing signal was discontinued. The continuation phase in dual-task trials began with five taps to allow tempo stabilization, after which the visual stimuli from the cognitive task (see below) were presented. After the end of the stimulus presentation phase participants produced another three taps before the end of the trial was signaled by a tone. To align single-task tapping trials at both target tempos to the average duration of dual-task trials, duration of the continuation phase in single-task trials was 44 seconds for both tempos to the average duration of dual-task trials, duration of the pacing signal was discontinued. The continuation phase in single-task trials was 44 seconds for both target durations, corresponding on average to 81 taps for the 550 ms and 21 taps in the 2100 ms condition.

Cognitive tasks. Cognitive tasks were variants of the NBack working memory (WM) task (Dobbs & Rule, 1989) and they were similar in their attentional demands. In all three of them randomized digit-sequences (1-9, immediate repetitions excluded) appeared on a computer screen at the same periodic interstimulus intervals (ISIs, 1800 ms or 2500 ms, as in the original Dobbs & Rule study). Participants’ task was to either name the currently presented digit (NBack0: low WM plus parallel response production), to name the digit that was presented two presentation cycles earlier (NBack2: high WM plus parallel response generation), or to monitor digits silently while counting the number of switches from odd to even and even to odd numbers (high WM, no parallel response production). Ten digits were presented in the NBack0 and 12 in the NBack2 task condition to guarantee similar amounts of verbalization. Number of items in the digit-switch task was also 12 to match processing challenges with the NBack2 task. At the end of each trial the experimenter gave feedback about the number of items correct. Visual stimuli were also presented during single-task tapping trials at ISIs matching those of the dual-task trials in the same session (see Table 1).

Familiarization. To overcome effects of task familiarity and initial learning we gave participants three individual training sessions lasting 1.5–2 hours in finger-tapping and cognitive tasks. In each session participants performed blocks of four tapping trials each at three fast (425, 550, 675 ms) and three slow target durations (1800, 2100, 2400 ms). Trials followed the continuation procedure and they consisted of five synchronization and 25 continuation taps. Tapping performance (means and variabilities) stabilized across the last two pre-training sessions and age groups were at similar levels of performance. A progressive testing approach was used for the three cognitive tasks: Participants received blocks of trials in a certain condition until they scored at least 90% correct (9 out of 10 items) in four out of five trials in the NBack tasks. The criterion for the digit-switch task was reporting the correct number of switches in four out of five trials.

Procedure

Data were collected in the course of five sessions lasting 1.5–2 hours each, including breaks at participants’ own dispositions. Sessions 1–4 consisted of 10 blocks of trials each, 5 blocks for each of the two tapping target durations (short: 550 ms; long: 2100 ms). Blocks 1 and 5 were single-task tapping, blocks 2–4 were dual-task blocks combining tapping at a certain target duration with each of the three memory tasks (NBack0, NBack2, digit-switch). ISIs of the memory tasks were 2500 ms in Sessions 1 and 3, and 1800 ms in Sessions 2 and 4. The order of tapping target

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Table 1

<table>
<thead>
<tr>
<th>Target durations</th>
<th>Context</th>
<th>ISI</th>
<th>Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>Familiarization</td>
<td>425, 550, 675, 1800, 2100, 2400 ms</td>
<td>ST</td>
<td>1800, 2500 ms</td>
</tr>
<tr>
<td>Session 1</td>
<td>550, 2100 ms</td>
<td>ST, DT</td>
<td>2500 ms</td>
</tr>
<tr>
<td>Session 2</td>
<td>550, 2100 ms</td>
<td>ST, DT</td>
<td>1800 ms</td>
</tr>
<tr>
<td>Session 3</td>
<td>550, 2100 ms</td>
<td>ST, DT</td>
<td>2500 ms</td>
</tr>
<tr>
<td>Session 4</td>
<td>550, 2100 ms</td>
<td>ST, DT</td>
<td>1800 ms</td>
</tr>
<tr>
<td>Session 5</td>
<td>—</td>
<td>—</td>
<td>1800 ms</td>
</tr>
</tbody>
</table>

Note. ST = Single Task; DT = Dual Task.
durations and concurrent memory tasks was counterbalanced across participants and sessions. Session 5 was post-test assessment of single-task memory performance.

After one warm-up synchronization trial in the beginning of testing for a certain target duration, participants performed a minimum of four continuation trials in single-task blocks and five dual-task trials within each target-duration × memory-task combination block. Numeric feedback about mean interval duration, variability, and outliers in tapping, as well as about memory performance (in dual-task trials) was given after each trial. Trials prematurely terminated by participants, deviating in their mean intervals from target durations by more than 15%, or memory-task errors were immediately repeated up to a maximum of six continuation trials per block for single-task and 12 trials for dual-task conditions. In Session 5 single-task performances in NBack2 and digit-switch were re-assessed with 5 trials each at an ISI of 1800 ms. All participants had reached perfect levels of NBack0 performance by the end of the familiarization phase and performances at longer ISIs in the other cognitive tasks were only collected from those participants who had not been perfect at pre-test.

Results

Cognitive Task Performance

A mixed-design analysis of variance (ANOVA) on aggregated pre- and post-test data with task (NBack2 vs. Digit-Switch) and ISI (1800 ms vs. 2500 ms) as within-subjects factors revealed next to perfect single-task performance in the NBack2 task (M = 96.47%, SD = 4.56) and lower accuracies in the Digit-Switch task (M = 91.82%, SD = 10.52), F(1, 42) = 8.90, MSE = 106.85, p < .005. Presumably due to extended training accuracy was slightly higher for short ISIs (M = 95.52%, SD = 5.21) compared with long ISIs (M = 92.76%, SD = 9.37), F(1, 42) = 4.59, MSE = 73.14, p < .05. As intended, overall single-task baseline performance was comparable for young and older adults, F(1, 42) = 2.00, p > .16, and age did not interact with any of the other factors.

To assess the effects of concurrent tapping on cognitive task performance we calculated proportional dual-task costs for percentages correct: the difference between single- and dual-task performances was standardized by single-task performance and percentages correct: the difference between single- and dual-task performances was standardized by single-task performance and performances at longer ISIs in the other cognitive tasks were only collected from those participants who had not been perfect at pre-test.

Timing Under Single- and Dual-Task Conditions

To accommodate the dual-task training effects in memory tasks described previously we focus on the second assessments of timing performance (Sessions 3 and 4). In single-task tapping conditions participants performed six trials per session for each target duration and these were averaged across Sessions 3 and 4 to estimate baseline performance. All trials were screened for premature terminations, extreme violations of target tempos, and individual outlier intervals.¹

We first consider mean produced interval durations and we then analyze drift as a measure of participants’ stability of timing control throughout trials. Finally, we address variability of timing taking into account the observed differences in interval means and drift. For all three measures we apply the full four-factorial mixed-design ANOVA with age group (young vs. older) as between and tapping tempo (slow target duration 2500 ms vs. fast target duration 550 ms), cognitive-stimuli ISI (2500 ms vs. 1800 ms), and task context (4) as between-subjects factors. Note that we compared the three dual-task conditions for different ISIs with their respective single-task baselines obtained in the same session (compare Table 1). Like under dual-task conditions repeated single-task assessments differed in the ISI of the stimuli presented although participants did not have to process them.

For the four-level task factor we specified an a priori Helmert contrast with three orthogonal, linear comparisons of (1) single-task performances vs. the mean of the three dual-task conditions, (2) concurrent silent processing (i.e., Digit-Switch) vs. the mean of the two tasks involving parallel response production (i.e., NBack0 and NBack2), and (3) shadowing with working memory updating (i.e., NBack0 vs. NBack2) when both tasks involved parallel response production. Post-hoc tests for interactions were conducted as t-tests with alpha levels adjusted for multiple comparisons using Bonferroni’s method. Given its theoretical significance for the role of parallel response production for age differences in dual-task costs, we conducted additional post-hoc comparisons between single-task conditions and silent dual-task performance (Digit-Switch task) for all three measures.

Mean produced intervals. For scaling reasons we show data for fast (Figure 1) and slow tapping temps (Figure 2) in separate figures. Single-task conditions are highlighted by shaded backgrounds.

¹ Premature trial terminations and trials with gross violations of target durations were excluded from analyses. The only condition where premature trial termination occurred was in NBack2 dual-task trials. Occurrences were the exception for young adults (M = .23%, SD = 1.07) but reliably higher for older adults (M = 2.05%, SD = 3.67), F(1,42) = 4.98, MSE = .07, p < .05, with more than 75% of aborted trials in this group occurring for concurrent slow tapping. Percentages of trials with mean intervals exceeding ±15% of the target duration were small for fast tapping trials (M = .10%, SD = .69), but higher for slower tapping (M = .97%, SD = 2.38, n(43) = 2.28, p < .05 with similar percentages for young and older adults. On average, 2.21% (SD = 5.19) of the trials contained individual outliers (±50% deviation from the mean interval), which were not considered in calculating statistics for respective trials. Age groups did not differ in this respect.
We conducted the full, four-factorial mixed-design ANOVA described above with mean produced intervals as dependent variables. ANOVA statistics for all significant effects are provided in Table 2. The middle-part of Table 2 shows effects related to the main task context contrast, which compared single-task performance with the mean of the three dual-task conditions. As predicted, this effect was reliable and it reflected a general tendency of participants to play faster under dual- compared with single-task conditions (with the only exception of NBack2 in older adults). The reliable four-way interaction indicated that this speed-up depended on tapping tempo, age, and cognitive-stimulus ISI.

As a first step in decomposing the four-way interaction we performed a mixed-design ANOVA on single-task baselines using age group as between- and tempo and session (Sessions 3 vs. 4, corresponding to different ISIs for cognitive-task stimuli) as within-subjects variables. The only significant effect related to tempo. Young and older adults performed at comparable levels that remained stable across sessions. Separate ANOVAs for the two tempos further revealed that effects of ISI were restricted to slow tapping tempos and we thus averaged dual-task conditions over ISIs for the fast tempos in Figure 1 and subsequent analyses. Finally, we performed pairwise t-tests, three for each age group, comparing single-task tapping with the average of the three dual-task conditions separately for temps and (for slow tapping) ISIs. Young adults produced almost identical means under single- and dual-task conditions when they tapped at fast tempos, but they showed dual-task speed-ups for slow tapping. When concurrent cognitive tasks were made more difficult through short ISIs this speed-up ($\Delta M = 41$ms, $SD = 64$) was reliable by adjusted standards, $t(21) = 3.06, p < .006$. Older adults showed a significant dual-task speed-up ($\Delta M = 12$ms, $SD = 10$) at fast tapping temps, $t(21) = 5.71, p < .001$. For slow tapping, speed-up in older adults was unreliable at long ISIs but pronounced ($\Delta M = 80$ms, $SD = 75$) when cognitive-task challenges increased due to rapid stimulus presentation (ISI 1800 ms). Additional post-hoc comparisons between single-task tapping and the silent Digit-Switch task replicated reliable shortening in older adults’ intervals under dual-task conditions for fast tapping, an effect that was pronounced for slow tapping.

As Table 2 indicates, the other two task contrasts were also significant, and they showed reliable three-way interactions with ISI and tapping tempo. None of these effects interacted with age group. Figures 1 and 2 illustrate that our predictions were met for fast tapping and slow tapping along with short ISIs for the cognitive tasks: speeding under dual-task conditions was stronger in conditions requiring concurrent verbalization compared with silent processing. Likewise, increased working memory load (NBack2) yielded stronger effects in these conditions than shadowing (NBack0). This pattern was violated for slow tapping and long ISIs where we observed the smallest speed-up in young and slight slowing down in older adults.

In sum, older adults at fast tapping tempos and both groups at slow tempos produced shorter intervals under dual- compared with single-task conditions. This effect was accentuated at slower tapping tempos and in older adults. With the exception of one con-
dition, magnitudes of dual-task effects reflected concurrent cognitive task difficulty, that is, stimulus ISIs, parallel response production, and working memory load.

**Stabilizing interval durations: Drift.** Drift was assessed through linear trends estimated from individual trials. We reasoned that the Weber-properties of duration judgment (Gibbon et al., 1984) would make detection of deviations inherently more difficult for participants at slower tempos. To take this relation into account, we standardized the absolute trend by target duration and expressed it in percent to attain a measure of relative effect on produced intervals. None of the analyses conducted on this measure produced effects of age group or related interactions, and thus, data in Figure 3 were averaged across age groups.

The four-way mixed-design ANOVA with percentages absolute drift in the two tempo, two ISI and four task conditions as dependent variables yielded the predicted main effects of tempo, first task contrast (single vs. average dual-task conditions), and their interaction (Table 3). Like before we first established that single-task baselines remained stable across ISI test sessions. We thus present averaged single-task baselines in the left part of Figure 3. To corroborate the above interaction we conducted two pairwise t-tests comparing single-task and the average of the three dual-task conditions separately for fast and slow tapping tempos. Absolute drift under single-task conditions was .042% (SD = .023) for fast tapping and .271% (SD = .112) for slow tapping. While both reliable by all adjusted standards, t(43) > 6.6, ps < .001, the increase under concurrent task load was smaller for fast (∆M = .024%) compared with slow tapping (∆M = .179%). The task(1) contrast also showed a reliable interaction with ISI (Table 3). As stated above, single-task baselines did not differ across different ISI sessions. In contrast, dual-task tapping (averaged across tempos) along with the more difficult, rapid (ISI 1800 ms) stimulus presentation showed stronger drift (M = .28%, SD = .10) compared with the long ISI (2500 ms) condition (M = .23%, SD = .09), t(43) = 4.23, p < .001. Additional comparisons restricting dual-task conditions to the silent Digit-Switch task replicated robust increases in drift, which were pronounced at slower tapping tempos.

Cognitive-Task complexity was further reflected by significant task(2) and task(3) contrasts and their respective interactions with the tempo factor (Table 3). The difference in drift between the silent Digit-Switch task and the two NBack tasks requiring parallel response production was minimal at fast tapping tempos, but reliable for the slow tapping conditions (∆M = .11%, SD = .17), t(43) = 4.25, p < .001. Likewise, small differences in drift were observed between the working memory and the shadowing conditions (NBack2 – NBack0), when participants tapped at fast tempos. Corresponding differences were robust for slow tapping (∆M = .13%, SD = .21), t(43) = 4.07, p < .001. The additional three-way interaction of the task(2) contrast with tapping tempo and ISI reflected the fact that, while drift was stronger in all individual comparisons, only the difference involving slow tapping and NBack-tasks with an ISI of 2500 ms was robust at adjusted alpha levels.

In sum, concurrent cognitive task load led to an increase in drift, which was similar for young and older adults. Although we adjusted for scalar properties, single-task percentage of drift already turned out to be higher at slow tempos. Moreover, the increase in instability (drift) was pronounced at slow tapping tempos with dual-task costs systematically reflecting the difficulty of concurrent cognitive tasks.

**Effects of concurrent tasks on variability.** To take the reported effects on mean produced intervals and drift into account for our evaluation of effects on variability, we calculated variation coefficients by dividing SDs of detrended time series by produced interval means at the level of individual trials. Besides a main effect of age group, the mixed-design four-way ANOVA on variation coefficients yielded the predicted task(1) effect and its two- and three-way interactions with age group and tapping tempo (Table 4). This pattern, namely mean coefficients for age groups for single- and dual-task contexts (averaged across concurrent memory tasks) is shown in Figure 4. Pairwise t-tests separately for groups and tempos confirmed that the increase in tapping variability from single- to dual-task conditions generalized across age groups and tempo conditions, t(s21) > 7, ps < .001. The largest

<table>
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<td>ANOVA Statistics for the Analysis of Percentage Absolute Drift</td>
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Note. task(1) = single vs. mean (3 dual task conditions); task(2) = silent (DigSwitch) vs. concurrent response (mean[NBack0, NBack2]); task(3) = shadowing (NBack0) vs. shadowing + working memory load (NBack2).

* p < .05. ** p < .01. *** p < .001.
dual-task increase was found for older adults during slow tapping where they showed a reliably higher coefficient ($M = .0651$, $SD = .0212$) compared with young adults ($M = .0515$, $SD = .0088$), $t(42) = 2.76$, $p < .009$. Baseline single-task measures did not differ across sessions, between fast and slow tempos, or between age groups. The same pattern of results could be replicated when dual-task performance was restricted to the silent Digit-Switch task.

Like in previous analyses significant task(2) and task(3) contrasts and their respective interactions with tapping tempo (Table 4) indicated that dual-task effects increased with cognitive-task difficulty as expected and this even more so at slow tapping tempos. Two pairwise t-tests comparing variation coefficients for the silent Digit-Switch task with the mean of the two NBack tasks showed robust increases in the verbalization tasks for both tempos, $t(43) > 4.2$, $p < .001$. However, the difference was almost twice as large in slow ($\Delta M = .0103$, $SD = .0160$) compared with fast tapping tasks ($\Delta M = .0057$, $SD = .0060$). Similarly, post-hoc comparisons of shadowing (NB0) and working memory load (NB2) tasks revealed reliable increases in variability $t(43) > 4.0$, $p < .001$, which were larger at slow ($\Delta M = .0100$, $SD = .0131$) compared with fast tapping tempos ($\Delta M = .0037$, $SD = .0061$). While values were always higher at slow than at fast tempos, shorter ISI led to higher variability at fast but not at slow tempos, causing the three-way interaction.

### Discussion

In this study we tested the assumptions that attention and working memory are critical for timing simple, repetitive movements, particularly at slower tempos, and that this causes specific performance costs for older adults. Overall, dual-task costs in timing directly reflected the processing demands of concurrent cognitive tasks in terms of working memory (WM) load, stimulus presentation rate, and need for concurrent response generation. Dual-task costs in memory performance were reliable when participants engaged in concurrent slow tapping, but not for concurrent fast tapping. Timing performance at fast and slow tempos was similar for young and older adults under single-task conditions. However, when attentional and WM resources were challenged by concurrent cognitive tasks, higher costs for timing control emerged at slow compared with fast tapping tempos and this effect was more pronounced in older adults. These findings support our assumptions about the differential role of attention and WM for timing control at fast and slow tempos. They also demonstrate the drawbacks of slow movements in old age. Taking things slowly might well enable older adults to perform motor patterns too complex to manage at fast tempos; however, this adaptation comes at a cost, namely pronounced loss in temporal precision, regularity, and stability. To keep these costs at bay older adults must invest considerable attentional and working memory resources, much more so than young adults. Such resources are sparse in older age to start with and they have to be withdrawn from other concurrent activities.

More detailed considerations of those aspects, which suffered under dual-task conditions can inform about the role of attention and WM for timing control. Under dual-task conditions, young as well as older participants showed reduced stability of produced intervals (increases in absolute drift), the produced intervals were shorter, and, at least in older adults, timing variability was higher even when drift and group differences in mean intervals were taken into account. In our view, these results are best understood in terms of the roles attention and working memory serve in stabilizing timing performance: current and recently produced intervals must be monitored, compared with each other and a standard (reference target duration), and correction must be applied to the upcoming interval, if participants start to deviate from target or to drift. In line with earlier studies (Collier & Ogden, 2004; Madison, 2001), we found drift already under single-task conditions highlighting the role of these stabilization processes even for unperturbed timing. Our findings support our assumption that drift is more of a problem at slow tempos, presumably because detecting deviations is more difficult and longer periods need to be represented to provide similar numbers of comparison intervals as for fast tempos. Drift and its increase under dual-task conditions were similar in young and older adults, suggesting that additional aspects of timing control depend on attention and working memory.

![Figure 4](image_url)

**Figure 4.** Age-differential effects of concurrent cognitive tasks on fast and slow tapping. Variation coefficients are based on SDs calculated after detrending divided by mean produced intervals. Data for the dual-task conditions were averaged across three concurrent memory tasks and short and long ISIs. Error bars represent two standard errors of the mean.
Our findings complement our knowledge on specific dual-task decrements in older adults. Different from earlier studies, we demonstrated conditions under which older adults were more punished by dual-task demands when performance was slower rather than accelerated. Based on our manipulations of concurrent task challenges we were also able to demonstrate pronounced costs in the elderly even when parallel response production could be ruled out as the critical factor.

Alternative Accounts

Other timing models have also addressed timing distortions under concurrent task load. Different from the predictions based on pacemaker-accumulator models, we found no evidence for prolonging of intervals. This is what one would have expected if participants had missed pacemaker pulses while attending to concurrent cognitive tasks (Fortin & Massé, 2000; Zakay & Block, 1997). Presumably, timing processes in duration judgment tasks and their even longer target intervals differ from the movement timing processes investigated in our study. The systematic shortenings of produced intervals we observed are in line, however, with the assumption of a speed-up of the internal pacemaker due to additional arousal (Treisman et al., 1990) from dual-task challenges. While much of the observed interval shortening can be attributed to (negative) drift resulting from impaired error correction, pacemaker speed-up remains a possible additional factor.

Parallel response production clearly had an effect on dual-task costs, however, neither the overall interference with timing control nor the age differences in dual-task costs can be reduced to its influence. Not only was the silent processing task (digit-switch) sufficient to perturb timing control, but robust differences also emerged between the NBack0 and NBack2 tasks. These tasks differed in WM load but not with respect to stimulus periodicity and response generation demands. This argument receives further support from the pattern of interval distortions shown in Figure 2: differential effects of short and long ISIs suggest that participants taps showed “entrainment” with stimulus presentation or their own responses. Note that participants produced shorter intervals than under single-task conditions even if memory ISIs were longer than tapping target intervals. The most pervasive effects related to a loss of stability in interval production under dual-task conditions, namely increases in drift and variability. In our view, entrainment under conditions of parallel response production is a consequence of decreased timing control rather than its cause.

One strategy that has been shown to support duration judgments at longer intervals is explicit counting (Grondfin et al., 1999). Musicians employ metric counting when analyzing novel rhythmic patterns and work out their interpretation, however, the benefit of explicit counting during actual motor performance is less obvious. All our concurrent cognitive tasks used period presentations of number stimuli, thus we have reason to assume that even the simplest task effectively prevented explicit counting. While this might have contributed to the observed effects, the systematic relation between costs and cognitive task difficulty suggests that other processes than counting were also progressively affected. Most notably, the findings related to drift point in the direction of error correction but additional mechanisms remain candidates for future investigation. For example, people benefit from (mental) subdivisions during their production of long intervals or pauses (Semjen & Summers, 2002). Such subdivisions need not be marked through explicit counting, but they can form part of the movement trajectory. In either case, related strategies will require attention and working memory.

Conclusions

Our results regarding the differential roles of higher-level cognitive processes for timing control at fast vs. slow temps resonate with outcomes of temporal discrimination (Gibbon, Malapani, Dale, & Gallistel, 1997; Grondfin et al., 1999), or neuroimaging studies (Lewis & Miall, 2003a, 2003b). At the same time, they do not support the strict dichotomy of automatic versus controlled processes advocated by some authors and its implication of attention-free timing at faster temps, We observed dual-task effects for fast tapping, at least in older adults. It seems more appropriate to consider low-level timing (Krampe et al., 2005) as a process that can run on autopilot at faster temps if necessary; however, its output is clearly improved by full attentional and WM support at any tempo. Unraveling the mechanisms supporting the monitoring and stabilizing of movement timing and incorporating them into extant models remains a future challenge.

References


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