The Time of Our Lives: Life Span Development of Timing and Event Tracking

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Life span developmental profiles were constructed for 305 participants (ages 4–95) for a battery of paced and unpaced perceptual–motor timing tasks that included synchronize–continue tapping at a wide range of target event rates. Two life span hypotheses, derived from an entrainment theory of timing and event tracking, were tested. A preferred period hypothesis predicted a monotonic slowing of a preferred rate (tempo) of event tracking across the life span. An entrainment region hypothesis predicted a quadratic profile in the range of event rates that produced effective timing across the life span; specifically, age-specific entrainment regions should be narrower in childhood and late adulthood than in midlife. Findings across tasks provide converging support for both hypotheses. Implications of these findings are discussed for understanding critical periods in development and age-related slowing of event timing.

Keywords: timing, preferred tempo, rhythm perception and production, entrainment, life span development

A challenging psychological question concerns how people effectively coordinate their behavior with the dynamic unfolding of events in the environment. At its core, this question relates to the problem of serial order (Lashley, 1951) and to issues of relative timing (Fraisse, 1963). In general, to respond appropriately to an event, an individual must not only produce a relevant response, but do so at the right time. One premise of the present research is that the time structure of an event tacitly influences an individual's ability to produce a temporally coordinated response. A second premise is that this ability depends on an individual's dynamic attunement to event time structure, which we propose changes systematically with age.

Event Time Structure and Attending

The backdrop for the present research derives from an orientation that assumes that the time structure of events is useful for attenders in various settings. Moreover, we extend this idea to consider the possibility that an individual's reliance on event timing changes over the life span.

The Function of Event Time Structure

Individuals' daily activities consist of a variety of different dynamic interactions with events. They engage in conversations and turn taking, listen and respond to music, and watch and respond to people walking, talking, and playing games, as well as performing various commonplace activities (Wilson & Wilson, 2005; Zacks & Tversky, 2001). Everyday events such as these are extended in time, with distinct beginnings, middles, and ends. Indeed, Quine (1960) identified temporal boundaries in space–time as criterial for events (vs. objects). In this article, we identify the whole structure of an event in time and its function for an attender as criterial for events (Boltz, 1995; Jones, 1976).

We claim that event time structure is important because events often unfold systematically in time in ways that support our moment-to-moment interactions with them. Thus, our ability to tune in to an event in real time affords anticipation of its future

course, thereby facilitating a temporally coordinated response. Together, the rate and the rhythm of an event may facilitate attentional synchrony. To follow some event in real time, one must presumably coordinate attentional processes with event time so that attention is allocated not only at the right place (e.g., in space), but also at the right instant (in time). If this were not the case, then individuals would miss much of what goes on around them. From our perspective, the event time scale at some level functions as an attentional hook that engages the attender at that scale (Jones & Boltz, 1989). Thus, if people pay attention to phonemic information in a speech event or follow a flute's trill within a symphony, more attention is carried over the time spans specific to these structural levels than to other levels associated with longer time scales that may carry meaningful discourse or whole musical phases. In this way, both the rate and rhythm of an event contribute to a dynamic selectivity of attention.

Support for a rhythmic attending view comes from several sources. First, studies of overt tracking of event sequences indicate less variability and greater accuracy in responding to rhythmically simple events than to complex events (Jones & Pfordresher, 1997; Large, Fink, & Kelso, 2002; Large & Palmer, 2002; Pfordresher, 2003). Second, in monitoring of event sequences, simple rhythms enhance performance with rhythmically expected targets, suggesting that attentional synchrony has a facilitating influence (e.g., pitch, timbre, time change; Jones, Boltz, & Kidd, 1982; Jones, Moynihan, MacKenzie, & Puente, 2002; Jones & Yee, 1997; Klein & Jones, 1996); as well, certain rhythms facilitate detection of temporal order of target pitches that are embedded in longer sequences (Jones, Kidd, & Wetzel, 1981). Third, in recognition memory tasks, people mistakenly identify decoy melodies as target melodies when the decoys occur in a target's rhythm (Jones & Ralston, 1991); relatedly, the recall of pitch sequences is better when various accents (e.g., pitch skips, contour changes) are timed regularly rather than irregularly (Boltz & Jones, 1986). Finally, such effects are not confined to auditory events. Monitoring visual sequences is enhanced in simple (vs. complex) rhythmic contexts (Jones & Skelly, 1993); moreover, reaction times and sequence learning are systematically influenced by the time structure of visual event sequences (T. Martin et al., 2005; Olson & Chun, 2001).

Converging evidence appears in the speech literature. Despite historical controversies over the role of isochrony in speech, recent research reveals that rhythmic patterning is fundamental to tracking linguistic utterances (Cutler & Mehler, 1993; J. G. Martin, 1972; Port, 2003; Quené & Port, 2005; Wilson & Wilson, 2005). Moreover, newborns appear to differentiate various languages on the basis of rhythmic classes (Cutler & Mehler, 1993; Nazzi, Bertoncini, & Mehler, 1998; Nazzi & Ramus, 2003; Ramus, Nespor, & Mehler, 1999), leading to a proposal that early language learning depends on an attentional bias for periodic sound patterns, that is, a *periodicity bias* (cf. Grieser & Kuhl, 1988; Lewkowicz, 2003).

In sum, there is emerging support for the view that event time structure functions as a vehicle for attentional synchrony, a claim that has been more formally developed elsewhere (Large & Jones, 1999; McAuley, 1995; McAuley & Jones, 2003). In this article, we focus on one aspect of event time structure, namely event rate, and consider its role in life span development of timing and event tracking.

The Role of Event Rate in Life Span Development

Our interest in event rate centers on the possibility that developmental shifts in attention piggyback on age-specific sensitivities to event rate (Jones, 1976). Specifically, we entertain the idea that a preferred event rate exists, which slows across the life span. Current evidence for this view is only suggestive because the topic has not been systematically addressed. Nonetheless, there are several lines of evidence consistent with this hypothesis. First, measures of preferred spontaneous tapping rate show that young children prefer faster rates than do older children and adults (Drake, Jones, & Baruch, 2000). Second, studies assessing overt tracking of simple and complex musical events have shown that young children more easily synchronize their responses when they choose to produce responses at a fast rate than at a slow rate (Drake et al., 2000; Provasi & Bobin-Bègue, 2003). Third, studies of language acquisition suggest a developmental shift in the relevance of particular embedded time scales within speech events. Specifically, with very young infants, early acquisition of speech appears more focused on structural levels that span smaller (faster) time scales (phonotactic properties), whereas slightly older infants tune into longer (slower) time scales that span sequences of phonotactic elements (Jusczyk, 1997). Finally, at the other end of the age spectrum, older adults tend to prefer slower spontaneous tapping rates (Vanneste, Pouthas, & Wearden, 2001) and slower speech utterances than do younger adults (Holland & Fletcher, 2000; Sutton, King, Hux, & Beukelman, 1995; Wingfield & Ducharme, 1999).

In sum, it appears that people of all ages use temporal properties of events, including event rate, to anticipate how events unfold in time. In addition, there is some evidence to suggest that a preferred rate of event tracking may slow over the life span, although clear-cut data on this issue are scarce. This is, in part, because differential preferences for event rates over the life span have not been thoroughly examined in a single study with a converging set of tasks.

Empirical and Theoretical Goals

We have two related goals in this research. The first goal is an empirical one; we aim to construct developmental profiles for children and adults (ages 4–95 years) for a number of simple event tracking tasks that vary event rate over a wide range. To focus on event rate, we strip away the rhythmic complexity of real world events (where rate and rhythm covary) and render event tracking overt by asking people to tap in synchrony with an auditory pacing signal and then to continue tapping at the same rate after the pacing signal stops (Stevens, 1886). Figure 1 illustrates synchronize–continue tapping for an auditory pacing signal that marks out a series of identical (target) time intervals, T, where T indexes overall rate. During continuation tapping, an individual's produced tap period, P, provides an estimate of T.

The second goal is theoretical. We evaluate two new hypotheses about life span development of timing and event tracking. The first is a *preferred period hypothesis*, which proposes a general slowing of preferred event rate across the life span. The second is an *entrainment region hypothesis,* which proposes that the range of event rates that individuals can readily track widens during childhood and then narrows again late in life. In the next section, we
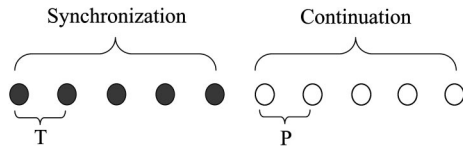
Figure 1. Schematic of synchronize–continue tapping task: The synchronize phase presents a sequence of pacing tones (solid ovals), spaced isochronously in time with fixed interonset interval, T. Participants are instructed to synchronize a series of hand taps with the tones and continue tapping once the sequence stops (open ovals). The continuation phase thus requires maintaining the target rate, T, such that the produced period, P (represented here by the intertap interval), approximates T, once the tones stop.

develop both hypotheses within the context of a formal *entrainment model*. In the subsequent section, this perspective is contrasted with an alternative *interval model*.

The View From an Entrainment Model

Entrainment models of timing embody the view sketched thus far, namely, that the rate and rhythm of everyday events engage people on a moment-to-moment basis through attentional synchrony (Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999; McAuley, 1995; McAuley & Jones, 2003). In broader terms, entrainment is a natural consequence of a ubiquitous biological process whereby some internal periodic activity (i.e., oscillation) becomes synchronized with an external rhythm (Roenneberg, Daan, & Merrow, 2003; Winfree, 2000). The most familiar examples of entrainment involve the entrainment of human circadian rhythms, such as the internal sleep–wake cycle, with various environmental *zeitgebers* (i.e., time givers; Moore-Ede, Sulzman, & Fuller, 1982). In the present work, however, we are considering a different role for entrainment, namely, in guiding overt perceptual–motor tracking of events on a time scale commensurate with speech and music.

In this article, we apply this dynamic view of attending to the specific task of synchronize–continue tapping. In this context, entrainment refers to the synchronization of an internal periodic process (oscillator) with an external pacing signal. Ultimately, successful entrainment means that "taps" generated by the oscillator are consistently aligned with the pacing signal; moreover, during the continuation phase of the task, the entrained (adapted) oscillator period (as a memory of the target interval, T) is able to persist to guide tapping. Mathematical models of entrainment have been proposed to account for a variety of different aspects of adult timing performance, including synchronize–continue tapping (Large et al., 2002; Large & Jones, 1999; Large & Palmer, 2002; McAuley, 1995; McAuley & Jones, 2003).[1] A formal discussion of these models is beyond the scope of the present work. However, we introduce several key elements below in order to consider predictions of two life span entrainment hypotheses.

From an entrainment perspective, it is critical to distinguish manifest (produced) oscillations from a latent (intrinsic) oscillator. With respect to overt perceptual–motor tracking, as in synchronize–continue tapping, a *manifest oscillation* refers to the produced tap period, whereas the *latent oscillation* refers to an internal oscillator that provides biological constraints on the range

of manifest—that is, produced—periods, P. This distinction links the range of observed tapping rates, P, to a single intrinsic period of the (latent) oscillator, P_0, as shown in Figure 2A. When a pacing signal is present (as in synchronization), it forces changes in the produced period, P, which adjusts (within limits) to event rate; in contrast, the intrinsic period, P_0, remains unchanged. Thus, if a sequence has an overall rate, T, that differs only slightly from P_0, then the latent oscillator readily promotes an adaptive shift of the manifest period, P, to match T. This results in *period matching* (i.e., P = T). But if T is remote from P_0, then the adaptability of P is restricted by the difference between T and P_0. Although P changes in response to the pace of some environment, the preferred period, P_0, does not. Thus, the effective P_0 depends on maturational and biological properties, not environmental ones.

The theoretical distinction between P and P_0 raises practical questions regarding their empirical correlates. Clearly, P refers to a produced period, as measured, for instance, during continuation tapping. By contrast, P_0 is estimated from performance in perceptual–motor tasks designed to reveal rate preferences; here we assume that P_0 is estimated by participants' preferred tapping rate, which we will refer to as their spontaneous motor tempo (SMT). This theoretical orientation leads to a predicted relationship between SMT in unpaced tapping and the produced periods manifest in other, paced, tasks. In addition, according to entrainment theory, the errors and response variability evident in continuation tapping at different rates should reveal lingering influences of SMT (i.e., of P_0). One reason for this is that manifest periods can adapt to match T only within a limited range of rates about P_0; this region of optimal adaptivity is termed the *entrainment region*.

Accordingly, within an entrainment region, we predict high accuracy (little difference between average P and T) and low variability (high stability) in continuation tapping. Figure 2A (solid line) shows a hypothetical accuracy profile for period matching as a function of event rate. This is an idealized *detuning function,* which indicates lower and upper limits of period matching; these limits define the range of event rates, about a preferred period, that should yield stable performance. Outside an entrainment region, T increasingly differs from P_0; here the detuning function implies that period matching is likely to fail, leading to errors (signed [P – T] scores) and increased variability (instability). The attractive pull of P_0 (SMT) determines the sign of detuning errors, and these suggest a drift toward P_0 (depending on event rate). This pull of P_0 should be most evident in continuation tapping where (absent a pacing signal) P is predicted to drift toward P_0 at extreme rates (Madison, 2001).

In extending these ideas to address life span development, we developed two hypotheses: a preferred period hypothesis and an entrainment region hypothesis. The first hypothesis, the preferred period hypothesis, proposes that individuals have a preferred rate

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[1] Mathematical formalization of synchronized tapping (vs. continuation tapping) given the entrainment view entails the assumption that a pacing signal induces a nonlinear phase correction that depends on the strength of a *phase coupling term*. Moreover, the value of the latter term is assumed to vary in a curvilinear fashion over the life span. Evidence for the latter assumption is found in synchronization data, where the circular variance changes in a curvilinear fashion with age (McAuley & Jones, 2005). However, theory and data concerned with synchronized tapping are beyond the scope of the present article.
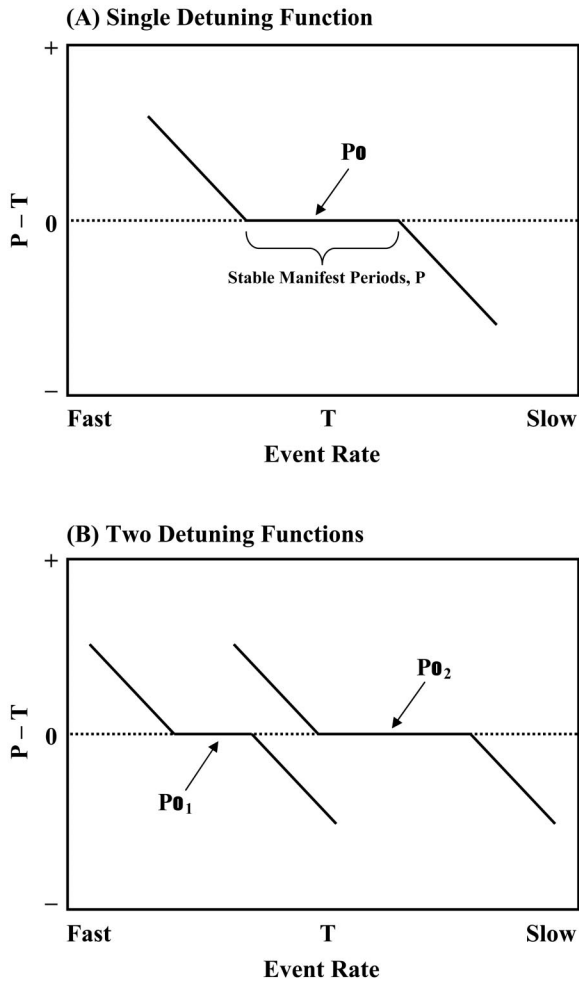
(A) Single Detuning Function

(B) Two Detuning Functions

Figure 2. A: A theoretical detuning function for an entraining oscillator with an intrinsic period, P_0, responding to a pacing signal of rate T. The region of stable manifest oscillations, P, is also shown (bracket) for this P_0. An entrainment region corresponds to the restricted range of event rates where P = T. B: Two detuning functions based on respectively different intrinsic periodicities, P_{0_1} and P_{0_2}; note that the entrainment region is wider for the oscillator with a longer intrinsic period, P_{0_2}.

of event tracking that is associated with an intrinsic "preferred" oscillator period, P_0, which should show a monotonic progression toward longer values over the life span. Thus, children rely mainly on oscillators with relatively brief periods, but as they age, oscillators with longer periodicities become active as well (Jones, 1976). We leave open issues surrounding whether oscillations with longer periods become gradually (continuously) or suddenly (discretely) active during critical times in the life span. The second hypothesis, the entrainment region hypothesis, proposes that the region of rates eliciting optimal entrainment widens throughout childhood but narrows again late in life.

A more formal overview of these two hypotheses is given in Figure 2B, which illustrates hypothetical detuning curves for children and young adults; here P_{0_1} and P_{0_2} indicate hypothetical short and long intrinsic oscillator periods for these two age groups, respectively. As shown, the preferred period hypothesis predicts an age-related shift in the intrinsic period, P_0, of a latent oscillator. Thus, people are predicted to prefer to listen to and produce slower rates as they age. The preferred periods, P_0, of children are predicted to be shorter, on average, than those of adults.

Two primary predictions of the preferred period hypothesis are considered in this research. First, SMT, which we assume provides an estimate of P_0, should slow with age. Moreover, if SMT is not specific to motor function, then SMT should be positively correlated with perceptual measures of preferred rate. Second, in continuation tapping, produced periods, P, should drift toward P_0. Specifically, signed errors (P – T) are expected to be negative for event rates, T, that are slower than an individual's preferred period, P_0, and to be positive for event rates, T, that are faster than an individual's preferred period, P_0. Overall, accuracy profiles in continuation tapping should mimic detuning curves (Figure 2B), with the degree of over- and underestimation dependent on the magnitude of difference between T and P_0 and on the width of the entrainment region. We next consider predictions of the entrainment region hypothesis.

The entrainment region hypothesis predicts that the width of the entrainment region follows a quadratic trend over the life span. This pattern is postulated to result from changes in synchronizing efficiency with age. Specifically, oscillator entrainment is proposed to be weakest early and late in life, yielding an age-specific entrainment region that widens during childhood and then narrows again in late adulthood. The entrainment region should be widest for age groups where entrainment is strongest, namely, for young and middle-aged adults.

Two primary predictions of the entrainment region hypothesis are considered in this research. First, during unpaced tapping, the range of accessible tapping rates (i.e., slowest possible rate to fastest possible rate) should widen during childhood and then narrow again late in life. Second, during paced (continuation) tapping, changes in the width of the entrainment region should affect stability and thus influence both accuracy and variability measures. Because the entrainment region is hypothesized to be narrowest for young children and older adults, these age groups should reveal the greatest restrictions on range of stable continuation tapping. This implies that at extreme event rates, produced periods in continuation tapping will drift toward an age-specific entrainment region, systematically influencing accuracy. Thus, the width of an entrainment region is predicted to mediate the amount of period drift; least drift (hence higher accuracy) should occur for event rates, T, within the entrainment region, and most drift (lower accuracy) should occur for rates (both faster and slower) that fall outside the entrainment region.

With respect to variability, predictions of the entrainment region hypothesis take the form of a restricted Weber function. Typically, the coefficient of variability (CV) during continuation tapping is used to assess the scalar timing prediction of Weber's law, namely, that the standard deviation is a constant proportion of event rate, as shown in Figure 3 (solid line). Also shown in Figure 3 is the generalized Weber law (dashed line), which allows for deviation from scalar timing at very fast rates. The entrainment region hypothesis proposes a new version of Weber's law, the restricted Weber function; it implies that scalar timing (i.e., constant CV) is maintained only within an age-specific entrainment region (Figure 3, dotted line). Thus, departures from Weber's law are expected for event rates outside an entrainment region (faster and
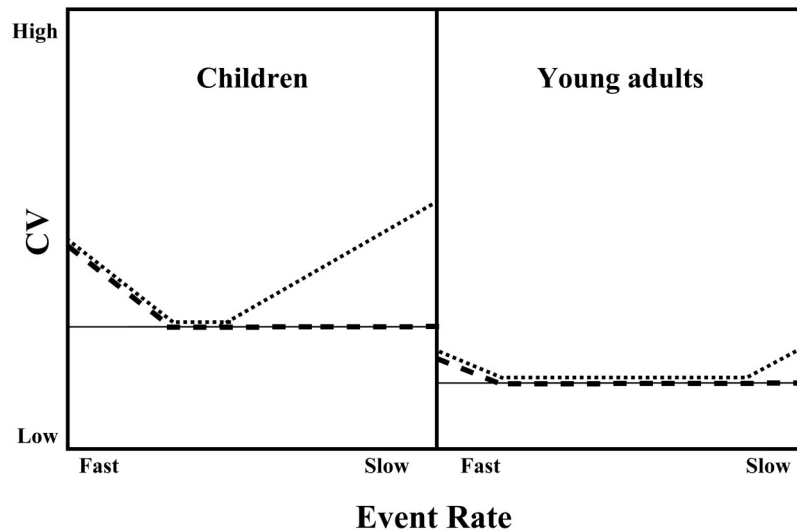
Figure 3. Comparative predictions of interval and entrainment models for coefficient of variability (CV) of continuation tapping of young children (left) and young adults (right). Solid line and dashed lines indicate, respectively, predictions of simple and generalized Weber laws. The dotted line indicates the restricted Weber function.

slower). Moreover, CV for slow events should be especially large for young children, who have the shortest P_0 values; thus, children should encounter the greatest disparities between event rate, T, and their preferred period, P_0, at slow event rates.

The View From an Interval Model

A contrasting view of the role of event rate in life span development is offered by an interval perspective on timing. Two prominent interval models are scalar expectancy theory (SET; Church, 1984, 2003; Gibbon, 1977; Gibbon & Church, 1984; Gibbon, Church, & Meck, 1984) and the Wing and Kristofferson (W&K) model (Vorberg & Wing, 1996; Wing & Kristofferson, 1973). Although both models share assumptions about temporal processing involving distinct clock, memory, and response stages, only the W&K applies directly to the synchronize–continue tapping task.

In the W&K model, synchronize–continue tapping entails a series of responses (taps) each triggered by an internal clock. The clock involves a pacemaker, which emits (over time) a continuous stream of pulses that flow into an accumulator via a switch (controlled by attention). The number of pulses accumulated during a target interval, T, provides a representation of the duration of that interval (an interval code). Once the clock encodes T (in synchronization), the number of pulses corresponding to the stored interval code (C) is used to meter out each time interval between successive taps. Thus, for continuation tapping, the nth produced interval (I_n) is described as an additive combination of the nth interval code (C_n) and the peripheral (motor) delays associated with the initiating (D_{n-1}) and terminating (D_n) taps:

$$I_n = C_n + D_n - D_{n-1}. \quad (1)$$

According to this model, the variability of produced intervals (I) derives from two sources: clock variance and motor variance.

Moreover, with an assumption of independence between clock and motor components, it is possible to decompose the total tapping variance (σ_I^2) into separate estimates of clock (σ_C^2) and motor (σ_D^2) sources of variability (Wing, 1980; Wing & Kristofferson, 1973).[2] Key model predictions involve these variance components (Ivry & Hazeltine, 1995; Peters, 1989; Wing, 1980). In the remainder of this section, we consider two predictions of the W&K model that are relevant to the present research.

The first prediction concerns tapping accuracy. Because the distribution of clock values (C_n) is assumed to be centered on the target interval, T, the averaged produced interval in continuation tapping always approximates T. Therefore, although random errors may occur in a series of produced intervals, I_n, systematic directional errors—that is, over- or underestimates—are not possible. In terms of life span assessments of continuation tapping, this means that period drift toward a preferred rate as a function of age is not predicted. Consequently, it is interesting that this assumption is often violated. Children and older adults frequently fail to maintain a constant rate of tapping, suggesting period drift (Greene & Williams, 1993; Ivry & Keele, 1989; Williams, Woollacott, & Ivry, 1992). In these cases, period drift is typically treated as a nuisance variable and eliminated from the time series by using a linear (or nonlinear) detrending procedure (Ogden & Collier,

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[2] Mathematical formalization of synchronized tapping given the interval view entails the assumption that feedback from a pacing signal induces a linear correction of absolute (rather than relative) phase errors. Equation 1 describes continuation tapping; it excludes any role for feedback (i.e., it is an open-loop model). Theory and data related to closed-loop models for synchronized tapping are beyond the scope of this article (Mates, 1994a, 1994b; Pressing, 1999; Pressing, Summers, & Magill, 1996; Semjen, Schulze, & Vorberg, 2000; Vorberg & Wing, 1996).

1999). From an entrainment perspective, detrending eliminates an important component of developmental change.

The second prediction of the W&K model is the centerpiece of this model; it concerns tapping variability. Indeed, this focus on tapping variability highlights its importance in evaluating all timing models. Specifically, for the W&K model, the decomposition of total tapping variance into clock and motor components is crucial because it leads to the prediction that clock variance increases linearly with the target interval, T, whereas motor variance remains constant. This is an important prediction, not only because it is the mainstay of the W&K model, but also because it deviates from conventional scalar timing accounts described in the preceding section (see Figure 3). Whereas both Weber's law and the generalized Weber's law (Getty, 1975) predict that the standard deviation of produced intervals, I, is linearly related to T, the W&K model predicts that the variance of produced intervals is linearly related to T. Nevertheless, applications of the W&K model to continuation tapping of young adults have been moderately successful (Wing, 1980). Success with respect to special populations is less clear-cut.

Using the W&K approach, several researchers have focused on variability predictions as these may apply to special populations. They have explored the possibility that children and older adults show increased clock variance, increased motor variance, or both. From this work, it is clear that the tapping of young children is more variable than that of adults for the reported event rates (Geuze & Kalverboer, 1994; Greene & Williams, 1993; Ivry & Keele, 1989). Such findings have often been interpreted as support for an interval model in which clock variance increases linearly with the magnitude of T (i.e., as sequence rate slows, motor variance remains constant). Less clear are reported differences at the other end of the age spectrum. In some cases, no age-related differences among young and older adults have appeared (Duchek, Balota, & Ferraro, 1994; Vanneste et al., 2001), whereas in other cases, age differences have been reported (Greene & Williams, 1993). In the most thorough study, Vanneste et al. found age differences only in unpaced, but not paced, tapping of young and older adults (i.e., in SMT values; cf. also Krampe, Mayr, & Kliegl, 2005).

A limitation of this research is that, despite theoretical predictions about the relationship between event rate and variability, the W&K model has been typically evaluated at only a single rate (T = 550 ms). One exception is the work of Vanneste et al. (2001), who examined continuation tapping in young and older adults for event rates between 300 and 700 ms. These investigators used a slope analysis method (Ivry & Corcos, 1993; Ivry & Hazeltine, 1995) to compare predictions of the W&K model with those derived for a scalar timing account. Consistent with scalar timing, Vanneste and colleagues found that for the tested range of event rates, the generalized Weber law provided a better account of age-related changes in timing variability than did the W&K model.

The current research broadens previous work in several respects. First, we offer a more comprehensive evaluation of aging and timing, here involving theoretical contrasts between interval-model predictions with those derived for the entrainment model. Second, we consider comparative predictions about the accuracy and variability of continuation tapping. Finally, we use a wider range of rates (150–1,709 ms) and a broader range of ages (4–95 years) than previously examined.

Method

Participants

Eighty-eight children and 217 adults (from 4 to 95 years), recruited from northwest and central Ohio, were divided into eight age groups (see Table 1). All 305 participants were English speaking with normal hearing. College-age participants, drawn from introductory psychology classes at Bowling Green State University and the Ohio State University, received course credit as compensation. Families of children received $25; adult nonstudents, recruited from newspaper ads and flyers, received between $25 and $40 in compensation. Adult participants (and parents of children) completed a background questionnaire.

Apparatus

Stimuli were generated, and responses (press and release times) were recorded (to the nearest millisecond) by a PC running customized software. Stimuli were acoustic sequences (comprising 440-Hz tones with a 50-ms duration) delivered at a comfortable listening level over small speakers located in front of the participant. A response board consisting of two copper plates was also located in front of the participant.

Procedure

All participants completed a battery of perceptual and motor timing tasks. Unpaced motor tasks consisted of an SMT task, which assessed preferred tapping rate, as well as fastest and slowest motor tempo tasks, which assessed the range of sequence rates that participants were able to produce. A paced motor task required synchronize–continue tapping at a wide range of rates. In all motor tasks, participants rested their nondominant hand on one copper plate and tapped the other copper plate with their dominant hand, while keeping their wrist on a wrist pad. A perceptual task required ratings of preferred listening rate (tempo) for stimulus sequences presented at different rates, T.

SMT. Participants produced a preferred tempo by tapping for 31 taps (30 time intervals) at their "most comfortable, natural rate of tapping." They were told to tap regularly, with a smooth gesture, at their favorite speed, defined as the rate that was neither too fast nor too slow, but felt "just right."

Fastest and slowest motor tempi. To assess fastest motor tempo, we asked participants to tap as fast as possible in a regular fashion (for 31 taps). Similarly, for the slowest motor tempo, they had to tap as slowly as possible, maintaining a smooth and continuous regular rhythm. When necessary, the youngest children were given supplemental encouragement by instructing them to tap as if they were tapping along to a really fast (or slow) song.

Preferred perceptual tempo (PPT). We assessed PPT by asking participants to rate isochronous monotone sequences presented at different

Table 1
Number of Participants in Each of the Eight Age Groups

Children		Adults	
Age group (yrs)	*n*	Age group (yrs)	*n*
4–5	27 (23)	18–38	119 (106)
6–7	21 (16)	39–59	52 (42)
8–9	20 (17)	60–74	25 (20)
10–12	20 (15)	75+	21 (19)

Note. Values in parentheses indicate the number of participants in each age group that showed spontaneous motor tempi (SMTs) across the four measurements (i.e., consistent SMT responders).

sequence rates. Using a 21-point rating scale, they rated each sequence rate as "too fast" (max = 10), "too slow" (max = −10), or "just right" (0) relative to their favorite speed. Ten of the sequences were faster than their composite SMT (an average of the first two SMT measurements), and 10 were slower; 2 sequences were presented at their SMT. The 10 faster sequences had T/SMT values of 0.904, 0.818, 0.74, 0.680, 0.606, 0.549, 0.497, 0.449, 0.406, and 0.367; T/SMT values for slower sequences were 1.104, 1.221, 1.358, 1.490, 1.648, 1.820, 2.012, 2.224, 2.458, and 2.718. The spacing of the sequences was logarithmic to cover a sufficiently wide range of perceivable rates with a limited number of sequences. Sequences were presented in one of two randomized orders.

Participants older than 12 years provided written ratings by using the 21-point scale, with zero anchoring their "most comfortable and natural tempo." Younger children provided ratings by using concrete visual stimuli; slow and fast rates were visually represented, respectively, by locations of a toy turtle and toy rabbits on a scaled board. A self-drawn picture of the child was placed in the middle (0) and identified as his or her favorite tempo. Each child placed a block on the board relative to his or her favorite tempo. Twenty-one colored lines marked equal intervals on the board (10 slow, 10 fast, 0 for favorite tempo), permitting numerical assessment of block placement. Initially, children were trained until they correctly answered questions about rates (e.g., "Where would you put the block if you heard something just a little slower than your favorite speed?").

Synchronize–continue tapping. Participants first synchronized a series of 30 hand taps with an isochronous pacing stimulus; then, in the absence of a pacing signal, they continued tapping for an additional 30 hand taps at the same rate as accurately as possible. Seven event (target) rates (T) were logarithmically spaced; beginning with the fastest rate, successive T values were equally spaced 1.5 log steps apart to span a wide range of rates in a limited number of steps: 150, 225, 337, 506, 759, 1,139, and 1,709 ms. Participants could listen until ready to tap. The first (practice) trial occurred at the rate of the participant's composite SMT (an average of the first two SMT measures); sequence rates were then presented in either ascending (slow to fast) or descending (fast to slow) order, starting with T = 150 ms or 1,709 ms, respectively. For children, the experimenter held up a sign that was green with the word "go," meaning "keep tapping," or red, with the word "stop," meaning "stop tapping."

Cognitive ability. Several nontiming measurement instruments were interleaved at various points within the session to gather information about factors that might account for individual differences in timing performance, aside from age. In this article, we focus only on the cognitive ability measure, which was assessed with the Naglieri Nonverbal Ability Test (NNAT; Naglieri, 1997; Naglieri & Ronning, 2000). The NNAT is a culture-fair nonverbal measure of cognitive ability that is an extension of the Matrix Analogies Test and does not require a participant to read, write, or speak. It produces a Nonverbal Ability Index (NAI), which is a normalized standard score with a mean of 100 and standard deviation of 15 that correlates strongly with the Stanford Achievement Test (Naglieri & Ronning, 2000). Application to older adults is typically justified by permitting longer response times for individuals above 55 years of age (J. Naglieri, personal communication, July 2001). For comparative purposes, adults were scaled relative to the level of young adults (18-year-olds); participants under 55 years of age were allowed 30 min to complete the test, and those above 55 years of age were allowed 45 min (although no adult above age 55 requested additional time).

Order of tasks. All perceptual–motor tasks were administered during a single session (1.5 to 2 hrs) interleaved with collection of demographic–individual difference information. Ordering of tasks in the first half hour of a session was as follows: the first SMT task, a 10-min rating task (unrelated to present research), the second SMT task, a survey measure of positive and negative affect (not reported here), and the PPT task. Following a short rest break, ordering of remaining tasks was as follows: the synchronization–continuation task, a survey measure of impulsiveness (not reported here), the third SMT task, the NNAT, the fourth SMT task, and,

finally, fastest and slowest tapping tasks (four times each). The session concluded with a debriefing questionnaire.

Preliminary Screening of Tapping Data

Prior to analyses, all motor responses were filtered according to the following criteria: (a) Produced intertap intervals (P) less than 50 ms (indicative of a "finger/hand bounce") were removed from further analyses. (b) For synchronize–continuation tapping, produced intervals greater than 150% or less than 50% of the average produced interval (indicative of missed or accidental taps) were also removed from further analyses (Helmuth & Ivry, 1996).

Results

In this section, we first present findings from unpaced tapping and perceived tempo tasks. Next we present accuracy and variability of paced (continuation) tapping.

Unpaced Tapping and Perception Tasks

SMT. Figure 4 summarizes relative frequency distributions of SMT for the eight age groups. Each of the four SMT productions yielded a median value for the 30-interval sequence; these were averaged. Resulting averages were binned (50-ms intervals) per age group, then twice smoothed by using a sliding three-bin window to eliminate noise in the raw data. Each curve thus represents a smoothed estimate of the distribution of participant SMT values for the specified age group. In Figure 4, modal SMT shows a clear shift across the life span, from a fast rate (i.e., $P_0 \approx$ 300 ms) for the 4- to 5-year-olds to a fairly slow rate (i.e., $P_0 \approx$ 700 ms) for participants over 75 years of age. The linear correlation between age (in years) and SMT for all participants was .21 ($p < .01$). To consider the possibility of a nonlinear trend across the life span, we used polynomial regression. We found a significant cubic relationship between age and SMT, $F(3, 301) = 13.38$, $p < .01$, $R^2 = .12$, suggesting that SMT slows with age during childhood and late adulthood but remains relatively constant otherwise; the cubic equation describing this relationship is given by the following: SMT = 266.0 + 28.9age − 0.71age^2 + 0.005*age^3.

One question that emerged from this analysis concerned whether there were any age differences in the consistency of SMT across the four productions. To address this question, we considered only those participants who yielded a normalized standard deviation of the four scores that was less than 25%. On the basis of this metric, most participants were consistent in their SMT, and no clear age trend in consistency appeared. Proportion of consistent responders in each group ranged from 0.75 (10- to 12-year-olds) to 0.90 (75+ age group). Table 2 reports mean SMTs with standard errors for consistent responders only. Overall, these data agree with those of Figure 4 and with the regression analysis involving all participants. Inspection of Table 2 suggests a potential blip in SMTs for participants ages 18–38. The mean SMT score for this age group was 630 ms; this was longer than the mean SMT for adjacent age groups (549 ms, 10–12 years; 522 ms, 39–59 years). Separate *t* tests showed that these differences were reliable for the comparison with the 39- to 59-year-old age group ($p < .05$), but not for the comparison with the 10- to 12-year-old age group. Nevertheless, consistent responders parallel the trend found for all participants; the largest SMT shifts occurred in early
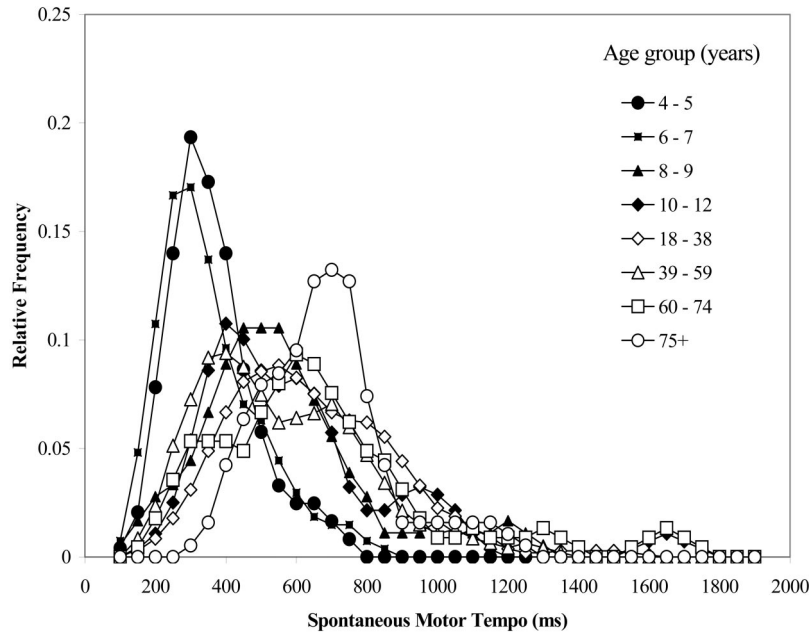
Figure 4.   Relative frequency distribution of spontaneous motor tempi for each of the eight age groups.

childhood and in late adulthood, but otherwise were fairly constant.

PPT and SMT: Are they related?   From the perspective of the preferred period hypothesis, we were interested in whether an individual's PPT would match his or her SMT. If a preferred internal tempo (period) exists, then it should be apparent in perceptual preferences as well as motor preferences; moreover, these two measures should be correlated. To address this, we first examined average tempo preference ratings for each age group. Figure 5A and B show ratings for children and adults, plotted as a function of sequence rate, T, relative to SMT, namely, T/SMT. If participants in an age group, on average, have a PPT that mimics their SMT, then they should consistently assign a zero rating (a "just right" tempo) to sequences that were presented at their SMT. Figure 5 shows that, as predicted, average rating curves crossed zero for all age groups at a point near a ratio of 1.00, that is, where T = SMT. One exception was the 4- to 5-year-old age group. The data of these children showed two zero crossings; the first zero crossing appeared at a ratio near 1.0 (corresponding to the group's SMT) with the second at a ratio near 1.5 (i.e., a tempo of 1.5 × SMT). This second zero crossing did not appear to be due to differences in reliability, although we cannot completely rule this out.

To assess the relationship between perceptual and motor preferences more directly, we fit a regression line to participants' PPT ratings and then used the resulting regression equations to estimate the sequence rate that produced a zero rating (i.e., that individual's PPT). We then examined the correlation between individual PPT and SMT estimates. A scatter plot of these data is shown in Figure 6. Consistent with the average rating data, individual estimates of PPT were highly correlated with SMT ($r = .75$, $p < .01$).[3] Together, results from the SMT and PPT tasks provide converging support for the preferred period hypothesis.

Accessible motor tempi: Limits in tapping rates.   The preceding findings concern predictions of the preferred period hypothesis. To examine predictions of the entrainment region hypothesis, we considered limits of accessible tapping rates (associated with fastest and slowest motor tempo tasks). This hypothesis predicts that the range of accessible tapping rates widens with age during childhood and narrows again in late adulthood. Results from both the fastest and slowest motor tempo tasks were consistent with this hypothesis (see Table 2). Fastest motor tempi (fast MT) showed a U-shaped profile across the life span. Limits on fast MT were slower for the youngest children and oldest adults than for other age groups. Conversely, slowest motor tempi (slow MT) showed an inverted U-shaped profile; limits on slow MT were faster for the youngest children and the oldest adults than for other age groups. Consistent with these observations, polynomial regression of fast and slow MT against age (in years) revealed significant quadratic trends across the life span: $F(2, 302) = 32.57$, $p < .01$, $R^2 = .181$, and $F(2, 302) = 6.91$, $p < .01$, $R^2 = .05$, respectively. The

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[3] When quantifying the formal mathematical relationship between two variables, it is important to distinguish two situations: (a) the problem of finding the best linear predictor of a dependent variable, *Y*, by using the values of an independent variable, *X*; and (b) the problem of finding the interrelationship between two dependent variables, *X* and *Y*, both of which may be measured with error (Isaac, 1970). Our interest in the relationship between SMT and PPT is an example of the second situation (termed a linear structural relation). Methods for estimating parameters for linear structural relations differ from those used in linear regression. When we applied the method proposed by Isaac (1970) to estimate the slope of the relationship between SMT and PPT, we obtained a value of 1.31, which is larger than the value of 1.04 obtained by using traditionally linear regression techniques (see Figure 4).

Table 2
Descriptive Summary of Unpaced Tapping Measures

Age group (yrs)	% consistent	Fast MT (ms)		SMT (ms)		Slow MT (ms)		NPR	
		M	SE	M	SE	M	SE	M	SE
4–5	85	262	13	312	16	731	257	2.21	1.40
6–7	76	221	7	300	26	1,728	387	4.78	0.94
8–10	85	182	4	521	61	2,691	511	5.73	1.22
10–12	75	186	7	549	65	2,951	360	5.80	0.92
18–38	89	169	3	630	22	2,532	139	4.22	0.30
39–59	81	171	13	522	34	2,264	185	5.03	0.61
60–74	80	211	24	632	59	2,660	459	4.46	0.92
75+	90	219	20	648	43	1,727	229	2.70	0.61

Note. Fast MT = fastest motor tempo; SMT = spontaneous motor tempo; Slow MT = slowest motor tempo; NPR = normalized produced range.

equations predicting these measures were given by the following: fast MT = $237.40 - 3.72\text{age} + 0.046\text{age}^2$, and slow MT = $1442.96 + 62.55\text{age} - 0.715\text{age}^2$, respectively.

Finally, we combined fast MT and slow MT measures with SMT to produce a new metric, normalized produced range (NPR), which indexes the range of accessible tapping rates relative to an individual's SMT. NPR was calculated as follows: NPR = (slowest − fastest)/SMT. Theoretically, in unpaced tapping, NPR was hypothesized to prefigure an entrainment region. As shown in Table 2, NPR was narrowest for the youngest children (4–5 years) and oldest adults (75+ years) where it was roughly half the size of NPR for other participants (ages 6−75 years). Consistent with the separate analyses of fast and slow MT, a polynomial regression of NPR with age (in years) as a predictor revealed a significant quadratic trend across the life span, $F(2, 302) = 4.09$, $p < .01$, $R^2 = .03$; NPR = $2.87 + 0.116\text{age} - 0.001\text{age}^2$. We also note that a small but significant proportion of the variance in NPR scores can be accounted for by NAI, that is, nonverbal ability. NPR correlated reliably with NAI ($r = .23$, $p < .01$); participants with higher NAI scores had larger NPRs (we return to this point in the Discussion). Assuming that the limits of unpaced tapping prefigure relevant aspects of an entrainment region, these data are consistent with the hypothesis that the entrainment region widens throughout childhood and then narrows again late in life. Next, we consider the entrainment-region hypothesis more directly by examining the limits of paced (continuation) tapping.

Paced (Continuation) Tapping

Accuracy. Accuracy measures are relevant to predictions of both entrainment and interval approaches to continuation tapping. In the former, the preferred period hypothesis predicts that during continuation tapping, participants should show a directional drift toward their intrinsic period, P_0. Specifically, at fast rates, mean P should be an overestimate of T, whereas at slow rates, mean P should be an underestimate of T. Moreover, according to the entrainment region hypothesis, the amount of period drift should be greatest in the youngest and oldest participants as a result of a reduced range of stable period matching at the two ends of the age spectrum. By contrast, the interval view, as outlined in the W&K model, does not predict drift during continuation tapping because tapping errors are assumed to be random.

Results were consistent with both entrainment hypotheses. A preliminary analysis of synchronization as well as continuation tapping demonstrated a clear pattern of systematic drift in the sequence of produced periods (see Appendix A, which is available on the Web at http://dx.doi.org/10.1037/0096-3445.135.3.348.supp). Figure 7 depicts accuracy profiles across the life span; it shows average signed errors (mean P − T) with standard error bars for the 30 intervals of continuation tapping as a function of T for children (Figure 7A) and adults (Figure 7B). These curves effectively represent empirical detuning curves; for comparison, see Figure 2 for theoretical detuning curves associated with the entrainment model. We first consider a qualitative description of these data; we then consider a more quantitative analysis.

As expected on the basis of theoretical detuning curves, Figure 7A shows that the youngest children produced positive error scores at the fastest rates (i.e., overestimates of T), negative errors at the slowest rates (i.e., underestimates of T), and error scores close to zero for the 337-ms target T (a value close to the average SMT for these ages). In general, the region of stable period matching (near-zero error scores) broadened with age during childhood. Accurate period matching rarely extended to slower rates for children in the two youngest age groups (4–5 years and 6–7 years). Figure 7B shows that, during adulthood, young and middle-aged adults showed little systematic drift at any target rate; this is consistent with the idea that these age groups operate with a relatively wide entrainment region. In late adulthood, however, the region of stable tapping appeared to shrink, with older adults showing more pronounced drift at the slowest rates in particular. Although there was a slight tendency for some older adults to slow their tapping rather than speed up at the 1,709-ms target rate, this trend reversed for the 75+-years age group, where the error pattern was strikingly similarly to the 6- to 7-year-olds.

In support of these observations, Table 3 shows the percentage of participants in each age group that exhibited a significant linear error pattern as a function of target, with positive errors at the fastest rates and negative errors at slowest rates, consistent with drift toward a preferred period. Also shown are three paced tapping measures that assess shifts in produced period at different rates; they are the averaged produced periods (with standard errors) for the fastest target rate (T = 150 ms), the slowest target rate (T = 1,709 ms), and the median target rate (T = 506 ms); these are
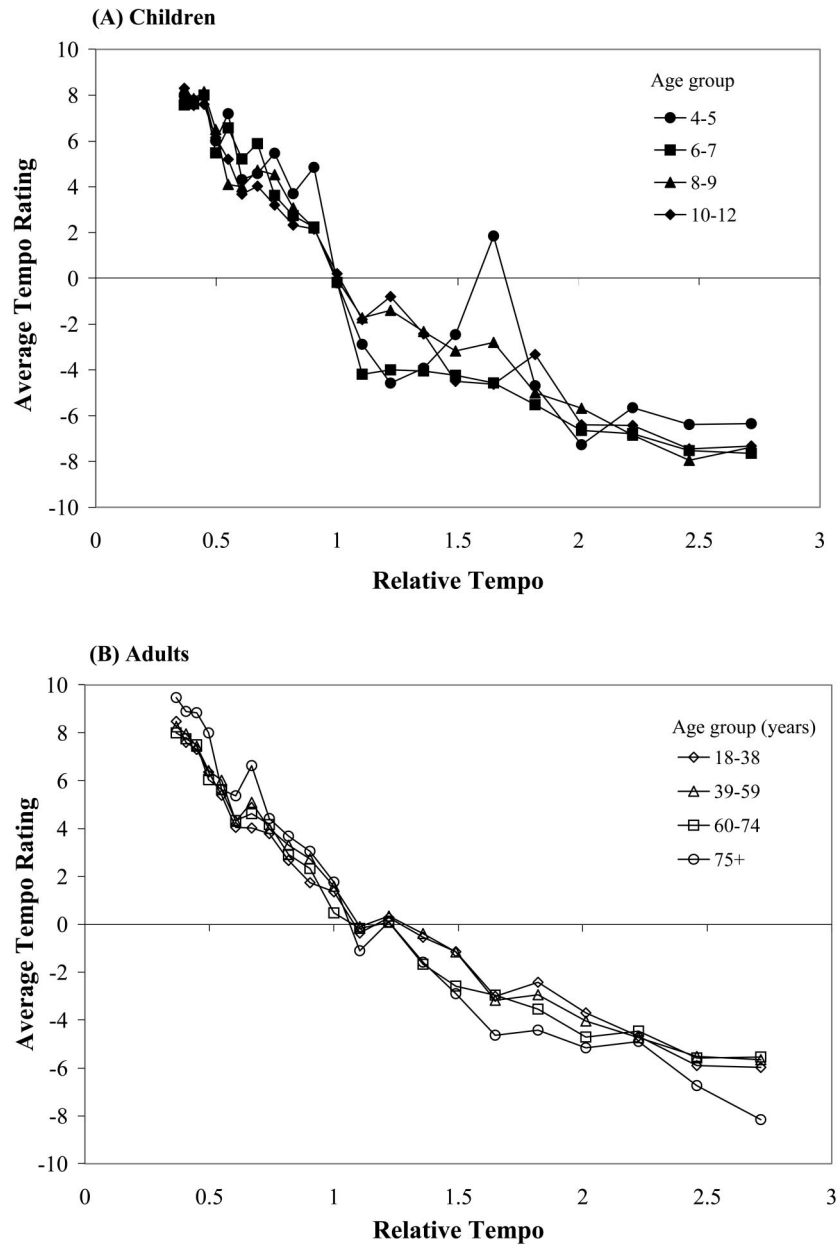
(A) Children

(B) Adults

Figure 5. Mean tempo ratings for the preferred perceptual tempo task as a function of T/SMT (target rate divided by spontaneous motor tempo). Panels A and B show the mean ratings at each normalized sequence rate (T/SMT = 1.0) for the children and adults, respectively.

labeled min P, max P, and median P, respectively. Min P and max P measures enable assessments of errors at the two extreme target rates of 150 ms and 1,709 ms, respectively.

On the basis of the entrainment region hypothesis, we predicted that because min P and max P are at the two extremes, these rates would be most likely outside the entrainment region for the youngest and oldest participants and thus should show significant quadratic trends over the life span. Moreover, because median P is at an intermediate rate, we expected it to be within the entrainment region and register relatively small tapping errors for most ages.

As expected, Table 3 shows that, in general, min P was an overestimate of the fastest target rate (P > 150 ms), max P was an underestimate of the slowest target rate (P < 1,709 ms), and that median P was very close to 506 ms. More important, when we examined these data as a function of age (in years) by using polynomial regressions for min and max P, our findings confirmed significant quadratic trends over the life span: $F(2, 302) = 51.08$, $p < .01$, $R^2 = .272$, and $F(2, 302) = 27.33$, $p < .01$, $R^2 = .17$, respectively. Predicted produced periods for the fastest and slowest rates as a function of age were given by the following: min P =
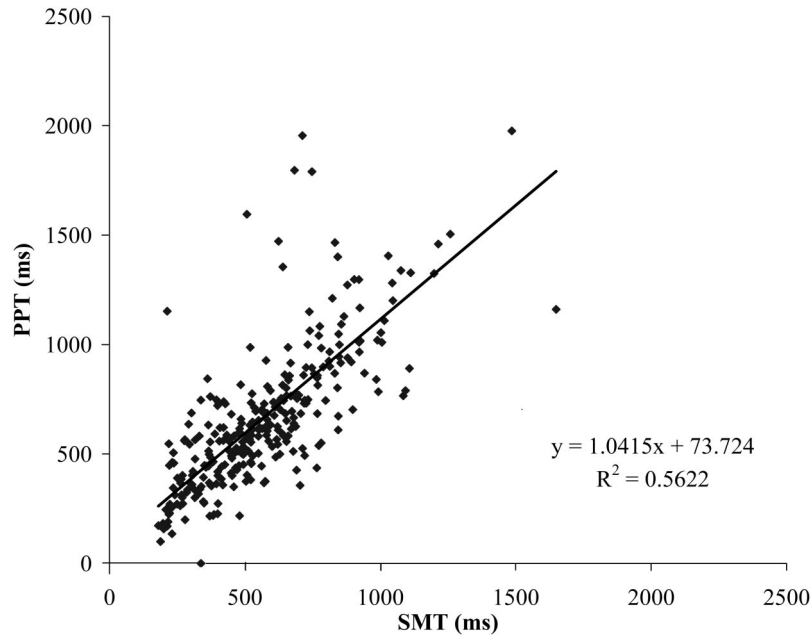
Figure 6. Scatter plot of individual estimates of preferred perceptual tempo (PPT) as a function of spontaneous motor tempo (SMT) with best-fitting linear regression line.

$248.33 - 3.92 \text{age} + 0.044 \text{age}^2$, and max P $= 1227.95 + 25.16 \text{age} - 0.273 \text{age}^2$, respectively.[4] Overall, analyses involving min and max P confirmed the qualitative descriptions of the empirical detuning curves in Figure 7.

Next, we directly pursued the relationship between our measure of preferred period and continuation tapping accuracy. We considered how well an individual's SMT (an unpaced measure) predicted the three paced tapping measures, min P, median P, and max P. These correlations appear in Table 4. It is revealing that individual SMT scores predicted all three accuracy measures. Most striking is the finding that SMT was positively correlated with median P ($r = .20$, $p < .01$); this indicates that the direction of drift from the 506-ms target rate (presumably a stable rate for most participants) varied systematically with an individual's average SMT. Similarly, SMT predicted the amount of overestimation at the fastest rate (min P, $r = -.29$, $p < .01$) as well as the amount of underestimation at the slowest rate (max P, $r = .19$, $p < .01$).

We have assumed that certain unpaced measures (fast MT, slow MT, unpaced NPR) may serve as indicators of the width of an entrainment region. To validate this assumption, we considered how these measures fared in predicting continuation tapping accuracy. Specifically, unpaced tapping measures, namely, fast MT, slow MT, and NPR, were used to predict their counterpart paced tapping measures, namely, min P, max P, and a paced NPR metric. The paced NPR metric was defined as follows: (max P – min P)/median P. Resulting correlations between the various unpaced and paced measures appear in Table 4. Consistent with the use of unpaced tapping measures as indicators of the width of the entrainment region, reliable correlations were found between all corresponding unpaced and paced measures (fast MT with min P, $r = .79$, $p < .01$; slow MT with max P, $r = .44$, $p < .01$; unpaced NPR with paced NPR, $r = .34$, $p < .01$).

In summary, accuracy profiles for continuation tapping reveal systematic effects of age and event rate that are consistent with both the preferred period and entrainment region hypotheses. Children and older people have the most difficulty period matching, especially at slower rates, with period drift toward preferred period most pronounced in young children; these findings are inconsistent with accuracy predictions of the W&K model. Overall, correlations between unpaced and paced measures of the average produced period at certain critical (extreme) target rates confirm the idea that the period drift is related to SMT. They provide converging evidence that, despite the strong influence of the pacing sequence, the periods produced during continuation tapping reflect both a persisting influence of a latent P_o on average tapping rates and inherent constraints on the range of target rates that yield stable continuation performance.

Variability. Predictions about variability of continuation tapping are at the heart of differences between interval timing models and entrainment theories. As we have seen, interval timing models (W&K, SET) differ in their predictions about variability changes as function of rate. The W&K model predicts a linear relationship between sequence rate, T, and tapping variance, SD_p^2, whereas the generalized Weber law (and SET) predicts a linear relationship between T and tapping standard deviation, SD_p. An entrainment

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[4] Median P also showed a weak quadratic trend as a function of age, although this appeared to be due to the tendency of the 4-year-olds to drift back to a rate near their SMT ($\approx$ 300 ms) for all targets rates, T (see Appendix A, which is available on the Web at http://dx.doi.org/10.1037/0096-3445.135.3.348.supp). When we eliminated just the 4-year-olds from the polynomial regressions, this eliminated the quadratic trend for median P ($p = .33$), but not the quadratic trends for min P or max P ($p < .01$).
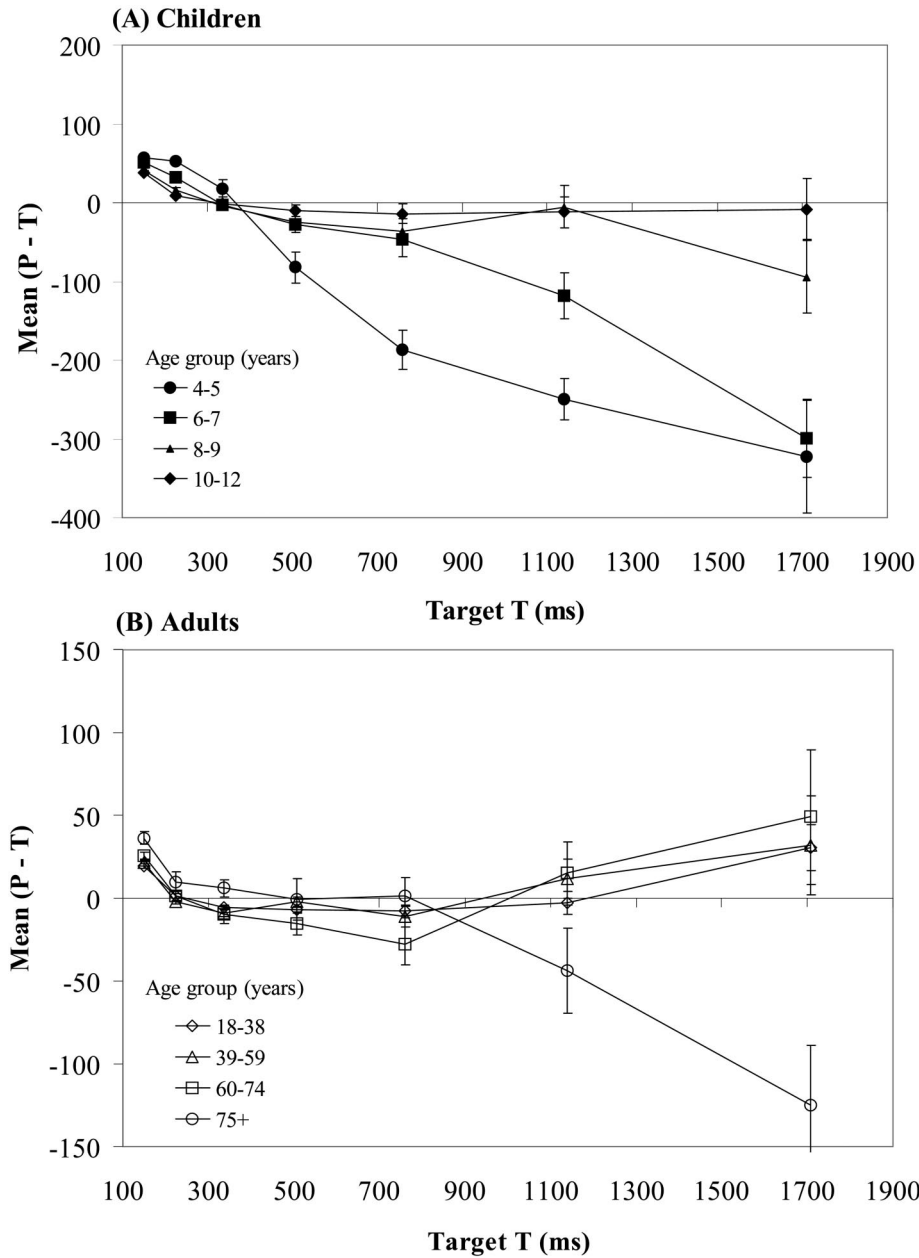
Figure 7. Mean (± *SE*) directional error scores (P – T) are shown for each target rate, T, for children (A) and adults (B). P = produced period.

model offers a third perspective: Like the generalized Weber law, it predicts a linear relationship between SD_p and T, but this relationship is postulated to hold only for a restricted range of rates associated with an entrainment region (see Figure 3). We termed this revised Weber's law a restricted Weber function.

In this section, we begin by focusing on variability predictions of the two main interval models, the W&K model and the generalized Weber's law. At least from an interval perspective, these two models represent gold standards in the analysis of tapping variability (cf. Vanneste et al., 2001). To assess their predictions, we relied on the component (slope) analysis method proposed by

Ivry and colleagues (Ivry & Corcos, 1993; Ivry & Hazeltine, 1995). This method rests on interval model assumptions: It uses linear regression of tapping variability against target rate, T, to decompose total tapping variability into two theoretical components: a central "clock" component (obtained from the slope) and a duration-independent "motor" component (obtained from the *y*-intercept).

Table 5 presents the results of our first comparative slope analysis involving the W&K model and the generalized Weber law. This table shows slope and intercept estimates and R^2 for the two models for each of the eight age groups. Slope values are

Table 3
Descriptive Summary of Continuation Tapping Accuracy

Age group (yrs)	% consistent	Min P (ms)		Median P		Max P (ms)		Paced NPR	
		M	SE	M	SE	M	SE	M	SE
4–5	88	288	15	406	21	926	98	1.56	0.25
6–7	80	233	8	485	20	1,305	77	2.20	0.15
8–10	60	196	5	479	11	1,556	59	2.88	0.16
10–12	58	189	3	504	8	1,721	38	3.05	0.08
18–38	58	174	2	491	3	1,697	20	3.12	0.05
39–59	63	173	3	500	10	1,742	65	3.20	0.15
60–74	65	195	15	491	14	1,672	64	3.07	0.17
75+	53	193	7	504	19	1,527	65	2.64	0.08

Note. % consistent = percentage of participants showing consistent linear error trend across all seven target rates ($p < .05$). Paced normalized produced range (NPR) metric = (Max P − Min P)/Median P. Min P = fastest target rate (T = 150 ms); Median P = median target rate (T = 506 ms); Max P = slowest target rate (T = 1,709 ms).

traditionally taken to estimate central clock sources of variability, whereas corresponding intercept measures putatively reflect estimates of peripheral motor sources of variability. Consistent with Ivry and Hazeltine (1995) and Vanneste et al. (2001), this analysis favored scalar timing, as expressed by the generalized Weber's law, over the nonscalar timing relationship predicted by the W&K model. Moreover, slope and R^2 values for young and older adults paralleled those reported by Vanneste et al. (2001). In general, slope estimates were larger for children and older adults. In terms of interval theories, this may suggest increased clock variability at the two ends of the age spectrum. However, intercept estimates were mostly negative, thus precluding a straightforward slope-analysis interpretation of these data. Negative intercepts are problematic because they imply negative motor variability, an implausible state that violates W&K model assumptions. In sum, although the generalized Weber's law provided a better fit to the data than the W&K model, it consistently yielded negative estimates of motor variance for the wide range of rates we tested and thus does not adequately explain our results.

Because the generalized Weber's law has been successfully applied to tapping data in the past, we ask why negative y-intercepts appear in the present study. One answer is that the present study used a wider range of rates than in previous research; therefore, following an entrainment account, tapping variability especially for relatively slow rates should be disproportionately large. This is because extreme rates will fall outside the entrainment region and lead to instability, particularly for certain age groups (e.g., children). Thus, the result of introducing relatively extreme rates into a slope analysis will be to introduce a relatively large increase in tapping variability for these T values; in turn, this artificially increases the slope of a regression line, leading to a negative y-intercept.

To test this possibility, our second theoretical comparison adapts slope analysis to assess the entrainment model predictions about age-specific regions of rates where Weber's law obtains. To isolate such regions, we used an iterative version of slope analysis. That is, we successively eliminated from a given slope analysis (per age group) any rate that produced negative intercepts to a scalar timing fit. If slower rates are responsible for the heightened variability observed above (i.e., negative slope intercepts), then an iterative removal of these rates will eventually yield a set of good rates, namely, a restricted range of rates that produce a positive y-intercept. In turn, for a given age group, this should identify limits of postulated age-specific entrainment regions. Because the generalized Weber law predicts a lower limit to scalar timing (i.e., heightened variability at fast rates), a good iterative fit of this law should reveal the upper (slower) limit of an entrainment region. Consequently, for each age group, we first omitted the slowest rate from analysis and assessed the fit of the generalized Weber law; if a negative intercept was found, we then removed the next slowest

Table 4
Correlation Between Unpaced and Paced Measures

Unpaced	Paced			
	Min P	Median P	Max P	NPR
Fast MT	.785 (.811)*	−.026 (−.012)	−.436 (−.441)*	−.531 (.540)*
SMT	−.289 (−.245)*	.201 (.170)*	.192 (.172)*	.199 (.177)*
Slow MT	−.364 (−.372)*	.301 (.303)*	.437 (.440)*	.408 (.409)*
NPR	−.224 (−.246)*	.199 (.216)*	.391 (.370)*	.344 (.350)*

Note. Values in parentheses indicate partial correlations after controlling for age. Min P = fastest target rate (T = 150 ms); Median P = median target rate (T = 506 ms); Max P = slowest target rate (T = 1,709 ms); NPR = normalized produced range; Fast MT = fastest motor tempo; SMT = spontaneous motor tempo; Slow MT = slowest motor tempo.
* $p < .01$.

Table 5
Summary of Tapping Variability for the Eight Age Groups By Using Slope Analysis (Ivry & Hazeltine, 1995)

Age group (yrs)	W&K model			Generalized Weber law		
	Slope	Intercept	R^2	Slope	Intercept	R^2
4–5	107.06	−37,305	.866	0.0608	−9,007	.981
6–7	33.12	−10,380	.924	0.0184	−1,293	.987
8–9	19.18	−5,929	.913	0.0107	−706	.996
10–12	15.74	−5,254	.852	0.0090	−1,119	.972
18–38	11.28	−3,356	.919	0.0063	−275	.997
39–59	9.24	−2,457	.932	0.0049	125	.936
60–74	16.36	−5,462	.788	0.0094	−1,237	.918
75+	17.82	−6,064	.831	0.0102	−1,434	.960

Note. For the W&K model, which assumes a linear relationship between the target rate, T, and variance, s^2, we used the equation $s^2 = bT + a$. For the generalized Weber law, which assumes a linear relationship between the target rate, T, and standard deviation (scalar timing), we used the equation $s^2 = bT^2 + a$. W&K = Wing and Kristofferson (1973) model.

rate and so on. Thus, the T value where an intercept becomes positive estimates an upper limit of the entrainment region. Below this T value are rates that collectively yield a positive intercept. In sum, for each age group, the recovered set of rates corresponds to the age-specific entrainment region proposed by a restricted Weber function.

Results of this iterative application of slope analysis appear in Table 6. Column 2 shows estimates of upper limits of postulated entrainment regions. At rates slower than these limits, we find significant departures from the generalized Weber law. Thus, for the youngest groups (i.e., those with fastest SMTs), the upper limit corresponded to a T of 506 ms. By contrast, the upper limit in remaining age groups is 759 ms, which identifies a wider range of stable tapping rates; in these groups, departures from the generalized Weber law are evident only in rates with T values greater than 759 ms. However, for two age groups, namely the 8- to 9-year-olds and the 60- to 74-year-olds, estimates for the *y*-intercept never became consistently positive in the iterative analysis. Possible developmental reasons for findings with the 8- to 9-year-old and 60- to 74-year-old groups are considered in the Discussion.

A summary of variability data appears in Figure 8. Data are plotted in terms of a normalized standard deviation, that is, the CV, to highlight departures from Weber's law. Figure 3 characterized CV predictions for a simple Weber's law (where CV is constant across all sequence rates), the generalized Weber's law (where CV is constant except at very fast rates), and the restricted Weber function (where CV is constant only within a limited range of rates). The data of Figure 8 indicate that, contrary to a simple Weber's law or a generalized Weber's law, CV tends to increase at the slowest rates, especially for the children. Although the generalized Weber's law correctly predicted increased variability at fast rates, slope analyses revealed that it failed to predict the CV increases at slow rates. Indeed, the iterative slope analysis provided most support for the restricted Weber function. Departures from Weber's law at slow rates were especially pronounced with young children and the oldest adults, supporting the view that there is an age-specific entrainment region that is narrowest at the two ends of the age spectrum.

Discussion

In this article, we have offered a novel assessment of life span development of timing and event tracking and an evaluation of two

theoretical hypotheses derived from an entrainment model: a preferred period hypothesis and an entrainment region hypothesis. In the following discussion, we first evaluate the evidence in support of these hypotheses and next consider related implications of this work for understanding (a) "critical periods" in life span development and (b) traditional views of age-related slowing.

Evaluation of Entrainment Hypotheses

The preferred period hypothesis. The preferred period hypothesis posits that individuals have a preferred rate of event tracking that on average slows over the life span. From an entrainment perspective, preferred rate is determined by a latent (internal) oscillator, with period P_0, which affects the range of measurable manifest (external) periods that an individual is able to produce when tracking an event. With maturation, the preferred period, P_0, is predicted to shift from shorter to longer average values. Consistent with the preferred period hypothesis, we found that over the life span, SMT shifts from approximately 300 ms for young children (ages 4–7) to near 700 ms for adults ages 75 and older. Moreover, PPT was shown to follow the same developmental time course. These findings agree with previous reports showing that spontaneous tapping slows with age, during childhood (Drake et al., 2000), and in adulthood (Vanneste et al., 2001). This is the first study, however, to show a similar developmental trend for a perceptual measure of preferred event rate and to show that perceptual and motor measures of preferred event rate are correlated; we cannot entirely rule out the possibility that session context accounts for some variability associated with this correlation.

An additional issue that is central to the preferred period hypothesis concerns the predicted relationship between unpaced and paced measures of tapping. According to the preferred period hypothesis, the latent oscillator period, P_0, not only should determine SMT, but should also play a hidden, but persisting, role during continuation tapping. Consistent with this hypothesis, we found that manifest produced periods, P, tended to drift toward P_0 and that individual estimates of P_0, given by SMT, predicted various measures of continuation tapping accuracy (e.g., min P, median P, max P). Period drift was most pronounced with children (ages 4–7) and the oldest adults (ages 75+), who tended to show very large underestimation errors at the slower rates. Most striking was the behavior of the 4- to 5-year-olds, who, by the end of the

Table 6

Entrainment Region Determined by Iterative Application of Slope Analysis Based on Generalized Weber's Law

Age group (yrs)	Upper limit (ms)	Slope	Intercept	R^2
4–5	506	0.0112	545.92	.886
6–7	506	0.0071	173.69	.999
8–10				
10–12	759	0.0048	22.834	.999
18–38	759	0.0048	49.854	.998
39–59	759	0.0035	42.007	.991
60–74				
75+	759	0.0047	109.58	.995

continuation phase, were almost invariably tapping at a rate close to their average P_0 independent of the target value of T.

Some of the participants in the 60- to 74-year-old age group showed a modest tendency to overestimate (rather than underestimate) the slowest rate (T = 1,709 ms). We note, too, that this age group also showed an inconsistent pattern of tapping variability (as evidenced by our iterative application of the slope-analysis method). These findings are somewhat puzzling. At present, we can only speculate on reasons for this difference. One possibility is that some of the 60- to 74-year-old participants reached an age where their overall tapping behavior became less stable, and they consciously tried to compensate for this. In other words, some individuals may have tried to correct a tendency to speed up toward P_0, but because of their increased instability, they overcompensated, yielding a somewhat unusual pattern of tapping variability. This also implies that participants above 75 years of age have more diminished compensatory abilities.

In summary, support for the preferred period hypothesis comes from three main sources: (a) SMT and PPT slow across the life span, (b) individual participant estimates of SMT and PPT are highly correlated, and (c) individual participant estimates of SMT predict manifest periods produced during paced (continuation) tapping.

The entrainment region hypothesis. Next, we consider empirical support for the entrainment region hypothesis. The entrainment region hypothesis posits that people are most capable of entraining to events with rates that differ from their preferred tempo in adulthood (middle age) and that they are least capable early and late in life. Thus, the width of an entrainment region should follow a curvilinear function over the life span, wherein the very young and the very old show narrower entrainment regions than do young adults.

Support for the entrainment region hypothesis was provided by both unpaced and paced tapping measures. During unpaced tapping, young children and older adults were not only unable to tap as fast as other participants (as measured by fast MT) but also unable to tap as slow (as measured by slow MT). Combining these measures with SMT produced an unpaced NPR metric that expanded and contracted over the life span. Moreover, consistent with the use of NPR as a measure of entrainment region width, we found that unpaced NPR predicted a participant's range of stable paced tapping performance. Overall, age-specific entrainment regions were narrowest for children (less than 8 years of age) and the oldest adults (ages 75+), with a fairly broad range of stable tapping performance observed otherwise.

Converging support for the entrainment region hypothesis was provided by analyses of tapping variability. Classically, the main measure of continuation tapping performance involves variability. Accordingly, our findings regarding tapping variability hold implications that extend beyond evaluations of the entrainment model because they raise questions about the generality of scalar timing. In the present research, we considered three interval-model alternatives to the entrainment region hypothesis. A simple (classic) version of Weber's law predicted scalar timing, namely, that CV should be constant over all rates regardless of age. A generalized Weber's law made a similar prediction, except that deviations from scalar timing were anticipated at fast rates. Finally, the W&K model predicted that the variance of produced intervals, not the standard deviation, should be linearly related to the target rate. None of these alternatives were supported by the data. Rather, we found that consistent with the entrainment region hypothesis and a restricted Weber function, scalar timing obtained only within an age-specific range of rates.

The key failure of the interval approach was that none of the three alternatives we tested predicted the disproportionately large variability in tapping that was observed at slow rates in children and the oldest adults. We suspect that previous studies have failed to show violations of scalar timing at slow rates because they simply did not consider a wide enough range of rates. Specifically, Vanneste et al. (2001) reported that tapping variability for young and older adults is consistent with the generalized Weber's law, but these authors tested rates only between 300 and 700 ms; from an entrainment perspective, this range of rates is well within the entrainment region for the tested ages.

In summary, support for the entrainment-region hypothesis comes from three main sources: (a) Both unpaced and paced NPR metrics show reliable quadratic trends across the life span, (b) individual participant estimates of entrainment region width for unpaced tapping predict the range of stable paced (continuation) tapping, and (c) variability in continuation tapping supports Weber's law only within a restricted range of event rates that is narrowest during childhood.

Broader Implications of Entrainment Theory

Critical periods in life span development. Our theory offers a new perspective on critical periods. Classically, a critical period refers to a developmental window in which extreme plasticity and enhanced learning exists. But exactly what is learned and how this occurs during such a period is a matter of debate (Johnson, 2005). One way of addressing these issues is by asking the question, At what time scale does a special window operate?

Recently, the critical period construct has been reframed by suggesting that, instead of a single critical period, a progression of sensitive—that is, optimal learning—periods emerges with age. At different ages, children become ready to acquire different kinds of information. Werker and Tees (2005) proposed that children show enhanced learning of distinct aspects of language at different sensitive periods during maturation. Thus, infants move from facile acquisition of relatively brief events, such as phonetic categories, to enhanced proficiency with longer events involving reading and spelling at successive ages. Trainor (2005) proposed a similar maturation progression for competencies in music. Thus, what is learned depends on age-specific sensitive periods.
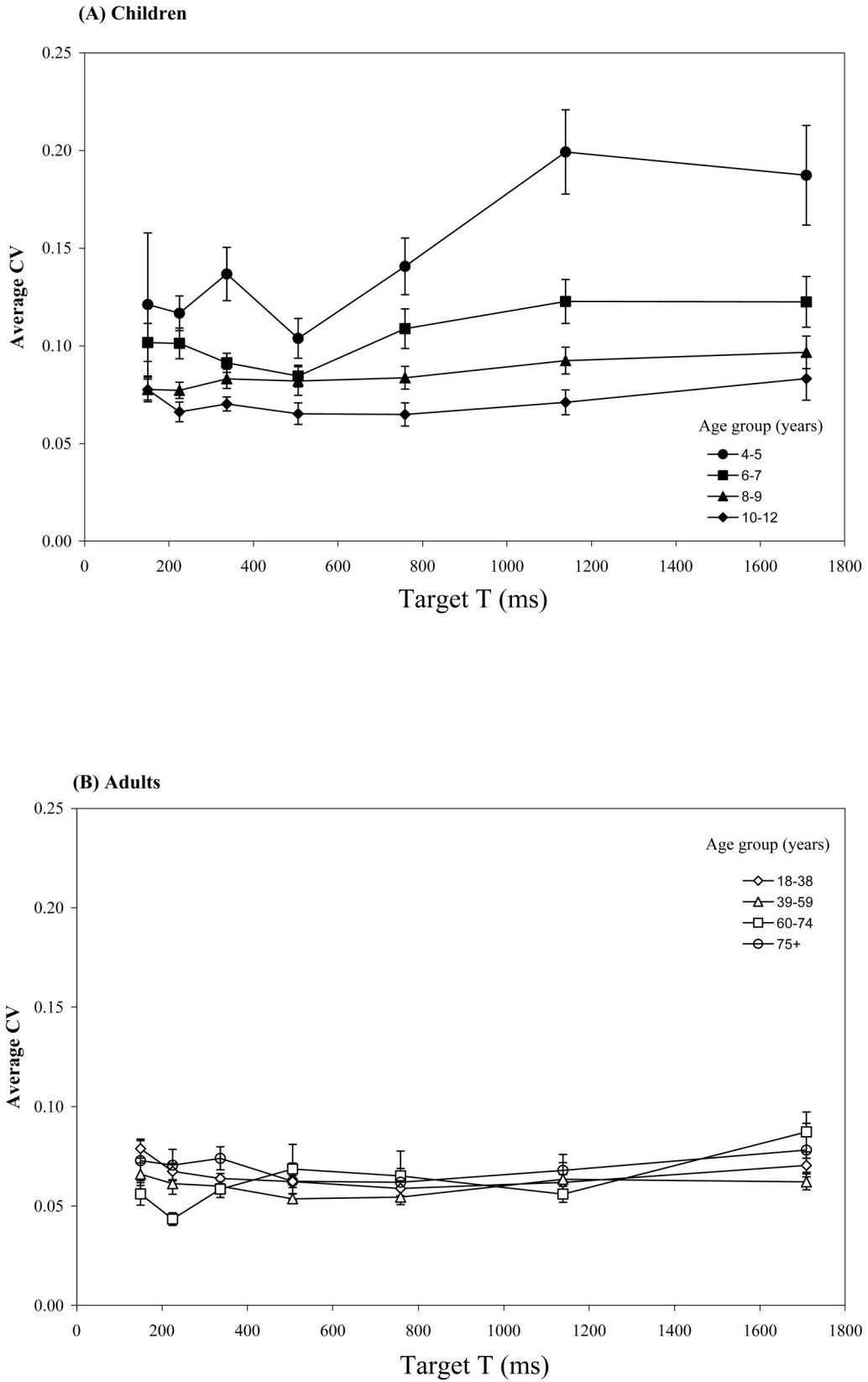
(A) Children

(B) Adults

Figure 8. Mean (± *SE*) coefficient of variability (CV) scores are shown for each target rate, T, for children (A) and adults (B).

The preferred period hypothesis offers a new slant on these findings. It implies that a crucial part of maturational progression is associated with change in sensitivity to time scales. As latent oscillations, with longer P_0 values, become active with maturation, a greater range of manifest oscillations can function as vehicles for enhanced learning. Early in life, latent oscillations with brief periods are active, and these selectively promote a range of manifest periodicities that enhance infant learning of information specific to relatively fast events.

As entrainment regions expand with age, early perceptual learning associated with short time spans paves the way for later learning of material that transpires over longer time spans. Maturation ushers in active latent oscillations with longer periods. When these emerge, a burst of new perceptual learning is possible. In complex events, this can involve attentional orientations to higher structural levels (longer time scales) permitting more effective focusing on larger structural units (syllables and words, musical phrases; Drake et al., 2000). Significant changes in listening skills happen around age 8, perhaps due to skill consolidation along with the offset of a significant optimal period in language learning (Harrison, Gordon, & Mount, 2005; Werker & Tees, 2005). Also at this age, similar changes occur in spontaneous motor movements (Eaton, McKeen, & Campbell, 2001) and in perceptual musical skills (Trainor, 2005). For instance, at 8 years of age, evoked potentials reveal a sudden heightening of amplitudes of P1, P2, and N1 components in response to individual tone onsets (Shahin, Roberts, & Trainor, 2004). Such findings are intriguing in light of the discrete shift in SMT for this age group in our research.

We speculate that the introduction of additional (longer) latent oscillations may happen relatively suddenly at certain points in the life span, and they are correlated with other developmental changes at that age. The change in SMT and the unusual pattern of continuation tapping variability we observed for the 8- to 9-year-old age group may be signatures of such a shift. In this interpretation, the onset of a period of optimal sensitivity is signaled by (a) a new (longer) preferred latent period and (b) the expansion of a related entrainment region. These are biological constraints on attending that together promote adaptive (e.g., learning) activities. Perceptual learning in a given sensitive period depends on an expanded range of manifest attentional oscillations surrounding a newly emerging age-specific preferred period (P_0).

This is a portrait of progressive possibilities for entrainment activities over the life span. Theoretically, it realizes environmental–maturational interactions: Maturation constrains the progression of latent oscillations (i.e., P_0 values), whereas the structure of environmental events modulates the resulting set of manifest oscillations (P values) as a function of learning. Although specifics of the growth profile remain to be sketched out, it is possible that the ontogeny of latent oscillations follows a classic growth function known as the logarithmic spiral (Jones & Hahn, 1986; Weyl, 1952). Such a function outlines a progression of expanding periodicities over time (i.e., a lifetime), which is lawful but not uniform.

Traditional views of age-related slowing. The present findings offer a new perspective on age-related slowing. Traditional explanations of cognitive decline have emphasized a general slowing of processing speed during adulthood, as reflected by reaction times; hence, age-related slowing hypotheses address effects of adult

aging in various cognitive tasks (Cerella, 2001; McDowd & Shaw, 2000; Park, 2000; Salthouse, 1996). Thus, the term "age-related slowing" has not applied over the life span because (not surprisingly) children show the reverse reaction time trend during childhood; reaction times increase in speed with maturation until leveling off in adulthood (Kail, 1991). Our entrainment perspective introduces two hypotheses that broaden the discourse on the roles of time and aging.

First, however, it will be important to distinguish reaction time measures, which reflect responding as quickly as possible, from measures, which reflect responding to an event at an appropriate time. These two kinds of measures reflect different entrainment components, which have distinctly different life span trends. Next, we claim that the responding at an appropriate time measure reflects the operation of a preferred period, which lengthens monotonically with increased age, whereas reaction time measures reflect constraints of an entrainment region, namely, stability; influence of the latter is revealed by a curvilinear function over the life span.

Performance in many tasks is likely to involve both components of entrainment. However, in tasks that emphasize speeded cognitive processing, reaction time measures will likely be constrained by entrainment region width and not an individual's preferred period. Indeed, in our research, life span profiles for fast MT and NPR both resemble the curvilinear age-related slowing profile often reported for reaction times in cognitive tasks (Verhaeghen & Salthouse, 1997). In addition, consistent with the idea that cognitive proficiency is related to speeded responding, we found that NPR was the best predictor of cognitive ability. Individuals with higher NAI scores could tap both faster and slower than could those with lower NAI scores. A conventional interpretation of the correlation observed between NPR and NAI holds that cognitive deficits cause a narrowing of accessible event rates. However, correlations are not dispositive of causality. Rather, in accord with Salthouse (1996, 1998), we claim that the reverse may be true, namely, that lower intelligence scores are consequences of limits on attentional accessibility to many rates. People's abilities to precisely synchronize their attention—hence, to track events over a broad range of rates—are reduced with narrow entrainment regions in the very young and very old. Consequently, in these extreme age groups, the ability to synchronously track relevant information is also reduced, leading to cognitive decline.

By contrast, other tasks do not emphasize speeded cognitive judgments, and in these tasks the influence of a preferred period on response times is more evident. Measures associated with the preferred period hypothesis, such as SMT and PPT (from unpaced tapping and perceptual tasks, respectively), reflect people's general tendencies to rely on favored periodicities and to produce well-timed responding to natural events. It is these preferred periodicities that we have shown tend to slow monotonically with increased age.

This task distinction, which derives from our two entrainment hypotheses, has an added advantage of resolving other, seemingly confusing, findings that appear in the time judgment literature. When people must directly judge the duration of a single time interval, as opposed to respond quickly to an arbitrary stimulus, there is mounting evidence that age-related slowing occurs over the entire life span and not just during adulthood (Block, Zakay, & Hancock, 1998, 1999). Although results with adults are mixed

(Lustig, 2003; Lustig & Meck, 2001), recent evidence suggests that relative to young adults, older adults are likely to produce longer periods and to verbally judge the same filled time interval to be shorter (Craik & Hay, 1999). Moreover, younger children, who produce shorter time intervals than young adults, tend to verbally estimate the same time interval to be longer than do young adults (McCormack, Brown, Maylor, Darby, & Green, 1999).

Curiously, these findings from time judgment tasks are puzzlingly at odds with a conventional age-related slowing hypothesis. This is because they favor a general slowing of the speed of an internal clock over the entire life span and not simply during adulthood. A resolution of this conflict builds on our distinction between tasks that favor a preferred period interpretation versus those that favor an entrainment region interpretation. Generally, time judgment tasks favor reliance on a single internal time standard; hence, performance will be affected by an individual's preferred internal period. In judging a given time interval, people tend to rely on internal standards that are closest to their age-specific preferred internal period. Long and short judgments are referenced to this internal periodicity, especially in extreme age groups. Younger children will be inclined to rely on relatively short internal referents; accordingly, they should verbally judge the same time intervals as longer than will older children, whereas the converse should hold for older adults who prefer relatively long internal standards. As we found for continuation tapping, the youngest and the oldest participants should drift toward reliance on favored internal reference periods in these judgment tasks. In sum, these paradoxical findings in life span research are meaningfully recast in light of the two entrainment hypotheses offered here if we distinguish between types of response time measures and different kinds of tasks.

Conclusion

This research yields two major contributions. First, we have established life span developmental profiles for a broad range of ages (4–95 years) for unpaced and paced perceptual–motor tasks over a wider range of rates than has been previously examined. In many ways, children appear to simply operate on a faster time scale than do adults; they reveal this by both their preference to listen to fast sequences and to tap at fast rates and by the constraints these preferences place on their ability to track events over a wide range of rates. Perhaps the most striking evidence supporting this claim is qualitative: In the PPT, one 5-year-old child responded to sequences that were comfortable rates for young adults by claiming they were "way beyond turtle" and then threw the marking block past the slow end of the board. At the same time, for some older adult participants, the same sequences seemed much too fast. Clearly, the internal reference frames for perceiving event timing differed for these individuals at the two ends of the age spectrum. Moreover, although the data reported in this article derive from perceptual–motor tasks, they do not mandate a strictly motor explanation; rather, we think the dynamics of attending and motor behavior are co-constrained with maturation (Semjen & Garcia-Colera, 1986; Thaut et al., 1996).

Second, we provide a plausible theoretical explanation of our findings on the basis of an entrainment theory of life span development of timing and event tracking. Figure 9 provides a conceptual summary of our findings in terms of the two proposed life
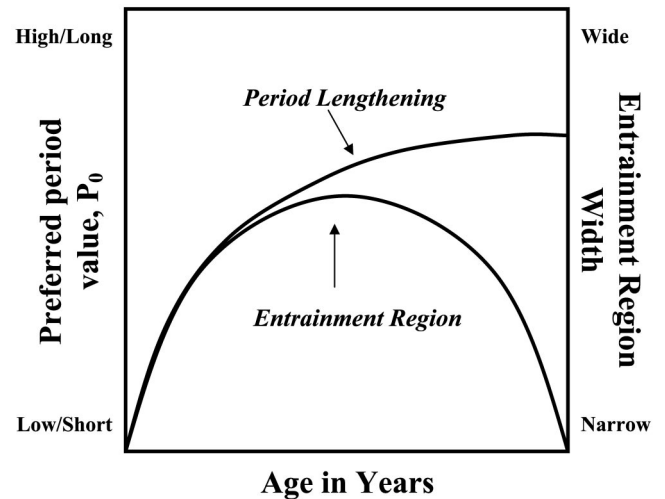
Figure 9. Conceptual trends over the life span implied by the preferred period hypothesis (left ordinate) and the entrainment region hypothesis (right ordinate). P_0 = intrinsic period.

span hypotheses, namely, the preferred period hypothesis and the entrainment region hypothesis. Both posit maturational changes in the way people interact dynamically with their world, but their life span profiles differ. The preferred period hypothesis projects a monotonic increase in preferred periods with age, whereas the entrainment region projects a curvilinear pattern of changes in the width of accessible tempi with age. These hypotheses render distinctly different predictions depending on tasks, measures, and phenomena involved. As a whole, the present research offers strong initial support for both hypotheses.

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