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Development of time

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The young children inherit a brain that is intrinsically adapted to processing the flow of events together with their temporal characteristics, that is a veritable time machine. However, this does not mean that there is no change in timing abilities over childhood. Indeed, the precision of time judgment improves with age and young children's time judgments are highly sensitive to contextual effects. The actual issue is to succeed to dissociate the effects on time judgment that are due to the development of specific time mechanisms from those that result from the development of general cognitive capacities.

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Introduction

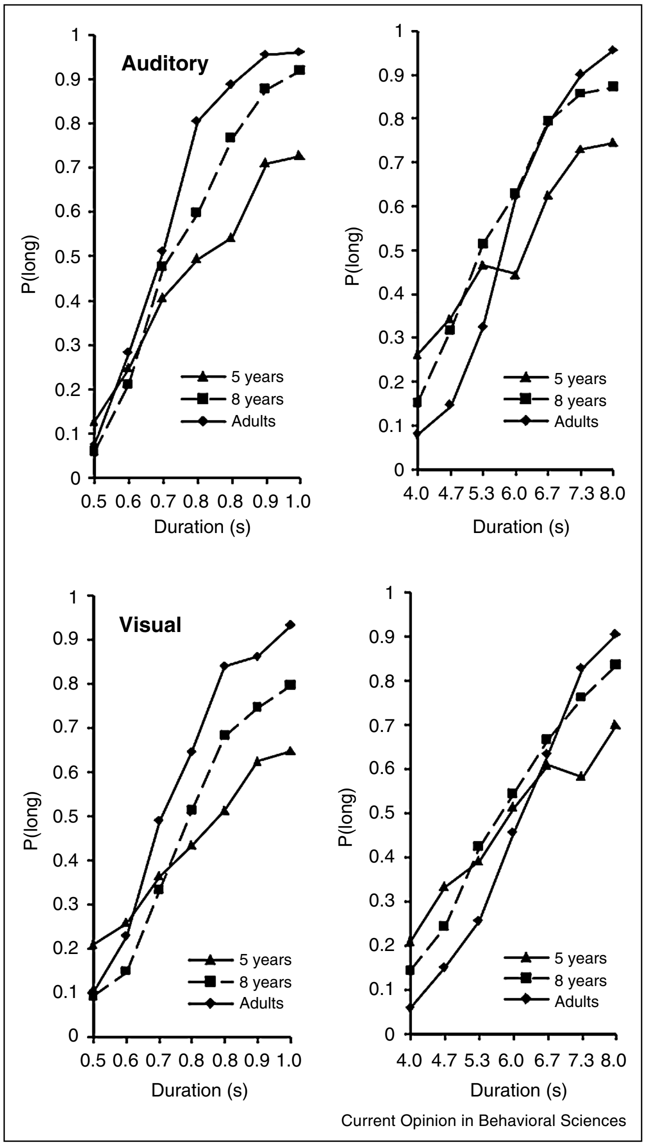
Philosophers and psychologists have long considered that infants are unable to time intervals because time is silent, invisible, and odorless. It does not affect any of our senses. Time is thought of as representation that is acquired throughout childhood and that gives meaning to the world in which we live. However, as the French philosopher Henri Bergson [1] argued, time is not an a priori representation, but the consequence of experience. There is 'a pure intuition of durations', that is a sense of time. Indeed, the infant lives in a dynamic world where all is temporal. Each event, each behavior unfolds in time. A recent study has shown that, some hours after their birth, neonates are already capable of detecting a difference of just a few seconds between event durations [2••]. They thus inherit a brain that is intrinsically adapted to processing the flow of events together with their temporal characteristics, that is a veritable time machine [3]. However, this does not mean that there is no change in timing abilities over childhood. Numerous studies have shown that the precision of time judgment improves with age and that young children's time judgments are highly sensitive to contextual effects. However the development of timing abilities arises from multiple factors, such as brain maturation, experience of the temporal regularities of events, or the emergence of conscious awareness of the passing of time. The actual problem of studies is to succeed to dissociate the effects on time judgment that are due to the development of specific time mechanisms from those that result from the development of general cognitive capacities.

Development of timing capacities

In the first months of life, babies are able to learn the temporal structure of rhythmic sequences of events (speech, maternal behavior) and react to the slightest temporal violations within the expected temporal structure [4–6]. Infants can also discriminate two simple stimulus durations that differ by a ratio of 1:2 or more at 4–6 months and by a smaller ratio of 2:3 at 10 months [7–9]. Furthermore, the scalar properties that are characteristic of timing in adults — mean accuracy and increased variability of time estimates as a function of stimulus duration — have been found at all ages, from 3 to 8 years [10•], and recently even in infants from 4 to 14 months [11•]. The early emergence of the fundamental properties of timing and their stability across ages demonstrates that the brain is equipped with a system for the processing of time intervals as of birth.

The fact that this timing system is functional as of a young age does not mean that there is no developmental change in the way it works. The use in our laboratory of the same temporal discrimination task (bisection) for participants from a wide range of age groups, from 3 to 25 years, has highlighted three main results on the development of timing [10•,12]. Firstly, at all ages, timing is accurate on average (mean accuracy). In bisection, there is indeed no age-related difference in the location of the point of subjective equality (PSE). However, in some conditions, the PSE shifts toward the right in very young children, a finding that is consistent with the idea of a shortening of perceived durations. Secondly, unlike mean accuracy, sensitivity to time (variance) systematically improves with age. This improvement nevertheless occurs earlier in the auditory than in the visual modality (Figure 1) [13]. Time sensitivity reaches an adult-like level at about 8–9 years. Some age differences in time judgment nevertheless persist in more difficult tasks, for example when a smaller ratio (<1:2) is used between the anchor durations (Figure 2) [14•], as well as with very short (<1 s) or very long (>8 s) durations (Figure 3) [15]. Thirdly, in the case of explicit temporal tasks similar to those used in human adults, children's time judgments are highly sensitive to

Figure 1

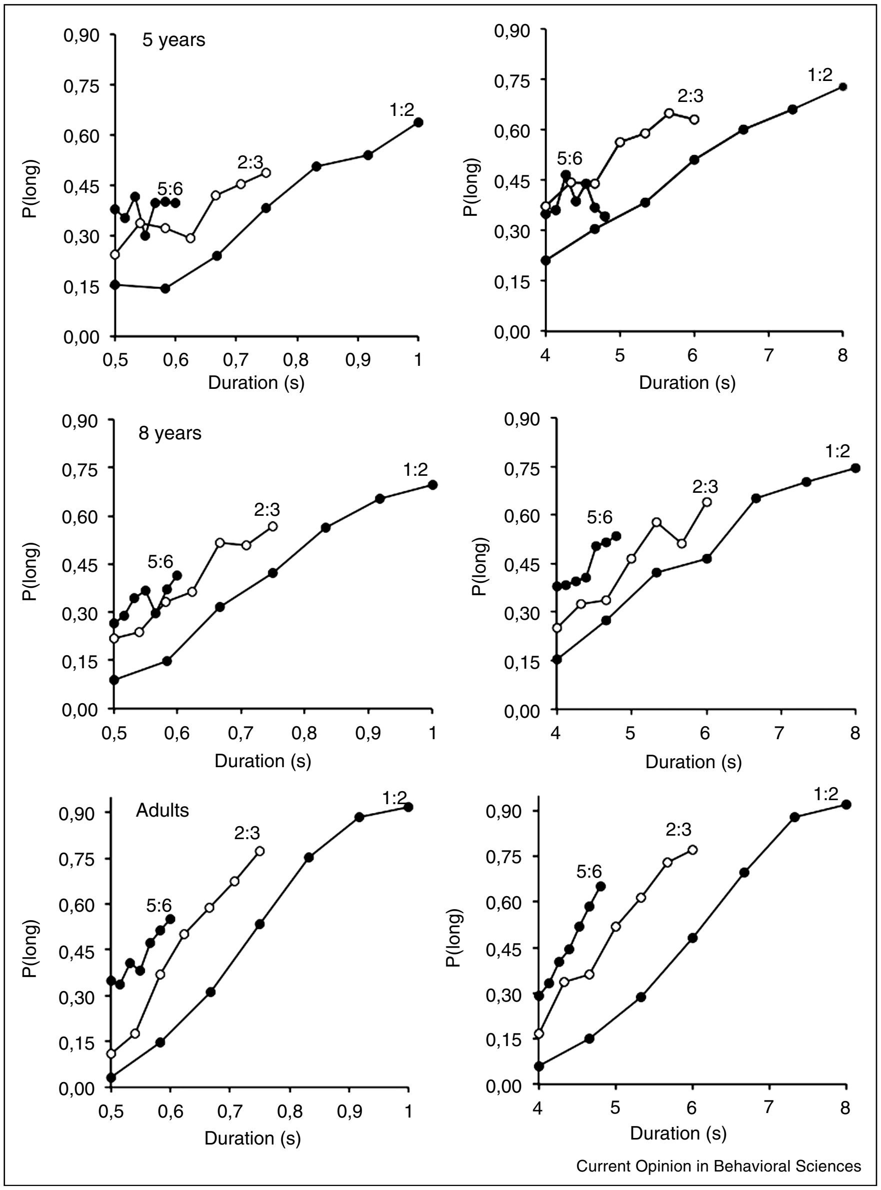


Temporal bisection in auditory and visual modality. Proportion of long responses plotted against stimulus durations in auditory and visual modality for the short (0.5/1.0 s) and long (4.0/8.0 s) durations, for the 5-year-olds, the 8-year-olds and the adults.

interference from non-temporal information (movement, light intensity), with the result that their time perception is greatly distorted and they are sometimes unable to discriminate time. However, the development of the conscious awareness of the passage of time promotes the self-control of the attention devoted to the flow of time as well as resistance to interfering effects.

The main question is: what causes the age-related increase in time sensitivity? According to scalar expectancy theory (SET) [16,17], time judgments are determined by a series of successive stages in temporal information processing. The first stage, called the clock stage, is dedicated to the reading of time. The second stage involves mnemonic processes whose purpose is to keep the perceived duration active in working memory and to store relevant durations (standard durations) in long-term memory. Finally, in the third decision stage, the current duration is compared with the standard durations in order to make a time judgment. In this theory, each component of time processing contributes to time judgment. A poor temporal judgment can thus result from downstream cognitive processes in the clock system. For example, the sense of time has often been described as deficient in patients with autism spectrum disorder (ASD) [18]. However, recent studies have not shown any deficiency in duration discrimination capacities in ASD children with normal intelligence [19]. Consequently, their failure is due to deficits in executive functions required in the temporal tasks used rather than to a specific timing deficit. One major problem in the investigation of inter-individual differences in timing abilities is that researchers have often used temporal tasks without further examining the cognitive capacities required for each task. It is therefore difficult to identify what causes age-related differences in the judgment of time, since cognitive abilities (working memory, attention control) also develop throughout childhood. Recently, using a series of neuropsychological tests, Droit-Volet *et al.* [20••] assessed cognitive capacities in adults and children aged 5 and 8 years, all of whom performed three different temporal tasks: bisection, generalization and reproduction. The results reveal that the time judgments of 5-year-old children are poorer in certain tasks than in others because these tasks require more cognitive resources. Time distortions were observed in the temporal reproduction task but not in the temporal discrimination tasks. Indeed, time estimates in reproduction directly depend on individual working memory capacities and information processing speed. The slower programming of the motor response in young children also explains their longer reproduction of short durations (<1 s) [21]. Moreover, a large portion of individual variances in the precision (variability) of time judgments is explained by working memory capacities in all temporal tasks, and in particular the individual scores on the attention/concentration test of the Children's Memory Scale, which requires the dynamic/continuous monitoring and updating of the content of working memory. However, the best predictors of individual temporal differences in the generalization task are attention control abilities (selective attention, inhibition), and those in the reproduction task information processing speed and working memory. In sum, these two temporal tasks appear to be more difficult for children than the bisection task because they require more cognitive resources. A large proportion of the age-related differences in time judgment therefore derives from the cognitive capacities required by the temporal task used.

Figure 2

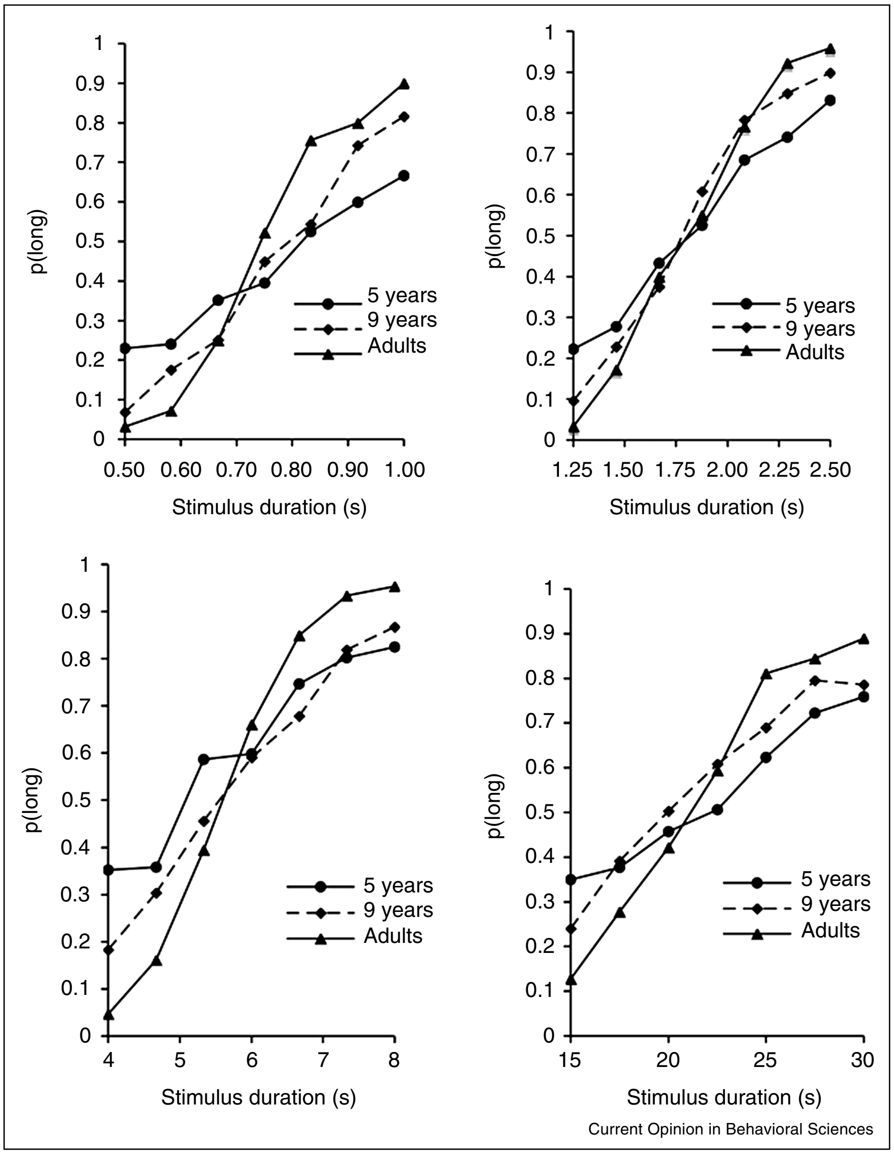


Temporal bisection with different ratios between anchor durations. Proportion of long responses plotted against stimulus durations with a ratio of 1:2, 2:3 and 5:6 between the anchor durations for the short (0.5/1.0 s) and long (4.0/8.0 s) durations, for the 5-year-olds, the 8-year-olds and the adults.

Memory, decision and attention

The SET suggests that the major source of variance in time judgment does not come from the clock system *per se*, which provides an accurate representation of objective time, but from a later stage in time processing: memory or/and decision-making. Obviously, the computational models that have been derived from the SET account well for the developmental data and highlight the critical role of downstream processes in the clock system [10•,12]. Younger children do indeed produce more random responses. Their representation of time in reference memory is more variable and fuzzy, and they are more conservative in their judgments because they are less confident in their responses in ambiguous cases (e.g. close to the PSE). As far as reference memory is concerned, behavioral studies have shown that the memory traces of durations decay more in memory in children than in adults when a retention interval is introduced between the encoding of time and its remembering, thus resulting in a greater shortening (greater loss of information) [22,23]. Consistently with this result, the neuropsychological studies have shown that the shortening effect

Figure 3



Temporal bisection for different duration ranges. Proportion of long responses plotted against stimulus durations for 4 different duration ranges (0.5/1.0 s, 1.24/2.5 s, 4.0/8.0 s, and 15/30 s) for the 5-year-olds, the 8-year-olds and the adults.

increases as short-term memory span decreases [14•,15]. However, this retention interval also increases the variability of time judgments and does so to a larger extent in younger children. In addition to the passive maintenance of temporal information in short-term memory, there is therefore also an active process by which traces are updated in memory. Recent working memory models suggest that the refreshing of information in memory requires attentional effort that is difficult for young children to produce due to their limited attentional control capacities [24]. In addition, unpublished data suggest that the representation of standard durations in reference memory seems to be contaminated by other durations presented within the task session due to children's difficulties in shifting from one duration to another between trials.

In sum, developmental data show that a proportion of the individual variance in temporal judgment is determined by memory and decision capacities. However, it is also recognized that the development of attentional capacities plays a crucial role in time processing, although this question has not been extensively examined in typically developing children. A large number of studies have indeed revealed low accuracy and precision in timing behaviors in children and adults with attention-deficit hyperactivity disorder (ADHD), which is characterized by dysfunctions in prefrontal cortex or/and fronto-parieto-cerebellar network [25,26]. In line with this finding, neuroimaging studies in humans have detected an activation of the dorsolateral prefrontal cortex during both timing and attentional tasks [27,28]. Furthermore, it is now clearly established that the prefrontal cortex matures slowly and reaches maturity in young adulthood [29]. Consequently, the development of different components of attentional control, which is incomplete in young children, goes a long way to explaining their difficulty in judging time correctly. For example, by manipulating cues alerting subjects to an imminent visual stimulus, Droit-Volet [30] demonstrated that the time required to initiate time processing (attentional switch closure) is longer and more variable in younger children. Similarly, in a dual-task paradigm, the shortening effect observed when attention is diverted away from time processing appears to be larger in young children [31,32]. The presence of distractors also increases time distortions and decreases temporal precision in young children more than in adults because the former are not able to produce the continuous attentional effort needed to resist distractors [33].

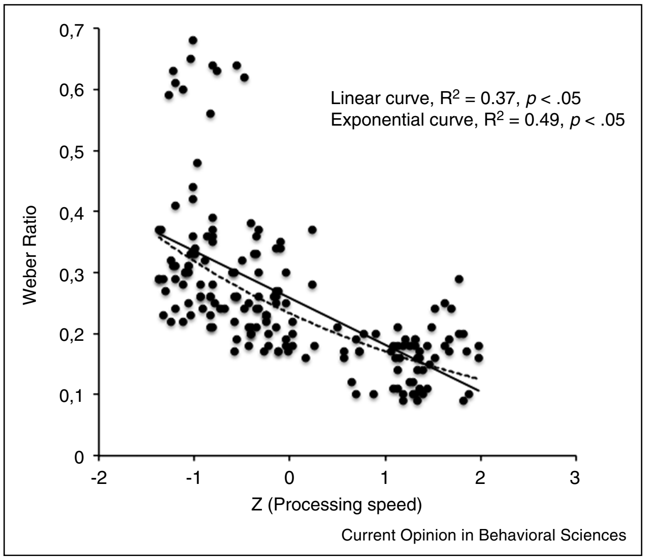
This is consistent with the finding that most non-temporal information interferes considerably with children's time judgments. As far as numerical and spatial interference are concerned, some researchers suggest that this reveals the existence a general system for all magnitudes, including time [34]. However, repeated experience of correlations between different dimensions (a greater number of events takes more time) does not mean that we can reject the idea of a dedicated mechanism for time, even though the magnitude systems may be linked and gradually become integrated during childhood [35••]. Whatever the case may be, the interfering effects of non-temporal information sometimes appear to be so strong that children are unable to pay attention to time. Consequently, although this has not been directly tested in children, it is easy to assume that the development of consciousness of the passage of time provides a conceptual framework that helps them to maintain their attentional focus on time. Recently, Droit-Volet *et al.* [36] showed that timing is indeed more accurate in people who are aware of being susceptible to time distortions. In sum, general cognitive capacities related to memory, decision-making and attention contribute to individual variations in time judgment, thus demonstrating their critical role in timing in the temporal tasks used in human beings. However, the specificity of attentional processes is that they produce noise and distortions in time processing at an early stage, that is at the clock level.

Developmental changes in clock functioning?

Contrary to the assumptions of the SET, one major source of noise in time judgment also originates in the clock system itself. However, at the clock level, it is difficult to dissociate the temporal effects produced by variations in the functioning of the clock *per se* from those produced by the flickering of the attention-controlled switch. According to the SET, the clock system is composed of a pacemaker, an attention-controlled switch, and an accumulator [16]. The pacemaker regularly emits pulses that are transferred into the accumulator via the attentional switch, which closes and opens at the onset and the offset, respectively, of the stimulus to be timed. Consequently, an increase in the clock speed and a reduction in switch flickering produce the same multiplicative effects on time estimates: a lengthening effect (number of accumulated pulses) that increases with lengthening duration. Nevertheless, it is possible, at least at the theoretical level, to distinguish between these mechanisms. The recent models of the internal clock, which claim to be more biologically realistic, have replaced the idea of a pacemaker with that of temporal oscillators [17,37,38]. According to the Striatal-Beat-Frequency model [39••], the coding of time is ensured by a subset of cortical oscillators (interconnected neurons with their own frequency) that are distributed in the brain and synchronized at the onset and offset of the duration. There is probably a single, unique configuration of oscillatory activity etched in the brain for each event duration. This, incidentally, would also account for young children's difficulty in transferring a particular duration learned with one action to another action [40]. The striatum in the basal ganglia, which receives numerous inputs from cortical and thalamic units, detects the coincidence of the oscillatory pattern associated with an event. Consequently, attention-related effects (e.g. interference) can affect the onset of the synchronization of oscillators, or produce a desynchronization in the oscillatory pattern. In contrast, the clock-speed effects can result in changes in the dynamic of the oscillators and the connections between them. Low sensitivity to time in children as the result of a noisy or less efficient clock system would therefore stem from low oscillatory frequencies, a broader network of less integrated oscillators (less focalized), and poor oscillatory synchronization.

However, there is as yet no direct behavioral evidence of age-related changes in the functioning of the clock system *per se*, thus suggesting that temporal development in human beings primarily involves the emergence of more diverse forms of temporal judgment that are made possible by the development of cognitive capacities, the acquisition of explicit knowledge or the introspective awareness of time. Some studies in animals and human adults have nevertheless manipulated the clock speed by injecting participants with dopaminergic drugs (methamphetamine, cocaine), or by presenting highly arousing emotional stimuli or trains of auditory clicks, which are believed to affect the frequency of brain oscillations [41,42]. Three bisection studies have tried to do replicate this approach with subjects aged from 3 to 25 years by

Figure 4



Time sensitivity and information processing speed. Significant correlation between Weber ratio and *Z*-scores on information-processing speed test.

using emotional stimuli [43,44] and a train of auditory click (8 Hz) [45]. In all these studies, time was systematically judged to last longer when the clock speeded up, even in the case of the youngest children. This demonstrates that this manipulation of the clock speed has an automatic and immediate effect on time estimates. However, no age-related difference in the clock-speed effect was observed. Consequently, the hypothesis of a slower, noisy internal clock in children has not as yet been experimentally validated, even though its existence seems probable. Ultimately, the problem is to find a method sensitive enough to detect clock effects at the behavioral level for different individual clock rates.

Recently, Droit-Volet and Zelanti [46••] showed a strong correlation between the increase in information processing speed across ages and improvements in time sensitivity (Figure 4). The scores on tests of information processing speed may constitute an indirect measure of clock frequency. As stated by Rammsayer and Brandler [47], the higher the frequency of neural oscillators, the finer the temporal resolution of the internal clock. More than 40 years ago, Survillo [48] established a link between neural oscillations and information processing speed: the faster the alpha rhythm, the faster information processing is. As the neural circuits mature, electrical brain activity in children changes from birth through to adolescence, with an increase in alpha frequencies (8–12 Hz) and a decrease in theta frequencies (4–8 Hz) [49]. Brain maturation also results in better synchronization between neuronal groups, with EEG coherence increasing up to the age of 5 years in the posterior-anterior direction, and up to 14 years for shorter distances [50]. In sum, the age-related changes in information processing speed may be an indirect index of the improvement in the efficiency of the timing circuits involved in the encoding of time.

However, the studies conducted in children have also shown that scores on information processing speed tests are strongly correlated with those on working memory tests. Furthermore, and as suggested above, the working memory scores reported in all neuropsychological studies of children subsume significant individual differences in sensitivity to time. Recent research into the dynamics of cognitive processes suggests that the functioning of working memory is based on the synchronization of neural oscillations in a way similar to that assumed by the SBF model with reference to time [51]. Finally, timing and working memory processes are intrinsically related, and this makes it difficult to identify the mechanisms that are specific to time [52••]. However, working memory cannot be thought of simply as an accumulator incremented by the rhythm of incoming information (clock speed). It is also necessary to consider the continuous integration of incoming information, as well as their maintenance and update in short-term memory. Therefore, the challenge for the future is to further examine the mechanisms shared by working memory and the clock system and those specific to each system. This can be done by comparing time and continuous or discontinuous non-temporal dimensions in order to identify the extra something that is required for time processing, in other words, to answer the question 'what is time'?

Conflict of interest statement

Nothing declared.

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This exciting review discusses the properties of interval timing and working memory, and proposes an extension of the striatal beat-frequency model suggesting that these 2 systems can originate from the same oscillatory processes.