**Abstract.** During the decades following Piaget’s work, it has been believed that correct judgments of durations require sophisticated reasoning abilities that emerge at about 8 years of age. However, a number of researchers have demonstrated that young children's poor judgments in classical Piagetian tasks are not due to their inability to judge time correctly, but rather to their limited attentional capacities. Recent research has therefore concentrated on further investigating the development of abilities to discriminate durations in young children on the basis of the temporal tasks initially used with animals within the framework of the internal clock theories. This manuscript reviews and discusses the results of these studies.

**Keywords:** Child; Time Perception; Timing; Attention

**1 Introduction**

*“What is real time unless it is time which has been or could be experienced.”*  
*Bergson (1968)*

What is time really? Time is what my watch shows me, most men and women would reply. And what does this watch show you? The movements of a hand about an axis. So time is movement! And do humans confuse time with movement, then? But time cannot be reduced to the way we measure it. The distance traveled that we read from our watches is only one representation of time among others invented by human beings in order to be able to measure its passing with precision. So what, truly, is time? What, after all, does it matter what time is, what does it matter whether it exists or not? If we experience it then, psychologically, it exists. As Bergson [1] says, “time is purely and simply an item of data relating to our experience… and we want to hold onto that experience”.

By adopting this postulate, psychologists have left the debate about the true nature of time to philosophers and physicists so that they, for their part, are free to try to study its psychological reality through the feelings and behaviors of human beings in the face of time. As a result, they have been led to ask a number of questions. If time exists at the psychological level, why should children, who have no sophisticated representation of time, not also be capable of precise temporal estimates? Is there a
"primitive sense" of time? What neurological mechanism is responsible for this sense of time? If such an internal mechanism for measuring time exists, then why and under what conditions do young children find it difficult to estimate time correctly? How can we explain the illusions to which they are frequently subjected in which time stretches and contracts as the context changes? Are they due to a specific problem in measuring time or to a more general cognitive problem? Over the last twenty years, this series of questions has reawakened considerable interest in the study of time. Nevertheless, due to methodological reasons, which are fairly easy to understand, studies of time estimation behaviors in children are still quite rare. We shall, nevertheless, attempt to summarize the most recent work conducted in this field by focusing on the behaviors involved in the estimation of durations in tasks similar to those employed in animals. As the young philosopher, Jean-Marie Guyau [2], said in his essay on the genesis of the idea of time, it is in the expectation and frustration of the child who cries as he stretches out his arms to his nurse that the idea of the future, the idea of time, is born.

2 The Pioneering Studies of Time Estimation Capabilities in Children

The work conducted by Jean Piaget has greatly influenced studies of child psychology in a number of different fields. In his constructivist theory of children’s intellectual development, Piaget described how young children explore their environment by means of their senses and actions. The primitive understanding of the physical world, therefore, appears to be grounded in sensorimotor knowledge. It is only at the transitional period of 7-8 years, when children accede to the concrete operational stage, that they think logically and manipulate the symbolic representations, which enable them to solve complex problems. As far as duration is concerned, Piaget’s theory consequently considers that young children are unable to evaluate time accurately since their time judgments are derived from their feelings concerning their internal states or from their sensorimotor experience. For example, children estimate durations as a function of the quantity of work accomplished or effort produced. Children, who were asked to transfer lead disks or wooden disks to a wooden box for a given period, thought that the task of transferring the lead weights took longer than that of transferring the wood because it required greater effort [3]. Numerous studies which have varied the nature of the non-temporal information (e.g., number of changes, speed, light intensity) presented during the period to be estimated have confirmed that young children initially estimate durations as a function of their content [4,5,6,7,8]. However, children’s ability to estimate time accurately emerges earlier than these pioneering psychologists thought. In most cases, the estimation of time does not require logical reasoning about time. As we will see below, infants with only limited conceptual capacities are able to estimate time. Finally, the fact that children distort time in certain conditions does not mean that they do not possess a basic time discrimination capability. The question is to determine the contexts in which children’s time judgments are or are not accurate and why?

When only a small number of cues are used or the duration of events is familiar, children's temporal estimations improve [9,10,11,12]. This finding led Fraisse [13] to
suggest that children's time estimates may be based only on a single cue. In other words, if children are to process time correctly, their attention must not be distracted by non-temporal information. Their attention must be to focus on time. They must be aware of the relevance of time. Pouthas, Droit, Jacquet, and Wearden [14] showed that children younger than 10 years of age, although with some exceptions at 7 years, did not spontaneously think about the temporal features of a task. That is why the temporal instructions given by adults play such an important role in the establishment of temporal behavior in young children. In a temporal operant conditioning situation, in which the responses were reinforced after a fixed interval of 30 s (FI), Droit, Pouthas, and Jacquet [15] showed that 60% of children aged from 4 to 6 years exhibited erratic response patterns when given minimal instructions, but succeeded in regulating their time-related behavior as soon as they were given temporal instructions.

When temporal behaviors are governed by verbal rules or when participants have to be aware of time in order to process it accurately, we talk about the explicit processing of time. A fundamental distinction must be drawn between the implicit and the explicit processing of time [16]. The former is involved in the processing of short durations, in motor timing as in the case of finger tapping, in time conditioning and in implicit temporal learning involving multiple trials and a long series of sessions such as those used in studies in animals. The latter is mainly involved in the processing of longer durations, in the judgment of new and unpredictable events, and in temporal tasks involving smaller numbers of trials. Precisely, most of the experiments conducted in human adults have used instructions and a small number of trials. The presented events are often new and the participants are not exposed to any repeated experience of their durations. In addition, as noted by Zakay [17], in real life, time is rarely relevant for an optimal adaptation to the environment. Finally, humans frequently make explicit judgments, with the result that accurate time judgments may well be the exception rather than the rule. Moreover, human adults use counting strategies because they are well aware of the inaccurate nature of their temporal estimates in most situations. To summarize, because the majority of the employed experimental conditions have used an explicit judgment of time, human subjects, and children in particular, have often been found to not judge time accurately. Their time estimations are distorted and they judge durations to be shorter or longer than they actually are. Consequently, time judgments in humans cannot be reduced to the reading of a sort of internal clock. As suggested by grounded time theory [18,19], time judgments are also derived from affective states and sensorimotor experiences. This is why, in our description of the development of time-related knowledge, we talk in terms of "multiple time" in the case of younger children and "unique time" when referring to children older than 7 years [20,21,22]. This “multiple time” takes the form of items of temporal knowledge specific to each event duration experienced in a particular context. In contrast, “unique time” reflects an awareness of a homogeneous time, which is independent of context, i.e., the concept of time referred to by Fraisse [13]. However this may be, after the work of the early psychologists had shown that children’s temporal judgments are context-dependent, the main aim of the next generation of psychologists was to find empirical data demonstrating children’s ability to estimate time accurately.
3 Temporal Conditioning

In order to find empirical demonstrations of children’s ability to estimate time accurately, psychologists have employed the same temporal tasks that have been successfully used to investigate timing in animals. First of all, they adapted temporal conditioning paradigms with arbitrary temporal intervals, which do not correspond to any biological rhythm, for use in children. The most frequently cited study in this domain is the study of the classical conditioning of an autonomic reflex (pupillary dilation and constriction) conducted by Brackill and Fitzgerald [23] in 1 month old infants. In this study, a 4 s change in lighting conditions (light offset or light onset) occurred at a constant temporal interval (20 s; unconditioned stimulus, UCS) and was systematically found to produce a pupillary reflex (UCR). During the test trials when the UCS was not applied, the infants’ pupils continued to contract or dilate. This clearly demonstrates that the infants had perceived the passage of time during the interval. The evidence relating to the temporal conditioning of heart rate responses and their deceleration in anticipation of the UCS is somewhat weaker [24]. However, Colombo and Richman [25] recorded the heart rates of 4-month-old infants during the repetitive presentation of a 2 s stimulus at an interval of 3 or 5 s, and observed a deceleration in the infants’ heart rates each time the stimulus was omitted. These different findings are consistent with the observations of Brannon and co-workers [26,27] who found that the brain activity of 10-month-old infants exhibited a change in negative polarity (mismatch negativity) amplitude when a temporal deviation occurred in a stream of tones produced at a regular 1500 ms interstimulus interval.

For a regular or rhythm temporal structure of stimuli, if infants are able to predict the occurrence of a stimulus at a precise temporal interval, then we can conclude that they have perceived the temporal regularity of events.

Faced with these findings showing that children are able to anticipate the temporal occurrence of events, researchers have used operant conditioning procedures to attempt to examine whether young children are also able to regulate their temporal behavior. Viviane Pouthas [28,29] used a Differential Reinforcement of Low response rate (DRL) schedule, replacing the lever in the Skinner box by a large red button and the food by slides displayed on a screen. In this experimental condition, when children aged of 2 to 5 years had to delay their responses by a given period in order to see a slide, some of them succeeded in spacing their responses at a given temporal interval (DRL 10 or 15 s). However, most of them failed to withhold their responses. The fixed-interval schedule of reinforcement (FI) has been tested in an attempt to overcome this problem of behavioral inhibition in young children. In contrast to the DRL, the responses produced during the fixed temporal interval have no consequence in FI. In this condition, some of the children aged from 4 to 7 years exhibited a low or a high rate of responding, i.e., they either waited for the required temporal interval before responding or they pressed the button constantly [15,30,31,32]. However, as in the DRL, most of the children produced erratic patterns when they did not receive any explicit temporal instructions, even after 10 training sessions [15,32,33]. It is very regrettable that the poor performances achieved by children are not always reported in the literature given that they illustrate a behavioral reality at a given age. Indeed, within the framework of operant temporal conditioning, young children’s poor
performances can be explained in terms of the difficulty they experience in preventing themselves from responding rather than on the basis of a specific timing deficit. It is well known that young children have limited motor inhibition capacities [34]. Moreover, temporal regulation in children has been found to improve when they are kept busy and engaged in motor activities (collateral activities) during the waiting period [29, 35]. Droit [36] compared two schedules of temporal reinforcement, one in which 3-year-old children had to produce a given temporal interval between two button presses (DRL 5 s) and the other in which they had to keep the button pressed down for a critical duration (differential reinforcement of response duration, DRRD).

In both conditions, an external clock indicated the target duration over a total of four training sessions. During the four test sessions that followed, only the children in the DRRD condition succeeded in producing accurate timing responses. In the DRRD condition, some 3-year-olds even reported that they had pressed hard on the button while they were timing their responses. The inhibition of motor responses is thus a critical factor in the emergence of temporal behaviors in children.

Finally, it is in infants that temporal performance in FI seems to be the best. Lowe, Beasty, and Bentall [37] reported examples of infants who were able to wait in an FI condition. More precisely, the response pattern they produced was similar to that observed in animals, i.e., a pause followed by a progressive increase in responses through to the end of the fixed interval. More surprising still, Darcheville, Rivière, and Wearden [38,39] observed low-rate patterns of responding in infants aged from 3 to 23 months for different FI values ranging from 10 to 80 s. The infants made long pauses that were appropriate given the duration of the fixed interval. They then touched the touch-sensitive screen to obtain reinforcement [40]. Taken overall, these results obtained in children by means of temporal conditioning procedures reveal that very young children can implicitly learn temporal intervals or event durations and adjust their temporal behavior accordingly. Consequently, one of the major challenges involved in the development of time discrimination abilities is to find an experimental task that can be used both in verbal and non-verbal children, i.e., at all the levels of the ontogenetic scale.

4 Early Ability to Discriminate Time in Bisection: Weber’s Law Holds!

After many attempts to use temporal conditioning procedures, simpler temporal discrimination tasks similar to those used in animals have been tested in children, namely the temporal generalization task [41,42,43], and the temporal bisection task [43,44]. Of these tasks, the one that has been most frequently used is probably the temporal bisection task [45]. This task was originally used in rats by Church and Deluty in 1977 [46]; and was then adapted for use in human adults by Allan and Gibbon [47] and Wearden [48]. In this task, the participants are presented with two signal durations: a short (S) and a long (L). In the test phase, they are then presented with comparison durations, which are either equal to S and L or have an intermediate value between S and L. The participants must either categorize the comparison
durations as short or long [47] or judge whether these durations are more similar to the short or to the long standard duration [48]. In addition, some studies have also provided feedback for the two anchor durations during the test phase [47,49,50] while others have not [51,52,53]. Despite these experimental variants, the psychometric functions obtained in bisection in human adults are close to those observed in animals. The proportion of comparison durations judged as more similar to L (p(\text{long})) systematically increases with the stimulus duration value. According to Church and Deluty [46], the results obtained in bisection in rats suggest “that they have some sort of internal clock that they can read” (p. 223). Consequently, Wearden [48] concluded that humans possess an internal clock that is in many ways similar to that found in animals.

We recently succeeded in adapting this temporal bisection procedure for use in infants as young as 4 months old [54]. During a training phase, the infants were presented with two sounds, namely a short (0.5 s) and a long sound (1.5 s). They were then trained to look to the left after S and to the right after L (counterbalanced order), with a correct response resulting in the appearance of a picture on the side toward which the infant had looked (left or right; reinforcement). During the test phase, the infants were presented with S and L and sound durations of intermediate values (750, 1000, 1250 ms). In this phase, S and L were followed by reinforcements either immediately or after a 3 s interval. The first look to the right, to the left or elsewhere, and the time spent by the infants looking in these directions for a period of 3 s following the sound were recorded. As shown in Figure 1, in this bisection procedure, the infants exhibited orderly psychometric functions with p(\text{long}) increasing with the stimulus duration (i.e., they looked to the right for longer after L). This indicates that they were sensitive to changes in sound durations. In addition, in bisection, three indexes of temporal performance are calculated: the Bisecti\text{on Point} (BP), the Difference Limen (DL), and the Weber Ratio (WR). The BP is the point of subjective equality, i.e. the stimulus duration (t) that gives rise to p(\text{long}) = .50. The DL is the just noticeable difference (t(p(\text{long}) = .75) - t(p(\text{long}) = .25) /2), i.e., the smallest change in stimulus durations that is detected and produces a change in behavior.
The WR is the DL divided by the BP. Participants with a low WR exhibit a fairly high sensitivity to change in duration and produce very steep psychometric functions in bisection tasks. In contrast, participants with a high WR exhibit variable temporal discrimination capabilities. In others words, their sensitivity to time is poor, and their psychometric functions particularly flat. In our study, the infants obtained a BP of 860, a value which was closer to the geometric mean ($\sqrt{S \times L}$) (GM) than to the arithmetic mean ($S + L / 2$) (AM) of the two anchor durations (500/1500). In addition, their WR was .32, thus indicating that they could discriminate differences in durations of 275 ms. This finding is consistent with the results obtained by means of a habituation paradigm in 6-month-old infants by VanMarle and Wynn [55] and by Brannon, Suanda, and Libertus [56]. These authors showed that the infants looked longer at the same event (Sylvester the cat moving his head from right to left during a sound, in one study, and a cow puppet opening and closing its mouth in the other) when its presentation duration varied by a ratio of 1:2 regardless of the absolute value of the durations tested (i.e., 0.5 vs. 1 s, 2 vs. 4 s and 1.5 vs. 3 s).

In addition, to account for the infant data obtained in bisection tasks, we modeled their data using the mathematical models proposed by the Scalar Timing Theory [57,58], namely the Sample Known Exactly (SKE) model developed by Gibbon [59] for animals and the Difference Modified (DM) model developed by Wearden [48] for human adults. These two models use the same parameters. They differ only in the
type of decision rule employed. In the DM model, this decision rule is based on
differences, whereas in the SKE model it is based on ratios. The DM model responds
long if \( |S^*-t| > |L^*-t| \) and short if \( |S^*-t| < |L^*-t| \). In contrast, the SKE model responds
long if \( (L^*/t) < (t/S^*) \), and vice versa. It appears that the modified SKE
model fits the data observed in infants better than the DM model, while the reverse
appears to be true for older children [44]. This finding is explained by a smooth age-
related rightward shift in the localization of the BP from a value close to the
geometric mean to a value closer to the arithmetic mean of the two anchor durations,
although a BP at the GM has also been observed in older children in certain
experimental conditions [60]. The BP has systematically been found to be close to the
GM rather than the AM of \( S \) and \( L \) in animals [46,61,62], while, with only a few
exceptions [47], it has regularly been found to be closer to the AM than the GM in
human adults. The development of decision processes is thus a major factor that may
explain age-related changes in the establishment of the BP [63,64]. In addition,
Wearden, and Ferrara [65,66] have demonstrated that the localization of the BP is
mainly determined by the ratio between the two standard durations. A small ratio (<
1:2) - when it is not easy to distinguish between \( S \) and \( L \) - shifts the BP from the AM
to the GM of \( S \) and \( L \). We can thus assume that infants find it more difficult than older
children or adults to bisect durations that differ by a ratio of 1:3. Using a habitation
paradigm, Brannon et al. [56] showed that 6-month-old infants were able to
discriminate two durations that differed by a ratio of 1:2 ratio (1.5 vs. 3 s) but not of
2:3 (1 vs. 1.5, 2 vs. 3 s) while older infants aged 10 months succeeded in both
conditions. Furthermore, in our temporal bisection model, which enables us to
account for infants’ bisection performances, we found it necessary to add a parameter,
which corresponds to the probability of producing a random response on each trial,
irrespective of the stimulus duration. In particular, this parameter explains the high
proportion of long responses for the shortest comparison durations. We can therefore
conclude that the clock system that is thought to be responsible for the perception of
time in animals and human adults is probably functional at an early age. However,
infants’ ability to discriminate time is often masked by the high proportion of random
responses that are produced. This is probably due to the inattentiveness of the subjects
or to the experimental procedures used which, despite all the experimental ingenuity
shown by researchers, rapidly become boring for young children.

Studies conducted in older children which have used a wide variety of durations,
both shorter (0.2/0.8; 0.15/1.05; 0.5/1; 0.4/1.6 s) [43,67,68,63] and longer than 1 s
(1.25/2.5; 1/4; 2/8; 4/8; 4/10; 8/20; 15/30 s) [44,60,69,70,71], and which have
primarily involved a ratio of 1:2 or 1:4, have obtained orderly psychometric functions
from children in all age groups, from 3 to 10 years. At all ages, these children detect
the differences in stimulus durations and the probability that they will respond long
varies in consequence. This observation, however, applies to duration ratios \( \geq 2:3 \)
(Zélanti & Droit-Volet, in preparation). In the case of smaller ratios (3:3.6), 30 % and
45 % of 5-year-old children, respectively, succeeded in producing quite orderly
psychometric functions with a short (0.5/0.6 s) and a long duration (4/4.8-s), while 80
% and 95 %, respectively, of children aged 8 years succeeded in these two duration
conditions. In addition, according to the scalar properties of timing, which have
received widespread confirmation both in animals and human adults, time estimates are
accurate on average, while temporal sensitivity also remains constant as durations
vary [72]. This is exactly what we have found in children of different ages [41,44,67]. Children's temporal behaviors conform perfectly to the scalar property of variance. Two methods are currently used to test this property. The first consists in calculating the WR, which is itself a sort of coefficient of variation (SD/M), and verifying whether it remains constant with different durations. The second consists in testing the superposition of the psychometric functions when plotted on the same relative scale. We found that children’s WR remained constant with different durations and that their psychometric functions superimposed well both for durations longer and shorter than 1 s as shown in Figure 2. We nevertheless found a violation of the scalar property for very long durations (15/30 s) [68]. Therefore, Weber's law holds in children at different levels of the ontogenetic scale. Overall, these results confirm that there is a primitive temporal discrimination mechanism that works well in young children.

5 Age Similarities and Changes in Time Discrimination Capacities

A debate is currently underway concerning the type of mechanism involved in the processing of time. According to the internal clock models [57,58,73], the raw material for the representation of time comes from a pacemaker-like system that emits pulses. At the onset of the stimulus to be timed, an attentional switch connecting the pacemaker to the accumulator closes, thus allowing the pulses emitted by the pacemaker to flow into the accumulator. At the offset of the stimulus, the switch reopens and stops the flow of pulses. The time estimate thus depends on the number of pulses accumulated during the elapsed period: The more pulses that are accumulated, the longer the duration is judged to be. Numerous neuroscience researchers have tried to identify the neural substrates of this type of internal clock system. However, they have so far been unable to identify a simple neural mechanism dedicated to the processing of time. Brain activations during temporal tasks are always dependent on the type and complexity of the task used [74]. This has led Eagleman [75] to conclude that “the neural basis of time perception remains shrouded in mystery”. However, current hypotheses consider that two main brain structures play a critical role in time perception: (1) the prefrontal cortex and (2) the striatum, or more precisely the caudate and putamen of the dorsal striatum via dopaminergic modulations [76]. In the striatal beat frequency model, Matell and Meck [77,78] suggested that the neural inputs that constitute the time code arise from the oscillatory activity of large areas of the cortex. At the onset and the offset of the stimulus to be
Fig. 2. Superimposition of psychometric functions for different duration ranges (1/4 and 2/8s) in 3-, 5- and 8 year-old children.

timed, the oscillatory activity of a subset of these cortical neurons is synchronized. The striatal spiny neurons that receive inputs from the cortex detect patterns of oscillatory firing (or beats) that match other patterns stored in memory. They then fire to indicate that the interval has elapsed. In other words, the striatum of the basal ganglia plays a central role in timing by reading the temporal code provided by oscillating neurons in the cortex. Other recent models have nevertheless completely abandoned the idea that there is a specialized brain system for representing time. They argue that the neural circuits are inherently capable of processing temporal information as a result of state-dependent changes in network dynamics [79,80]. Time is therefore an emergent property of changes in neural firing patterns. However, these models only account for the automatic processing of short durations of tens or hundreds of milliseconds (< 500 ms). Whatever the case, the time courses of maturation of the prefrontal cortex and the striatum are totally different. Subcortical structures that are phylogenetically older mature earlier. The structures that constitute the basal ganglia (e.g., caudate, putamen, substantia nigra) are effectively the first of the telencephalic structures to begin to myelinate. In contrast, the prefrontal cortex
matures slowly [81]. More precisely, the frontal cortex matures relatively quickly from birth through to 2 years of age before reaching a stable volume at the age of 5 years old. However, it then continues to develop gradually until the end of adolescence, a period characterized by neural elimination and reorganization and an increase in white matter [82,83]. Finally, the type of temporal judgment required and the underlying processes may partly explain similarities and differences in temporal performance as a function of children's age.

The basal ganglia influence time perception via the dopaminergic (DA) system. Many pharmacological studies have shown that the administration of a drug that increases the level of DA in the brain (metamphetamine, cocaine) speeds up subjective time, thus producing a lengthening of the stimulus duration to be encoded [61,62,84,85,86]. In response to negative emotions such as fear, when the organism detects a danger, there is also a release of DA in the brain. According to Kienast et al. [87], the feeling of stress is directly dependent on the DA storage capacity in the brain. Numerous studies on the perception of time have shown that time is overestimated in response to a threatening stimulus (e.g., angry faces, threatening events) compared to a neutral stimulus [88,89,90,91,92]. More interestingly here, the lengthening effect produced by highly arousing emotional stimuli (angry faces) has been observed in children of different ages (from 3 to 8 years) in the absence of any developmental effect [93]. These results have since been replicated in children aged 5 and 8 years as well as in adults, although the magnitude of the emotional effect has been found to be larger in the youngest children (Figure 3) [94,95]. One of the stimuli that are renowned for speeding up the internal clock is the presentation of periodic events (repetitive clicks, flickers) [96]. As recently concluded by Wearden et al. [97], the click train effect on the perception of time due to a speeding up of the internal clock is one of the more robust effects to be observed in time psychology. In this condition, in exactly the same way as in adults, children’s psychometric functions in bisection shift toward the left in flicker compared to no-flicker conditions [98]. In other words, in the same way as in adults, children overestimate time in the presence of flickers. Between 3 and 8 years, there is no age-related difference in the flicker effect on time perception. Furthermore, the magnitude of this leftward shift in bisection functions does not appear to be constant but instead proportional to the duration values. This observation is more compatible with a multiplicative effect due to a speeding up of the internal clock than with an additive effect related to an earlier closure of the attentional switch. Although the mechanisms underlying the production of temporal overestimation in the presence of click trains or flickers are far from clear [99,100], when considered in combination with those found in response to highly arousing emotions, these findings illustrate that the mechanisms underlying the perception of time conform to the scalar property of time at all ages. Weber’s law holds under all circumstances.
Fig. 3. Psychometric functions in a bisection task with neutral and angry faces.

Beyond phylogenetic and ontogenetic similarities in the perception of time, there are also developmental changes in the ability to discriminate time. All the bisection studies cited above have revealed that children's sensitivity to time improves with age. As Figure 4 illustrates, when the durations are easy to discriminate (ratio of 1:4 or
1:2), and whatever the absolute value of the durations shorter than 1 s, between 1 and 4 s, or longer than 4 seconds, the slope of the psychometric functions in bisection always increases with age. Children aged 3 and 5 years systematically produce flatter psychometric functions than older children. At the age of 8 years, the slope of the bisection curve becomes close to that produced by adults, although some age differences subsist and especially for very long durations (> 8 s) [68]. A calculation of the mean WR values obtained in our bisection studies reveals that the mean WR values obtained were .17 for adults, .21 for 8-year-olds and .32 for 5-year-olds, with the greatest inter-study variations in these values being observed for the youngest children and the longest durations (> 4 s) (see Table 1). The question, which we now have to answer, is why young children have a lower sensitivity to time. To try to find the sources of this developmental change in time sensitivity, we have modeled children’s bisection data on the basis of parameters taken from bisection models used in animals and human adults. We have also experimentally manipulated variables, which specifically affect memory, attention and decisional processes, and, more recently, we have evaluated the differences in cognitive abilities by means of neuropsychological tests. Taken together, our findings demonstrate that the development of attention-related cognitive capacities as well as that of the executive functions, which depend upon the slow maturation of the frontal cortex, explain in great part developmental changes in the ability to discriminate time.

Table 1. Bisection Point (BP), Difference Limen (DL) and Weber Ratio (WR) for the children aged 5 years old and 8 years old, as well as in the adults for durations that differ by a ½ ratio in different duration ranges (Zélanti & Droit-Volet, 2011).

<table>
<thead>
<tr>
<th></th>
<th>PB</th>
<th>DL</th>
<th>WR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td><strong>5 years</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5/1-s</td>
<td>0.88</td>
<td>0.32</td>
<td>0.34</td>
</tr>
<tr>
<td>1.25/2.5-s</td>
<td>1.76</td>
<td>0.30</td>
<td>0.52</td>
</tr>
<tr>
<td>4/8-s</td>
<td>5.16</td>
<td>1.40</td>
<td>1.86</td>
</tr>
<tr>
<td>15/30-s</td>
<td>21.74</td>
<td>5.88</td>
<td>8.34</td>
</tr>
<tr>
<td><strong>9 years</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5/1-s</td>
<td>0.81</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>1.25/2.5-s</td>
<td>1.80</td>
<td>0.19</td>
<td>0.37</td>
</tr>
<tr>
<td>4/8-s</td>
<td>5.63</td>
<td>0.89</td>
<td>1.40</td>
</tr>
<tr>
<td>15/30-s</td>
<td>19.92</td>
<td>5.39</td>
<td>6.97</td>
</tr>
<tr>
<td><strong>Adults</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5/1-s</td>
<td>0.77</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td>1.25/2.5-s</td>
<td>1.82</td>
<td>0.14</td>
<td>0.32</td>
</tr>
<tr>
<td>4/8-s</td>
<td>5.73</td>
<td>0.44</td>
<td>0.97</td>
</tr>
<tr>
<td>15/30-s</td>
<td>21.5</td>
<td>2.74</td>
<td>5.02</td>
</tr>
</tbody>
</table>
Fig. 4. Psychometric functions in different duration ranges in children and adults (from Zélanti & Droit-Volet, 2011).
6 The Cognitive Sources of Children's Lesser Ability to Discriminate Time

As suggested above, several models have been proposed to account for bisection performance in animals and humans based on the scalar timing theory [48,50,57]. These models have generally provided good fits for the bisection data on the basis of two parameters. The first parameter, $c$, is the coefficient of variability of the representation of standard durations ($S$ and $L$) in memory. This parameter is a kind of sensitivity parameter that controls the slope of the psychometric function in bisection. When the memory representation of $S$ and $L$ is fuzzier, the psychometric function becomes flatter. The second parameter, $\beta$, is related to the localization of the BP. This is a sort of decisional bias toward responding long when faced with ambiguous cases, i.e. when the participants cannot tell whether the comparison value is closer to $S$ or $L$.

In these models, the main source of temporal variance lies in the memory processes rather than in the perception of time, which is thought to be accurate. The models that have used these two parameters also fit well with children's data in bisection tasks, even though it has often been necessary to include an additional parameter relating to random responses [44,67]. This therefore suggests that children’s lower sensitivity to time might be due to their fuzzier memory representations of the standard durations. However, in their model, McCormack et al. [43] added another parameter, $q$, which represents noise in the perceived duration. In accordance with Weber's Law, the proportion of noise in the perceived duration should be proportional to the length of the duration. Children would therefore have a "noisier" perception of time.

Finally, the question that has to be answered is what is it that leads to greater variability in young children's memory representations of standard durations. One initial hypothesis consists in the idea that there may be a specific problem relating to the memory retention of standard durations. Rattat and Droit-Volet [71,101,102] showed that the bisection task is a temporal task involving explicit memory, and that young children remember durations better in an implicit than in an explicit memory task. In bisection, when a long retention delay (15 min, 24 h) or an interference task has been introduced between the phase in which the standard durations are presented and the test phase, psychometric functions have been seen to become flattened in 5-year-olds and their time sensitivity poorer. Under the same conditions, 8-year-olds and the adults change their strategies. They no longer refer to the representation of standard durations in memory but instead partition the comparison durations into short and long. However, using a temporal bisection task, Droit-Volet and Rattat [70] showed that developmental differences in time sensitivity subsist even in a partition task when no standard durations are stored in reference memory. A second hypothesis would therefore consist in supposing that the representation of standard durations in reference memory results from what has previously been encoded, i.e., during the perception of time before inclusion in reference memory. Delgado and Droit-Volet [103] tested the reference memory of standard durations in bisection by introducing variance in the samples of standard durations and showed that the value of the memory parameter, $c$, used in the bisection model depends directly on the initial noise introduced during the encoding of temporal samples.
Instead of pointing to a major problem of retention in the memory for durations, developmental studies suggest that the difficulties young children experience in focusing and sustaining their attention on the continuous flow of time accounts for the variability of their time judgments. This explains why time estimation is often impaired in children with Attention Deficit Hyperactivity Disorder (ADHD) [104,105,106]. Recently, Zélanti and Droit-Volet [68] used a series of neuropsychological tests to assess cognitive abilities in children. The results enabled them to point out significant correlations between temporal sensitivity (WR) and the attention/concentration index of the Children’s Memory Scale (CMS) [107]. The higher the attention/concentration score, the lower the WR value, and the better sensitivity to time. The attention/concentration index of the CMS also involves working memory. According to the leading models in this domain [108,109], working memory consists of a central executive system, which manages attentional resources by directing attention toward relevant information, suppressing irrelevant information and keeping the information present in memory active. Precisely, the working memory capacity assessed in our study by means of the backward memory span test, (and, in particular, the visuo-spatial component) also predicted the age differences in time sensitivity for the long durations (> 1 s, and more particularly > 4 s). For short durations of less than 1 s, the short-term memory span (forward memory span) was the only reliable factor allowing us to predict age changes in bisection performance.

Our findings on working memory and time in children are entirely consistent with those of recent studies that have studied temporal reproduction in adults and shown that temporal precision improves with increased working memory capacity [110,111,112].

As reported above, according to scalar timing theory, the clock system consists of a pacemaker, a switch and an accumulator. When the behavioral data obtained in bisection tasks suggest the presence of an effect related to clock rate (multiplicative effect), this may be due to variations in the speed of the pacemaker or to the flickering of the switch-accumulator system [113]. In behavioral studies, it is difficult to distinguish between these two types of mechanism (pacemaker vs. accumulator/switch) because they have the same effects on temporal performance (multiplicative effect). Nevertheless, studies conducted among children suggest that the development of time sensitivity is better explained in terms of an impairment to the switch/accumulator system than the idea that the pacemaker runs more slowly in children than in adults, although both explanations are possible. More precisely, the accumulator/switch system would be less efficient in young children due to their limited attentional capacities. The accumulator/switch system is indeed thought to depend on both mental load in working memory and attentional demands [114]. While the passage of time is being tracked, it would be more difficult for the switch to stay closed in children than in adults. In other words, the “child switch” would be more variable and would flicker more often than the “adult switch”.

It does indeed appear that the accurate processing of time involves all the dimensions of attention: oriented attention, divided attention, selective attention and sustained attention. At the risk of losing some of the temporal information, attention must be prepared so that the subject can capture the beginning of the forthcoming stimulus. Droit-Volet [115] showed that a signal warning participants of the onset of a visual stimulus which they had to time produced a temporal overestimation of this
stimulus because the attentional switch have closed earlier. More importantly, however, this warning signal also reduced the variability in time discrimination in the younger children. The warning signal thus reduced the children’s variability in the attentional capture of the onset of a visual stimulus to be timed. Furthermore, if individuals are to be able to process time correctly, they must have sufficient attentional resources available to them. As a number of studies have demonstrated, when attention is divided between a temporal and a non-temporal task, time is judged shorter [116,117,118]. Using a dual-task paradigm, it has been demonstrated that 5-year-olds, who possess a limited pool of attentional resources, produce greater temporal underestimations than older children [119,120,121,122]. The development of selective attention capacities also allows children to resist attentional distractors and focus their attention on the processing of time. The introduction of attentional distractors in a temporal bisection task has thus been found to impair children's time discrimination to a greater extent at the age of 5 years than at the age of 8 [121]. In sum, children’s distractibility and their deficit in inhibitory control prevent them from correctly apprehending the continuous flow of time.

The attentional control deficit exhibited by young children explains why they are more subject than adults to temporal illusions. Two temporal illusions have been widely investigated in time psychology: (1) the visual-auditory illusion, and (2) the empty-filled illusion. The visual-auditory illusion consists in the fact that the duration of an auditory signal is judged longer than that of a visual signal presented for the same period. The empty-filled illusion is reflected in the fact that an empty duration (temporal interval between two short signals) is judged to be shorter than a filled duration (duration of a signal). Developmental studies of these visual-auditory temporal illusions have shown that these illusions are greater in 5-year-olds than in 8-year-olds or adults [67,123,124]. Similarly, the scale of the empty-filled illusion has been shown to decrease as children develop [125]. A greater level of attention is indeed involved in the control of the switch-accumulator system during the processing of visual rather than auditory signals as well as that of empty compared to filled durations. In the case of visual signals, young children have to keep their attention focused on the computer screen, whereas in the case of empty durations, they must not become distracted during the temporal interval, i.e., they must wait without doing anything.

In addition to attentional processes, as previously suggested, the development of decision processes may also modify time judgments in children [63,64]. However few studies have focused on the decisional strategies and the “metacognition of time”. We do not know the precise role of the development of knowledge and beliefs concerning time in our own time judgments. This is a new avenue of research that we have decided to investigate. In our studies, we have nevertheless already shown that children have a lesser feeling of knowing (whether the duration is long or short) and that this affects the localization of their PB in bisection. According to the mathematic models of bisection, children’s feeling of knowing should be related to the variability of their representation of time in memory [41]. What, ultimately, is the cause of this lesser feeling of knowing concerning time discrimination: children's awareness of their poor temporal abilities or a general problem of metacognition? Finally, developmental studies reveal that the explicit judgments of time are highly dependent upon contexts, because the flow of time must always remain in the attentional focus.
or awareness. It therefore seems to be very important to investigate in greater detail the differences between implicit and explicit time judgments in children.

References

48. Wearden, J.H.: Human performance on an analogue of an interval bisection task. The


This work was supported by a grant from the ANR (Agence Nationale de la Recherche) N° ANR-07-NEURO-048-02, France. It was also supported by the European Cooperation in Science and Technology (TIMELY)