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Cognitive abilities explaining age-related changes in time perception of short and long durations

Pierre S. Zélanti, Sylvie Droit-Volet *

Laboratoire de Psychologie Sociale et Cognitive, CNRS (UMR 6024), Université de Clermont, 63037 Clermont–Ferrand, France

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ABSTRACT

The current study investigated how the development of cognitive abilities explains the age-related changes in temporal judgment over short and long duration ranges from 0.5 to 30 s. Children (5- and 9-year-olds) as well as adults were given a temporal bisection task with four different duration ranges: a duration range shorter than 1 s, two duration ranges longer than 3 s (4–8 s and >15 s), and an intermediate duration range (1.25–2.5 s). Their cognitive abilities were also assessed using a series of neuropsychological tests. The results showed that temporal sensitivity improved with age for each duration range but that this improvement occurred earlier for the short durations than for the long durations. Furthermore, the results revealed that the age-related improvement in time sensitivity for the durations shorter than 1 s was explained by the development of short-term memory span, whereas that for long durations was explained by the development of attention/executive functions. To summarize, the development of the abilities required to process long durations seems to be explained mainly by the development of attentional resources.

Introduction

Time is a fundamental dimension of everyday life that children experience at an early age. Recent studies have shown that, as of 4 months of age, infants are able to discriminate event durations (Brannon, Suanda, & Libertus, 2007; Provasi, Rattat, & Droit-Volet, 2010; VanMarle & Wynn, 2006) and to detect a temporal deviation in the rhythmical presentation of sounds (Brannon, Libertus, Meck, & Woldorff, 2008; Brannon, Wolfe, Meck, & Woldorff, 2004). At 3 years of age, children's behavior also exhibits

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* Corresponding author.
E-mail address: sylvie.droit-volet@univ-bpclermont.fr (S. Droit-Volet).

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the fundamental properties of time perception found in human adults and animals, that is, mean accuracy and the scalar property of variance (Droit-Volet, Clément, & Wearden, 2001; Droit-Volet, Meck, & Penney, 2007; Droit-Volet & Wearden, 2001). Indeed, their estimates vary accurately in line with real time, and the variability of these estimates (i.e., standard deviation) grows proportionally with the duration value. Consequently, the coefficient of variation of estimates—the Weber ratio (*WR*)—remains constant for different duration ranges, demonstrating that young children's perception of time obeys Weber's law. Overall, these results suggest that the neural mechanism (i.e., clock system) that enables children to estimate time is functional as of an early age (Brannon et al., 2008; Droit-Volet & Wearden, 2002).

However, the idea that the neural clock system is able to function at an early age is not incompatible with age-related variations in the processing of time. Indeed, temporal judgments result not only from an internal clock but also from the complex interaction among several different cognitive processes. Recently, a number of researchers have even suggested that time might be an emergent property of the neural dynamics of the brain and might not be dependent on a dedicated timing mechanism (Ivry & Schlerf, 2008; Mauk & Buonomano, 2004; Wittmann, 1999). In the scalar timing models, which are the most influential models of timing, temporal judgment is considered as the outcome of an interaction among an internal clock, memory abilities, and decisional processes (e.g., Gibbon, Church, & Meck, 1984; Treisman, 1963). According to these models, the raw material for duration comes from an internal clock that accumulates pulses emitted by a pacemaker during the stimulus to be timed. Memory processes then retain the current duration and store significant durations in reference memory, whereas decisional processes compare these two durations to provide a temporal judgment. In addition, the processing of time has been demonstrated to demand attentional resources. When attentional resources are diverted away from the processing of time, fewer pulses are accumulated and the duration is judged to be shorter (e.g., Brown, 1997; Coull, Vidal, Nazarian, & Macar, 2004). To summarize, changes in any of the cognitive components—memory, decision, or attention—may result in age-related variations in time discrimination.

However, a debate is currently under way concerning the distinct cognitive processes involved in the estimation of short and long durations, with the idea being that attention is primarily involved in the processing of long durations during which it is necessary to expend greater mental effort in order to keep track of the passage of time. Although the debate is still unresolved, an outline consensus according to which the boundary lies at approximately 1 s has emerged (e.g., Ivry & Schlerf, 2008; Lewis & Miall, 2009; Rammsayer, 1994). Fraisse (1984) and Pöppel (1997) placed the boundary between the temporal processes at a longer duration of approximately 2 to 3 s, below and above which they talked about time perception (psychological present) and time estimation, respectively. Whatever the case, the processing of short durations seems to be more automatic and less dependent on attentional capacities. For instance, Rammsayer and Lima (1991) showed that short durations (500 ms), unlike longer durations, were not affected by a concurrent cognitive task. Neuroimaging studies have also shown that the prefrontal cortex (right hemispheric dorsolateral prefrontal cortex), which plays a fundamental role in high-level cognitive capacities, is specifically activated during the processing of durations longer than 1 s (Ivry & Schlerf, 2008; Lewis & Miall, 2006; Meck, Penney, & Pouthas, 2008). Therefore, the purpose of the current study was to investigate what dimensions of cognitive development assessed by neuropsychological tests explain the age-related variations in the discrimination of short and long durations.

Recently, the development of temporal discrimination has been examined systematically using the temporal bisection task, which is a task that is easy to use in young children and has been used extensively both in animals (Church & Deluty, 1977) and in human adults (Allan & Gibbon, 1991; Wearden, 1991). In the temporal bisection task, children are initially presented with short (*S*) and long (*L*) anchor durations. They are then presented with comparison durations (*t*) that either are the same as or lie between the anchor durations. Children's task is to categorize *t* as more similar to *S* or to *L*. In this task, the results are represented in the form of a psychophysical function, with the proportion of long responses, *p*(long), being plotted against the comparison durations. The psychophysical functions that have been found in young children are orderly (i.e., *p*(long) increases with the stimulus duration value), thereby revealing their ability to discriminate time (Droit-Volet, 2008; Droit-Volet & Izaute, 2009; Droit-Volet, Tourret, & Wearden, 2004; McCormack, Brown, Maylor, Darby, & Green, 1999). However, they appear to be flatter in younger children (3- and 5-year-olds). The associated *WR* value is also higher, thereby indicating a lower sensitivity to time in children. More precisely, time sensitivity increases between 3 and 10 years of age and becomes close to the adult level at 8 to 10 years. However, these developmental studies in bisection have used either short durations (<1 s) (e.g. McCormack et al., 1999) or long durations (2–8 s) (e.g., Droit-Volet & Wearden, 2001) but have never examined the differences in children's sensitivity to time when comparing durations shorter than 1 to 2 s and durations longer than this. Therefore, in the current study, we decided to investigate temporal bisection performance in children as well as adults with different duration ranges: a duration range shorter than 1 s, duration ranges longer than 3 s, and an intermediate duration range between 1 and 3 s.

So far as the cognitive abilities that might explain young children's lower sensitivity to time in bisection are concerned, if long durations require more attentional resources, we may assume that age-related differences in time sensitivity for these durations are primarily due to difficulties children have in focusing their attention on time and resisting attentional distractions. Indeed, attentional functions largely depend on the prefrontal cortex, which develops slowly throughout childhood and into young adulthood (Casey, Tottenham, Liston, & Durston, 2005; Diamond, 2002; Tsujimoto, 2008). Furthermore, studies on time perception that have used both divided and distracting attention tasks have shown that the attention-related shortening effect is greater in 5-year-olds than in older children (Droit-Volet, Delgado, & Rattat, 2006; Gautier & Droit-Volet, 2002a, 2002b; Zakay, 1992). This explains why time estimation is often impaired in children with attention deficit hyperactivity disorder (ADHD) (e.g., Smith, Taylor, Rogers, Newman, & Rubia, 2002; Toplak, Dockstader, & Tannock, 2006). Therefore, in the current study, we used the neuropsychological subtests of the NEPSY, which assesses attention/executive functions in children (Korkman, Kirk, & Kemp, 1998). More precisely, participants performed tasks from the Auditory Attention and Response Set, which is used as a measure of selective attention with an inhibitory component (Cromer, Stevens, DePrince, & Pears, 2006; Klenberg, Korkman, & Lahti-Nuuttila, 2001). In these tasks, which are described in more detail later, participants must, for example, put a yellow square in a box when they hear the word "red" in a sequence of different words and put a red square in the same box when they hear the word "yellow".

However, the functioning of attention is closely associated with working memory load. In addition, the processing of long durations requires participants to be able to accumulate and maintain the flow of temporal information in working memory. Some studies that have used the temporal reproduction task in adults have suggested that the processing of long durations (>2–3 s) is related to working memory processes assessed by psychological tests such as the backward memory span (e.g., Baudouin, Vanneste, Pouthas, & Isingrini, 2006; Franssen & Vandierendonck, 2002; Ulbrich, Chuzan, Fink, & Wittmann, 2007). With regard to children, there is considerable evidence that working memory capacities improve between 5 and 11 years of age (Gathercole & Alloway, 2006). Consequently, the development of working memory capacities may also help to explain the age-related changes in bisection, particularly for the durations longer than 1 to 2 s. Therefore, in the current study, we evaluated the backward memory span for each individual. In this test, participants must repeat—in reverse order—the sequence of digits stated by the experimenter (i.e., 9–1–7 for 7–1–9). In addition, to take account of the relationship between attention and working memory, we also calculated the attention/concentration index of the Children's Memory Scale (CMS) (Cohen, 1997), which assesses working memory and attention within this domain. Indeed, as described below, this index is calculated on the basis of performance on digit span tests and sequence tests that require the maintenance of a high level of concentration in order to repeat complex sequences.

Cognitive resources are required during the processing of the continuous flow of temporal information. However, in the case of particularly short durations (<1 s), the attention demand is lower. According to Baddeley and Hitch's (1994) model of working memory, the traces in memory of a limited amount of information are held in a short-term storage component of working memory for a few seconds ($\sim$2 s). Beyond 2 s, the traces in memory decay without rehearsal activity. Using other temporal tasks (temporal generalization and temporal reproduction), some studies have suggested that young children's variability in time judgments may be due to the difficulties they encounter in maintaining the duration that is to be judged in short-term memory (Droit-Volet, 2010; Droit-Volet, Wearden, & Delgado-Yonger, 2007; Yang et al., 2007). There is now a body of evidence showing that the single-digit short-term memory span increases with age (Gathercole, 1999; Gathercole & Hitch, 1993; Gathercole, Pickering, Ambridge, & Wearing, 2004). Consequently, children's performance on a single-digit span test measuring short-term storage in memory would probably be insufficient to account for age-related effects in the timing of long durations but not in that of short durations (<1 s).

Therefore, in the current study, we used a set of developmental neuropsychological tests to assess individual cognitive abilities (short-term memory, working memory, and attention) in children (5- and 9-year-olds) as well as in adults. We considered that these tests might well be able to explain some of the differences in time performance that are observed in a bisection task as a function of the duration values. Four duration ranges were used: a duration range shorter than 1 s ($S = 0.5$ s, $L = 1$ s [0.5/1 s]), two duration ranges longer than 3 s ($S = 4$ s, $L = 8$ s [4/8 s], and $S = 15$ s, $L = 30$ s [15/30 s]), and an intermediate duration range ($S = 1.25$ s, $L = 2.5$ s [1.25/2.5 s]). We expected to find that sensitivity to time would be lower in the youngest children, especially for the longest duration ranges. Multiple regressions were also run to determine which cognitive abilities are the best predictors of the age effect on time sensitivity in bisection for these different duration ranges.

Method

Participants

The final sample consisted of 57 participants: 18 5-year-olds (*M* = 5.86 years, *SD* = 0.31), 19 9-year-olds (*M* = 9.11 years, *SD* = 0.39), and 20 adults (*M* = 22.75 years, *SD* = 3.52). Three additional children (2 5-year-olds and 1 9-year-old) were excluded from the final sample because they obtained *p*(long) values greater than .50 for all probe durations in all anchor duration conditions. The children were recruited from nursery and primary schools at St. Germain des Fossés, France, and the adults were students at Clermont University.

Materials

Children and adults were tested individually in a quiet room at their school and university, respectively. E-Prime software was used to present the experimental stimuli and record responses on a PC. The responses (short vs. long) were given orally. During the training and testing phases, the stimulus for timing was a red circle (6 cm in diameter) presented in the center of the computer screen. In addition, the short and long anchor durations were followed by 500-ms feedback. In the case of correct responses, this feedback took the form of cartoon pictures that varied from trial to trial (positive feedback), whereas for incorrect responses, a picture of an unhappy Calimero (i.e., a cartoon duck) was displayed (negative feedback).

Procedure

Bisection task

Each participant took part in four sessions, one for each anchor duration condition: 0.5/1, 1.25/2.5, 4/8, and 15/30 s. Participants performed one session per day, with the session order being randomized. In the 0.5/1-s condition, the short anchor duration was 0.5 s and the long anchor duration was 1 s. The probe durations were 0.5, 0.583, 0.666, 0.749, 0.833, 0.916, and 1 s. In the 1.25/2.5-s condition, *S* and *L* were 1.25 and 2.50 s, respectively, and the probe durations were 1.25, 1.458, 1.666, 1.874, 2.083, 2.291, and 2.5 s. In the 4/8-s condition, *S* and *L* were 4 and 8 s, respectively, and the probe durations were 4, 4.666, 5.333, 5.999, 6.666, 7.333, and 8 s. In the 15/30-s condition, *S* and *L* were 15 and 30 s, respectively, and the probe durations were 15, 17.5, 20, 22.5, 25, 27.5, and 30 s.

In each duration condition, participants underwent three successive phases: pretraining, training, and testing. During the pretraining phase, *S* and *L* were presented three times each in alternation. The experimenter said, "Look at this circle; it appears for a short [long] time." During the training phase, participants were trained to respond "short" and "long" after *S* and *L*, respectively. A correct response resulted in the appearance of positive feedback, and an incorrect response resulted in the appearance of negative feedback. Each participant performed a series of training blocks of 10 randomly presented trials (5 *S* and 5 *L*) with an intertrial interval between 0.5 and 2 s. The training terminated after a block of at least 75% correct responses. In this experimental condition, most participants required only one training block, with the exceptions of four 5-year-olds and one 9-year-old who did not achieve this correct response level in one block of trials. These children did not continue this experiment, which was particularly long.

Testing used the same experimental conditions as training except that no feedback was given for the intermediate probe durations. Each participant completed three series of three blocks of 11 trials each (i.e., 99 trials): 3 trials each for *S* and *L* and 1 trial for each intermediate duration. The presentation of the trials within each block was random. Although children did not spontaneously count time, both they and adults were instructed not to count and were told how counting time may bias the data. In addition, as numerous studies have demonstrated, the counting of time leads to a violation of the scalar property of time that was not observed in the current study (e.g., see Clément & Droit-Volet, 2006; Getty, 1976).

Neuropsychological tests

After the bisection sessions, participants performed a series of neuropsychological tests, with the order of presentation being random across participants. These tests assessed participants' individual cognitive abilities in terms of short-term memory, working memory, and attention.

To assess short-term and working memory capacity, we used the Wechsler Memory Scale.[1] More precisely, we used two subtests to assess different memory components (Alloway & Gathercole, 2006). The first, short-term memory, was forward digit recall, which is a standard measure of short-term memory span. The second, working memory, was backward digit recall, which calls on central executive functions in working memory (Baddeley & Hitch, 1994). In the first test, participants were presented with a sequence of digits (e.g., 4–2) and immediately needed to recall this sequence in the correct order. In the second test, they again needed to recall each digit sequence but in reverse order. For each test, the number of digits per sequence increased progressively from 2 to 8, with two trials being administered per sequence. One point was awarded for each correct trial, and participants' scores were the total number of points obtained. The test ended after two consecutive failed trials for one and the same sequence length.

In our study, various attention-related components were also measured. To measure attention/executive function, we selected one subtest of the NEPSY (Korkman et al., 1998) that assesses selective attention to rapidly presented auditory stimuli, namely Auditory Attention and Response Set tasks. In this subtest, children listened to a series of 180 words presented at 1-s intervals, for example, "red . . . square . . . put . . . yellow . . . empty . . . thing . . . now." Children were initially instructed to attend only to the word "red" and, when they heard this word, to select a red square from a set of squares of different colors and put it in a box. Next, they needed to put a yellow square in the box when they heard the word "red" and to do the same with a red square when they heard the word "yellow" and with a blue square when they heard the word "blue". If children responded rapidly (i.e., within 1 s), 2 points were scored. If they responded within 2 to 3 s, 1 point was scored. However, 1 point could be lost when an error was made, for example, choosing a blue square for the word "red". The score on this task was calculated out of a possible maximum of 72 points (i.e., 36 targets for 11 yellow, 11 red, and 14 blue).

To measure the relationship between attention and working memory, we also calculated the attention/concentration index of the CMS (Cohen, 1997) based on two subtests. The first, referred to as Numbers, measures a forward or backward digit span. The second, called Sequences, measures the ability to mentally manipulate a sequence of verbal material as quickly as possible, for example, saying the days of the week backward or counting by fours. The raw scores for these two subtests were converted into a raw score for the attention/concentration index.

Results

Temporal performance

Fig. 1 presents *p*(long) plotted against probe durations for the 5-year-olds, 9-year-olds, and adults in each anchor duration condition. We also used three further measures of bisection performance: the

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[1] In line with a number of other studies, the same scales were used for all of the participants to make it possible to test the age-related changes in the scores. The homogeneity of variance was tested systematically.

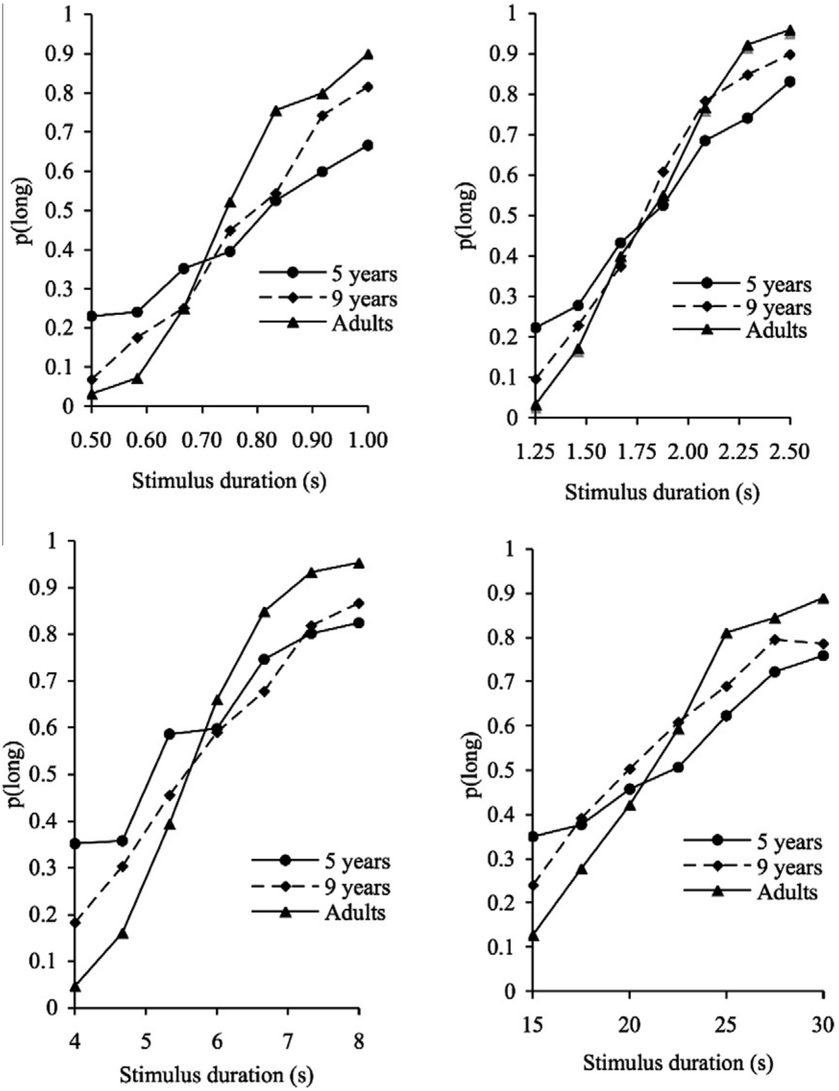

Fig. 1. Proportions of long responses, *p*(long), plotted against probe durations for 5-year-olds, 9-year-olds, and adults in the 0.5/1.0-, 1.25/2.5-, 4.0/8.0-, and 15.0/30.0-s anchor duration conditions.

bisection point (*BP*), the difference limen (*DL*), and the *WR*. The *BP* is the point of subjective equality, that is, the probe duration that is judged to be long as often as short (*p*(long) = .50). The *DL* is the just noticeable difference, that is, half the difference between the probe duration giving rise to *p*(long) = .75 and that giving rise to *p*(long) = .25. In other words, it is a measure of absolute temporal sensitivity. Larger *DL* values indicate flatter bisection curves and lower temporal sensitivity (i.e., a poorer ability to distinguish one duration from another). The *WR* is the *DL* divided by the *BP*. According to Weber's law, the *DL* is supposed to increase with the *BP*. Consequently, the *WR* should remain constant as the anchor durations change. Therefore, the *WR* measures temporal sensitivity standardized on the estimated intervals and permits a direct comparison of timing variability across different anchor durations. There are several ways of calculating these three temporal measures. However, they

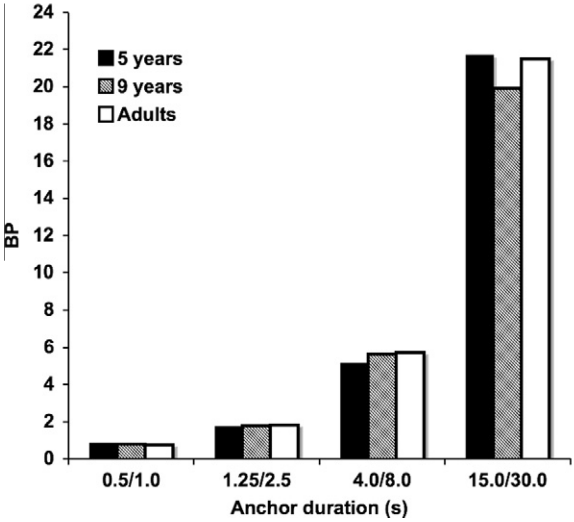

Fig. 2. Mean bisection points (*BP*) in the 0.5/1.0-, 1.25/2.5-, 4.0/8.0-, and 15.0/30.0-s anchor duration conditions for 5-year-olds, 9-year-olds, and adults.

yield similar results (Wearden & Ferrara, 1995, 1996). Therefore, we decided to fit the logarithmic function to the individual participant data. The fit was not significant for five children in specific anchor duration conditions (three in the 4/8-s condition, 1 in the 0.5/1-s condition, and 1 in the 15/30-s condition). Therefore, these participants' results for these duration conditions were excluded from the subsequent analyses.

An analysis of variance[2] (ANOVA) was run on each temporal index with duration as a within-participant factor and age as a between-participants factor. The ANOVA run on the *BP* (Fig. 2) revealed neither a significant main effect of age, $F(2, 49) = 0.51$, $p > .05$, nor any significant Age × Duration interaction, $F(6, 147) = 0.86$, $p > .05$. There was only a significant main effect of duration, $F(3, 147) = 812.40$, $p < .05$, indicating that the *BP* value increased with duration range. When we calculated the ratio between the *BP* and the arithmetic mean of *S* and *L*, we observed that the significant effect of duration did not disappear, $F(3, 147) = 9.30$, $p < .05$. The ratio did indeed differ between the shortest duration range (0.5/1 s: 1.09) and the other duration ranges (Bonferroni tests, all *ps* < .05), whereas no difference was found between these latter durations (1.25/2.5: 0.96; 4/8 s: 0.92; 15/30 s: 0.94). This is due to the fact that the *BP* was greater than the arithmetic mean (*AM*) of *S* and *L* for the short duration range (0.5/1 s, *BP* = 0.82), whereas it was close to the geometric mean (*GM*) of *S* and *L* for all durations greater than 1 s (1.25/2.5, *BP* = 1.79; 4/8 s, *BP* = 5.52; 15/30 s, *BP* = 21.09).

With regard to *DL*, there was also a main effect of duration, $F(3, 147) = 279.61$, $p < .05$, indicating that the *DL* increased with the value of the anchor durations (Fig. 3). However, unlike in the case of the *BP*, we observed both a significant main effect of age, $F(2, 49) = 13.53$, $p < .05$, and a significant interaction between age and duration, $F(6, 147) = 5.72$, $p < .05$, for *DL*. The ANOVA run on *DL* for each duration range taken separately revealed that the main effect of age always reached significance: 0.5/1 s: $F(2, 53) = 14.46$; 1.25/2.5 s: $F(2, 54) = 19.56$; 4/8 s: $F(2, 54) = 27{,}08$; 15/30 s: $F(2, 53) = 8.34$, all *ps* < .05. As revealed by pairwise comparisons using post hoc Scheffé tests, the estimates made by the youngest children were more variable than those made by the 9-year-olds and adults in all duration ranges (all *ps* < .05) except for the longest duration condition (15/30 s) in which 9-year-olds' sensitivity to time was particularly low ($p > .05$). In fact, at 9 years of age, time sensitivity reached the same level as that exhibited by adults but only for the anchor durations shorter than 2.5 s (i.e., 0.5/1 and 1.25/2.5 s,

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[2] A Greenhouse–Geisser correction was used when the condition of sphericity was not met.

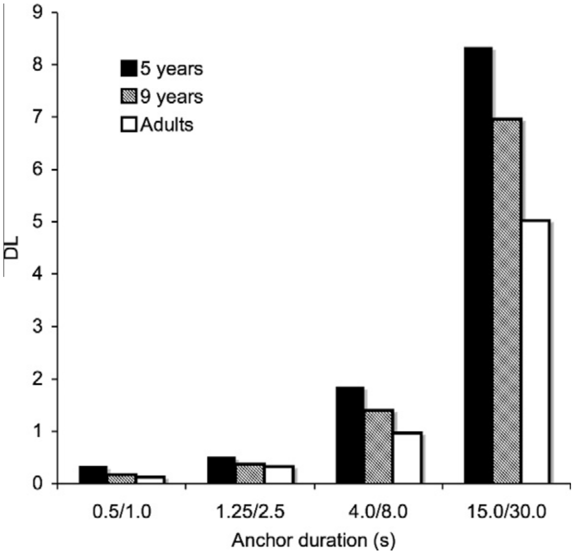

Fig. 3. Mean difference limens (*DL*) in the 0.5/1.0-, 1.25/2.5-, 4.0/8.0-, and 15.0/30.0-s anchor duration conditions for 5-year-olds, 9-year-olds, and adults.

Scheffé tests, both *ps* > .05). Once the duration exceeded 2.5 s, 9-year-olds' time sensitivity dropped below the values observed in adults (4/8 and 15/30 s, both *ps* < .05).

When we considered not an absolute but a relative index of sensitivity (*WR*) (Fig. 4), we found that the main effect of duration still reached statistical significance, $F(3, 147) = 7.08$, $p < .05$, and that duration did not significantly interact with age, $F(6, 147) = 1.34$, $p < .05$. The significant effect of duration violated Weber's law, according to which the *WR* should be constant across different duration values.

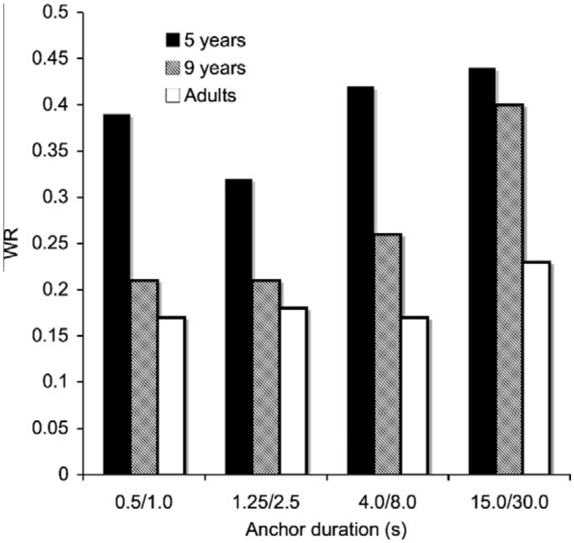

Fig. 4. Mean Weber ratios (*WR*) in the 0.5/1.0-, 1.25/2.5-, 4.0/8.0-, and 15.0/30.0-s anchor duration conditions for 5-year-olds, 9-year-olds, and adults.

This deviation from Weber's law was due to the stimulus durations longer than 15 s, for which participants obtained a *WR* value ($M = .36$) greater than the *WR* values obtained for the other durations (5/1 s, $M = .26$; 1.25/2.5 s, $M = .24$; 4/8 s, $M = .29$, post hoc Bonferroni comparisons, all *ps* < .05). In contrast, for the durations between 0.5 and 8 s, Weber's law held and no significant differences were observed between the *WR* values of these shorter durations (all *ps* > .05). Whatever the case, with the relative index of sensitivity, the main effect of age was always significant, $F(2, 49) = 25.76$, $p < .05$. Therefore, relative sensitivity to time increased with age, with the *WR* being significantly higher for 5-year-olds ($M = .39$, $SD = .02$) than for both 9-year-olds ($M = .27$, $SD = .02$) and adults ($M = .19$, $SD = .02$) and being higher for 9-year-olds than for adults (pairwise comparisons with post hoc Scheffé tests, all *ps* < .05). Overall, our results demonstrate that temporal sensitivity in bisection tasks improves during childhood, whereas the point of subjective equality (*BP*) appears to be similar in all age groups. Therefore, we decided to examine the role of the development of cognitive abilities with reference to indexes of temporal sensitivity only.

Neuropsychological tests

We calculated the raw scores obtained by the children and adults in different neuropsychological tests assessing short-term memory (forward digit span) and working memory (backward digit span) as well as two components of attention: the attention/executive and attention/concentration functions (Table 1). There was a significant age effect in each test—short-term memory, $F(2, 54) = 43.07$; working memory, $F(2, 54) = 27.31$; attention/executive, $F(2, 54) = 119.71$; attention/concentration, $F(2, 54) = 205.98$ (all *ps* < .0001)—and all of the comparisons between age groups were significant (Scheffé tests, all *ps* < .05). There were strong and significant correlations between age and the raw scores obtained in these different neuropsychological tests (all *ps* < .05). Therefore, we calculated *z*-scores within each age group to scale performance within age. Table 2 presents the correlation matrix among the different timing measures (for which an interaction with age was found), age, and the *z*-scores for the neuropsychological tests. We then ran hierarchical regression analyses on the temporal sensitivity indexes to determine which factor best predicts variation in time perception in children and adults.

As reported above, in the case of absolute time sensitivity (i.e., *DL*), there was a significant interaction between age and duration. Therefore, we ran regression analyses on *DL* for each duration taken separately, with age and *z*-scores in the different neuropsychological tests being entered into the equation. The analyses revealed that age was the major predictor of improvement in sensitivity to time for all duration conditions (0.5/1 s, $R^2 = .20$; 1.25/2.5 s, $R^2 = .29$; 4/8 s, $R^2 = .41$; 15/30 s, $R^2 = .24$, all *ps* < .05). For the intermediate duration ranges (1.25/2.5 and 4/8 s), age was the only significant predictor of sensitivity to time. Adding the scores from the neuropsychological tests slightly increased the proportion of variance explained with ΔR^2 values of .05 and .09, respectively. Unlike the intermediate durations, the shortest durations (<1 s) and the longest durations (>15 s) were explained at a significant level by predictors other than age. For the durations shorter than 1 s, the short-term memory index (i.e., forward digit span) was also a significant predictor that increased the proportion of

Table 1
Scores on the neuropsychological tests for 5-year-olds, 9-year-olds, and adults.

	5-year-olds		9-year-olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
Short-term memory						
Forward digit span	5.33	1.19	8.16	1.95	10.75	2.07
Working memory						
Backward digit span	2.50	0.71	4.58	1.57	6.30	2.08
Attention/executive function						
Auditory attention	27.39	8.35	46.89	7.56	62.50	4.71
Attention/concentration function						
Attention/concentration	26.89	7.58	62.32	9.06	85.50	9.86

Table 2
Correlation matrix among timing measures, age, and neuropsychological tests (*z*-scores).

	1	2	3	4	5	6	7	8	9	10
Difference limen										
1. 0.5 /1 s	1									
2. 1.25/2.5 s	.45**	1								
3. 4/8 s	.35*	.56**	1							
4. 15/30 s	.10	.29*	.43**	1						
Weber ratio										
5. *WR*	.65**	.73**	.73**	.42**	1					
Age										
6. Age	−.45**	−.54**	−.64**	−.49**	−.63**	1				
Short-term memory										
7. Forward digit span	−.31*	.00	−.10	−.08	−.13	−.05	1			
Working memory										
8. Backward digit span	−.17	−.08	.16	−.04	−.11	−.01	.35**	1		
Attention/executive function										
9. Auditory attention	.06	−.12	−.07	−.29*	−.06	.01	.07	.01	1	
Attention/concentration function										
10. Attention/concentration	−.28*	−.19	−.11	−.11	−.26*	−.04	.44**	.37**	.23	1

* Correlation significant at .05 level.
** Correlation significant at .01 level.

explained variance ($R^2 = .31$, $p < .0001$). Adding the other factors into the equation step by step did not change the R^2 value. Therefore, for the short anchor durations (<1 s), the greater the memory span was, the better the time sensitivity was. In the case of the longest durations (15–30 s), it was not short-term memory but rather the attention/executive function that significantly predicted the improvement in absolute time sensitivity ($R^2 = .32$, $p < .001$), although the ΔR^2 value was relatively low. The other cognitive scores were not significant predictors, and adding them into the equation changed the proportion of explained variance by only 2%.

The regression analyses run on relative sensitivity (*WR*) confirmed the fundamental role of attention in variations in the processing of time. Indeed, because no significant Age × Duration interaction was found, we performed a hierarchical regression analysis on *WR* averaged over all duration ranges with age and the *z*-scores from the other neuropsychological tests entered into the equation. This analysis revealed that there were two significant predictors of the increase in the *WR:* age and the attention/concentration index. These two scores explained 48% of the variance ($R = .69$, $p < .001$). No other factors were reliable predictors. Simply adding the scores relating to the attention/executive function into the equation slightly changed the proportion of explained variance ($\Delta R^2 = .04$). However, as explained in the Method section above, the attention/concentration index also involved working memory, whereas the attention/executive test focused more on selective attention and included an inhibitory component. To summarize, as shown in Fig. 5, the higher the attention/concentration score was, the lower the *WR* value was and the better the sensitivity to time was.

Discussion

The current study of temporal bisection in children and adults who attended a variety of sessions involving a wide range of durations revealed no age-related change in the point of subjective equality (*BP*). However, it did show that the location of the *BP* differed as a function of whether the duration was shorter or longer than 1 s. For the shorter durations, the *BP* was closer to the arithmetic mean (*AM*) of *S* and *L* than to their geometric mean (*GM*), whereas the opposite was true for the longer durations. A shift in the *BP* between the short (<1 s) and longer anchor durations, despite the fact that the *S*/*L* ratio remained similar (2:1), could be explained by the fact that temporal discrimination was easier for the short durations than for the long durations. In an in-depth examination of bisection performance using different ratios and different intervals for one and the same ratio, Wearden and colleagues demonstrated that the *BP* is generally closer to the *AM* than the *GM* when temporal

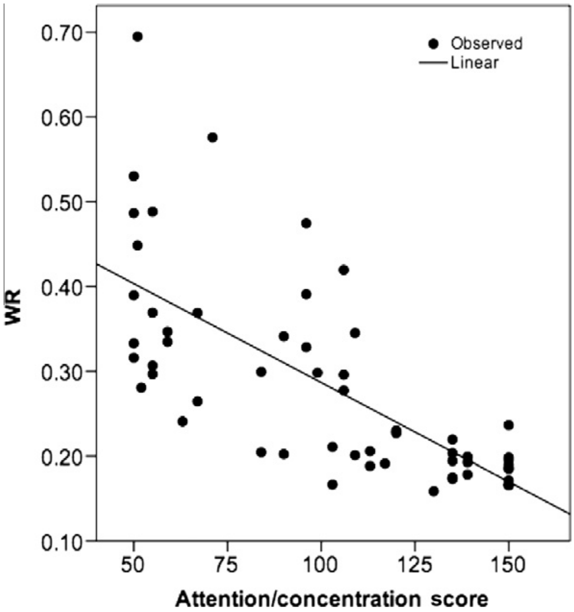

Fig. 5. Linear regression between individual participant Weber ratios (*WR*) and attention/concentration scores.

discrimination is easy and is closer to the *GM* when it is more difficult (Wearden & Ferrara, 1995, 1996; Wearden, Rogers, & Thomas, 1997). Therefore, given the same 2:1 ratio, a shift of the *BP* from the *AM* to the *GM* when the duration values exceed 1 s may indicate that the long durations were judged to be more difficult to discriminate. This is entirely consistent with our analyses of time sensitivity, which suggest that the processing of the short anchor durations was less demanding in terms of high-level cognitive abilities.

The current study clearly shows that sensitivity to time increases throughout childhood, with both the *DL* and *WR* values being higher in 5-year-olds than in 9-year-olds. This is entirely consistent with earlier bisection results obtained with children (Droit-Volet, 2008; Droit-Volet & Wearden, 2001; McCormack et al., 1999). However, the original feature of our study lies in the fact that the participants completed a series of bisection tasks (one per day) with a wide range of anchor durations. This allowed us to show that the developmental course of bisection performance changes as a function of the durations that are to be discriminated. When the anchor durations were shorter than 2.5 s, 9-year-olds achieved a level of time sensitivity (*DL*) close to that observed in adults. However, when the anchor durations were longer than 2.5 s, their sensitivity to time remained low, especially for durations longer than 15 s. For the 15/30-s anchor durations, their temporal sensitivity was the same as that for 5-year-olds. Finally, the longer the durations to be processed were, the more variable and poorer their discrimination was. Therefore, the development of children's ability to discriminate time takes the form of an increased capacity to process longer and longer durations accurately and, thus, resembles an increase in some sort of temporal span. Therefore, the precise processing of durations is achieved earlier for short durations (<2.5 s) than for longer durations.

Our study, which used neurological tests to assess a variety of individual cognitive abilities, revealed that the age-related differences in temporal sensitivity for long durations (>15 s) were specifically mediated by higher level cognitive functions (i.e., the attention/executive function). More precisely, the function involved was selective attention and the associated inhibitory capacities as assessed by the tests from the NEPSY used in our study. Several studies have shown the importance of attention for the processing of long durations (Coull et al., 2004; Lewis & Miall, 2009). So far as young children are concerned, when they estimate durations while performing a concurrent nontemporal task or in the presence of attentional distractors, they systematically produce shorter and more variable durations (Arlin, 1986; Droit-Volet et al., 2006; Gautier & Droit-Volet, 2002b; Zakay, 1992). These findings have been explained in terms of the lesser volume of attentional resources available to young children for the processing of temporal information. Young children do indeed find it difficult to maintain the focus of their attention during the overall passage of time and to resist distractions. This observation is consistent with the idea that that the prefrontal cortex, which is involved in executive functioning, matures slowly throughout childhood. Although a critical period between 4 and 7 years of age has been identified, this maturation continues until a focused, fine-tuned system emerges (Bunge & Wright, 2007; Casey et al., 2005; Tsujimoto, 2008). Therefore, the maturation of the prefrontal cortex and its role in the control of executive functions may explain the development of time sensitivity and its variation as a function of duration values.

In contrast to the processing of long durations, the regression analyses performed in the current study showed that the cognitive factor that mediated the improvement in time sensitivity for the shortest anchor durations (<1 s) was the forward digit span score. This score reflects the involvement of the temporary storage component of working memory, short-term memory, which is considered as the more passive and less controlled aspect of memory (Baddeley & Hitch, 1994). Developmental studies have shown that as of the age of 9 to 11 years, children's short-term memory spans acquire a level similar to that of adults (Gathercole, 1998, 1999). In line with this finding, the sensitivity to time of the 9-year-olds in our study was close to that of the adults for the short durations, whereas their sensitivity to time remained lower for the longer duration values (>2.5 s). Finally, this suggests that the ability to discriminate shorter durations emerges earlier than the ability to discriminate longer durations due to the fact that fewer cognitive resources are required for short durations than for long durations.

Our study was unable to identify any cognitive abilities that significantly predict individual differences in time discrimination in a temporal bisection task between the shortest and longest durations (1.25/2.5 and 4/8 s), with age remaining the main and only significant predictor. Therefore, other factors linked to other general cognitive abilities than those tested in our study or to a specific acuity in the mental representation of time would appear to be responsible for the differences in the processing of durations between 1 and 8 s. However, when we consider the *WR*, a measure that corresponds to the variability in time judgments (*DL*) divided by the *BP* (i.e., a temporal sensitivity standardized on the specific estimated durations), the attention/concentration index appeared to be the only reliable cognitive factor that significantly predicted the individual variations in the *WR*. The attention/concentration index assesses working memory and children's ability to continue to concentrate on a mental activity that requires the manipulation of verbal material. As Riccio, Garland, and Cohen (2007) explained, this index takes account of the necessary overlap between working memory and concentrated attention in a number of cognitive tasks. So far as attention is concerned, several studies have shown that there is an overlap between attention and working memory. First of all, in Baddeley's model of working memory, the central executive administers the attentional resources (Baddeley, 1992). In addition, various developmental studies have indicated the close link between attention and working memory (Alloway & Gathercole, 2006; Cowan, 1997). Consequently, our results suggest that the processing of durations in general is fundamentally related to attentional and working memory capacities that increase during childhood. The specificity of time lies in the fact that it is a continuous flow of information to be accumulated in memory (Droit-Volet, 2010; Droit-Volet, Clément, & Fayol, 2008). Therefore, our results in children are consistent with those reported in studies that have used the temporal reproduction task in elderly people and revealed that deficits in working memory affect time estimation (Baudouin et al., 2006; Perbal, Droit-Volet, Isingrini, & Pouthas, 2002; Ulbrich et al., 2007). For instance, Ulbrich and colleagues (2007) showed that temporal reproduction was longer in participants with a high working memory span than in those with a low working memory span but that the difference between these two participant groups decreased for durations shorter than 3 s. Baudouin and colleagues (2006) also showed that the working memory storage component assessed by the digit span task is the best predictor of performance in a simple temporal reproduction task but that if this task is made to be more complex through the introduction of a concurrent task, the central executive function of working memory becomes the best predictor of temporal performance. The originality of our child study was to show that individual differences in the processing of time are fundamentally linked to attention and working memory capacities and that the scale of individual differences increases as the working memory load grows as a function of the length of durations to be estimated.

To summarize, our studies, which used a bisection task with different anchor durations from a few milliseconds to several seconds, revealed age-related improvement in sensitivity to time and indicated that this improvement occurs earlier for the short durations than for the long durations, with the boundary between these durations lying at approximately 1 to 2 s. The regression analyses revealed that the general development of attention and working memory capacities explained some of the individual differences in time discrimination. Finally, the processing of long durations primarily seems to involve attentional selective functions.

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