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Publisher: Routledge

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The Quarterly Journal of Experimental Psychology

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/pqje20>

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Published online: 02 Mar 2015.

To cite this article: S. Droit-Volet, J. H. Wearden & P. S. Zélanti (2015): Cognitive abilities required in time judgment depending on the temporal tasks used: A comparison of children and adults, *The Quarterly Journal of Experimental Psychology*, DOI: [10.1080/17470218.2015.1012087](https://doi.org/10.1080/17470218.2015.1012087)

To link to this article: <http://dx.doi.org/10.1080/17470218.2015.1012087>

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Cognitive abilities required in time judgment depending on the temporal tasks used: A comparison of children and adults

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The aim of this study was to examine age-related differences in time judgments during childhood as a function of the temporal task used. Children aged 5 and 8 years, as well as adults, were submitted to 3 temporal tasks (bisection, generalization and reproduction) with short (0.4/0.8 s) and long durations (8/16 s). Furthermore, their cognitive capacities in terms of working memory, attentional control, and processing speed were assessed by a wide battery of neuropsychological tests. The results showed that the age-related differences in time judgment were greater in the reproduction task than in the temporal discrimination tasks. This task was indeed more demanding in terms of working memory and information processing speed. In addition, the bisection task appeared to be easier for children than the generalization task, whereas these 2 tasks were similar for the adults, although the generalization task required more attention to be paid to the processing of durations. Our study thus demonstrates that it is important to understand the different cognitive processes involved in time judgment as a function of the temporal tasks used before venturing to draw conclusions about the development of time perception capabilities.

Keywords: Timing; Time; Temporal tasks; Children; Neuropsychology.

Studies on time perception have shown that humans, like other animals, can accurately discriminate durations, and that the variability (standard deviation) of their estimates (sensitivity to time) increases with the length of the intervals to be timed. This led researchers to consider that humans and animals share a primary time sense with its hallmark characteristic—the scalar property

—and the same underlying cerebral mechanism called the internal clock. Developmental studies of time perception have observed this scalar property of time in children of different ages (Droit-Volet, 2002; Droit-Volet, Clément, & Wearden, 2001; Droit-Volet & Wearden, 2001). However, they also found an improvement in time sensitivity throughout childhood. The question is: what are

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We thank all the teachers at the nursery and primary schools in St Germain des Fossés, especially M. Poncet, M-C Ségrafredo, and P. Raynaud.

This study was funded by a Grant (TIMESTORM) from European Commission, Horizon 2010 research and innovation action (H2020-FETPROACT-2014).

the sources of this age-related difference in time sensitivity, given that the internal clock mechanism seems to be functional at an early age?

To examine the perception of time in human beings, many researchers have used tasks similar to those used in animals, namely temporal generalization (Church & Gibbon, 1982), or temporal bisection (Church & Deluty, 1977). These tasks have been adapted to human beings. For example, participants are presented with very few examples of reference durations (usually between three and five) whereas animals are given several sessions, involving hundreds of trials, to learn reference durations. Verbal instructions are also given to humans explaining that they must pay attention to stimulus durations to correctly judge time. However, adjustments of these temporal tasks have modified the nature of the time judgment, with an explicit time judgment being now required rather than an implicit one. Recent studies have shown that explicit time judgment requires high-level cognitive skills linked to executive functions (Block, Hancock, & Zakay, 2010; Brown, Collier, & Night, 2012; Ogden, Salominaite, Jones, Fisk, & Montgomery, 2011; Zélanti & Droit-Volet, 2011, 2012). It is thus likely that differences in time sensitivity across ages would be linked to the development of the cognitive control abilities required in explicit judgment of time (Droit-Volet, 2013).

There is indeed ample evidence that the different components of executive functions including working memory, attentional control (selective attention, inhibition) develop throughout childhood (e.g., Anderson & Reidy, 2012; Gathercole, 2002). This is explained by the slow maturation of the brain with a progressive increase in activation of prefrontal cortex and in the efficiency of its connections with striatal and parietal regions (e.g., Casey, Tottenham, Liston, & Durston, 2005; Rubia, 2013; Sowell et al., 2003). Recently, in a series of studies on time judgment in children, Droit-Volet and Zélanti showed that the sensitivity to time improved along with the increase of working memory capacity as children aged (Droit-Volet & Zélanti, 2013a; Zélanti & Droit-Volet, 2011, 2012). However, these authors only tested sensitivity to time in children with the temporal bisection

task without analyzing the degree of involvement of different cognitive functions as a function of the temporal tasks used. The extent to which the judgment of time depends on cognitive resources may indeed depend on the temporal tasks used. Time judgment could therefore be more difficult in certain tasks than in others for children with limited cognitive resources. The aim of the present study is thus to assess children's capacity in terms of working memory, attentional control and processing speed with a series of neuropsychological tests and to examine how the scores on these tests account for individual differences in time judgment as a function of the temporal tasks used.

In our study, children aged 5 and 8 years, as well as adults, were submitted to 3 temporal tasks currently used with children: the temporal bisection task (e.g., Droit-Volet & Wearden, 2001; McCormack, Brown, Maylor, Darby, & Green, 1999), the temporal generalization task (e.g., Droit-Volet, 2002; Droit-Volet et al., 2001; McCormack, Brown, Smith, & Brock, 2004), and the temporal reproduction task (e.g., Crowder & Hohle, 1970; Droit-Volet, 2010; Szélag, Kowalska, Rymarczyk, & Pöppel, 2002). In temporal bisection, participants are initially presented with two reference durations (one short, s , and one long, l), and must then judge whether comparison durations (equal to s or l , or of intermediate value) are more similar to s or l . In temporal generalization, they are presented with only one reference duration, g , and must judge whether comparison durations (equal to, shorter or longer than g) are equal or not to g . The temporal reproduction task differs from these two temporal discrimination tasks, because the reference duration, r , is given at the beginning of each trial. The participants must reproduce r by pressing a button when they judge that a second, comparison, stimulus has lasted for the same time as r .

To date, no study has directly compared children's time judgment on these 3 tasks by taking into account individual differences in cognitive resources. Temporal reproduction has, however, been compared with temporal production in young and elderly adults (Baudouin, Vanneste, Isingrini, & Pouthas, 2006b; Baudouin,

Vanneste, Pouthas, & Isingrini, 2006a; Perbal, Droit-Volet, Isingrini, & Pouthas, 2002). The results showed that working memory capacities explained a larger proportion of individual variance in temporal performance in the reproduction task than in the production task (Baudouin, Vanneste, Isingrini et al., 2006b; Baudouin, Vanneste, Pouthas et al., 2006a; Perbal et al., 2002). The judgment of time thus requires greater working memory capacity in temporal reproduction than in temporal production. Recently, Ogden, Wearden, and Montgomery (2014) have also compared the young adults' performance on the temporal generalization and the temporal reproduction tasks. They found that working memory capacities were significantly correlated with time accuracy on both generalization and reproduction. Indeed, both these tasks required the monitoring and the maintenance of reference durations and comparison durations in working memory. However, the attentional control-related capacities also explained part of the individual differences in temporal accuracy for temporal reproduction. Ogden et al. (2014, p. 92) suggested that temporal reproduction requires participants to maintain the referent duration in working memory whilst concurrently maintaining the duration of their reproduction. Thus temporal reproduction is more demanding in terms of attention than the other temporal discrimination tasks.

Some developmental studies have identified the critical role of the development of attentional capacities in determining age differences in temporal reproduction performance (for a review see Droit-Volet, Delgado, & Rattat, 2006). According to attentional models of timing (Zakay, 1989; Zakay & Block, 1996, 1998), the less a person attends to time, the more they underestimate stimulus durations. Consistently with these predictions, developmental studies have found a greater shortening of judged time in young children aged 5 years than in older children or adults in a dual-task paradigm, when they processed temporal and non-temporal information in parallel (Arlin, 1986a, 1986b; Gautier & Droit-Volet, 2002a, 2002b; Zakay, 1992). In addition, Block, Zakay, and Hancock (1999) argued that

children are impatient during the reproduction phase and terminate their response early, thus increasing the shortening effect. Consequently, the development of inhibition capacity is also assumed to play an important role in temporal reproduction in children. Its role nevertheless depends on durations used. In temporal reproduction, children underestimate long durations, but overestimate short ones (Droit-Volet, 2010). In her modelling of children's reproduction, Droit-Volet (2010) suggested that the implementation of the motor response involved in the reproduction took longer in 5-year-old children, and that this lengthens their reproduction of short durations (<1 s). Slow processing speed is also characteristic of cognition in young children (Kail, 1991, 2001), so this can also account for age-related differences in temporal reproduction, especially for short durations. In the present study, children and adults were given 3 temporal tasks with both short (<1 s) and long durations. We assumed that the reproduction task would demand more cognitive capacity (working memory, attentional control, processing speed) than do the temporal discrimination tasks (generalization and bisection), as these primarily require working memory capacities (Droit-Volet & Zélandi, 2013a, 2013b; Zélandi & Droit-Volet, 2011, 2012). Consequently, individual scores on neuropsychological tests assessing working memory but also attention and processing speed would explain a larger proportion of individual variance in temporal performance for the reproduction task than for the discrimination tasks (generalization and bisection), and this to a greater extent in young children.

The interest and originality of the present study also lies in its attempts to model individual subject data by using common parameters for the 3 temporal tasks tested, as this will enable a comparison of these tasks using the same statistical analyses and will allow us to evaluate the respective weight of these parameters as a function of the task (see Results for details). In the models of temporal bisection and temporal generalization that fitted well the results from both adults and children (see Church & Deluty, 1977; Droit-Volet, Tourret, & Wearden, 2004; Droit-Volet & Wearden, 2001;

McCormack et al., 1999; Penney, Gibbon, & Meck, 2000; Wearden, 1991, 1992; Wearden & Jones, 2013), there is always a memory variability parameter, C . In models derived from scalar timing theory, indeed the main source of variance in time judgment results from the variability (noise) in the representation of reference durations (Gibbon, 1977; Gibbon, Church, & Meck, 1984). The C parameter which measures this is a sort of coefficient of variation of the value of reference durations in memory: The higher its value, the fuzzier the representation of reference durations is. To account for children's temporal behaviour, McCormack et al. (1999) added a memory distortion parameter, K , to their model of temporal generalization. This idea was then successfully employed by Droit-Volet in modelling generalization (Droit-Volet et al., 2001) and bisection (Delgado & Droit-Volet, 2007). This distortion parameter is a simple multiplicative factor applied to reference durations. If K is 1.0, the reference duration value is remembered on average correctly. If K is $<$ or $>$ 1.0, it is remembered on average as shorter or longer, respectively, than it really was. For the temporal reproduction task, there is no model similar to those used for the bisection and the generalization task (see Droit-Volet, 2010), because the reference duration is not stored in long-term memory and reactivated during the judgment of comparison durations, but instead maintained in working memory on each trial. However, from a comparative perspective, we can apply the same parameters, C and K , to reference durations in reproduction. In this case, these parameters indicate that the representation of reference durations is more or less fuzzy from one trial to another, and distorted (shorter or longer than it really is). Our hypothesis was that reference durations are fuzzier and more distorted in the reproduction task than in the two discrimination tasks, especially in younger children, and that their poor representation of reference durations in temporal reproduction is associated with their low cognitive capacity in terms of working memory, attentional control and processing speed.

In sum, in the present study, we present the results of performance on 3 different temporal

tasks (bisection, generalization, reproduction) in both children and adults, and we examine how working memory, attentional control and processing speed capacities assessed by a battery of neuropsychological tests might explain inter-individual differences in performance on each temporal task. Then, we give the results of C and K parameters resulting from our modelling of individual data and use statistical analyses examining the effect of age on these parameters as a function of the temporal task type. In addition, correlation and hierarchical regression analyses were conducted to determine which cognitive abilities, as assessed by neuropsychological tests, would best explain inter-individual differences in these parameters.

EXPERIMENTAL STUDY

Method

Participants

The sample was composed of 68 participants: 21 5-year-olds (8 girls and 13 boys; mean age = 5.71, $SD = 0.45$), 26 8-year-olds (12 girls and 14 boys; mean age = 8.31, $SD = 0.45$) and 21 adults (11 females and 10 males; mean age = 24.78, $SD = 2.82$). The children were recruited from nursery and primary schools at Saint-Germain-des-Fosses, and the adults were students in Clermont-Ferrand, in the Auvergne region of France. The adults and the parents of the children signed a consent form for participation in this experiment. At the end of the experiment, the children received cartoon cards and the adults 10 Euros to thank them for their participation.

Material

The children and the adults were tested individually in a quiet room in their school or in their university, where they were seated in front of a PC computer that controlled the experimental stimuli and recorded data via E-prime software. The responses were verbal responses for the bisection and the generalization task, and motor responses for the reproduction task. In the reproduction task, the participants pressed the space bar on the computer

keyboard. In the other tasks, they gave their responses orally, and the experimenter pressed the corresponding key to record their response. For all tasks, the stimulus to be timed was a red circle (6 cm in diameter), which was presented in the centre of the computer screen. In addition, in the bisection and the generalization task, a 500-ms feedback stimulus in the form of a cartoon picture (which varied from trial to trial) was presented for a correct response and a picture of unhappy Calimero (a cartoon duck) was presented for an incorrect response.

Procedure

The participants performed 6 temporal tasks at a rate of one per day (a bisection, generalization, and reproduction task), each with 2 duration conditions: 0.4/0.8-s and 8/16-s. In the 0.4/0.8-s condition, the 7 stimulus durations used were 0.4, 0.47, 0.53, 0.6, 0.67, 0.73, and 0.8 s, and in the 8/16-s condition, 8.0, 9.33, 10.67, 12, 13.33, 14.67, and 16 s. The temporal task order was randomized across participants. Furthermore, the experimenter instructed the participants not to count and explained that counting time may bias the scientific data (for a test of the methods used to prevent counting, see Rattat & Droit-Volet, 2012). The results found in our study clearly differed from the accurate time judgments found when participants use counting to make time judgments (Clément & Droit-Volet, 2006; Rattat & Droit-Volet, 2012), suggesting that our instruction not to count was effective. Each day, the participants also completed a series of neuropsychological tests assessing their cognitive capacities.

Temporal bisection task. In the bisection task, the participants were initially presented with the short reference duration (s) (0.4 or 8-s) and the long reference duration (l) (0.8 or 16-s) five times each in alternation. They were then trained to respond “short” or “long” on a series of 4 training trials presented in random order (2 for s and 2 for l), with an inter-trial interval randomly chosen between 0.5 and 2 s. Each response was followed either by the “correct” or “wrong” feedback. This training phase was immediately followed by a testing phase

using the same experimental conditions, except that the participants were presented with the 7 comparison durations described above. In addition, feedback was given for the 2 comparison durations which were the same as the 2 reference durations, but not for the 5 intermediate comparison durations. Each participant completed 9 series of 11-trial blocks (i.e., 99 trials): with 3 trials for each reference duration, and 1 trial for each of the 5 intermediate durations. The trial presentation order within each block was random. After 3 blocks, the participants were again twice presented with each reference duration.

Temporal generalization task. In the generalization task, the participants were initially presented 5 times with the same reference duration (g) (0.6 or 12 s). They were then trained to judge whether the presented durations were (yes) or were not (no) the same as the reference duration. There were 4 training trials: 2 for the reference duration and 2 for 2 other durations (0.3 and 19 s). The inter-trial interval was randomly chosen between 0.5 and 2 s. In this training phase, a “correct” or “wrong” feedback display was given when the response was correct and incorrect, respectively. Immediately after the training phase, the participants were given the testing phase. This was subject to the same experimental conditions as those used in training, with feedback being given after each response. In the testing phase, the participants were given 9 series of 9-trial blocks (81 trials): 3 trials for the comparison duration identical to the reference duration (0.6 or 12-s) and 1 trial for each of the 6 other comparison durations. The trial presentation order was randomized across each trial block. The reference duration was presented twice after every 3 blocks.

Temporal reproduction task. In the temporal reproduction task, the participants were instructed to reproduce as accurately as possible the reference duration of the stimulus they saw on the computer screen. On each trial, a first (reference) stimulus duration (r) was presented followed, after a 500-ms interval, by a second stimulus whose onset was indicated by a symbol. The participant had to

press the space bar of the computer keyboard when he/she judged that the presentation duration of the second stimulus was the same as that of the first stimulus. The participants received 2 demonstrations and were trained on 4 trials with 2 durations (0.3 s and 19 s) presented in random order. In the testing phase, they were given 42 trials: 6 trials for each of the 7 probe durations. Both the stimulus presentation order and the inter-trial interval (between 0.5 and 2 s) were randomized.

Neuropsychological tests. In our study, we used a battery of neuropsychological tests to assess working memory, attention and information processing speed (see Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). To assess working memory capacities, we used the backward version of the Corsi Block-Tapping test from the Wechsler Memory Scale (WMS-III; Wechsler, 1998) which has been shown to account well for individual differences in the estimation of the duration of visual stimuli (Ulbrich, Churan, Fink, & Wittmann, 2007; Zélandi & Droit-Volet, 2012). In this test, the experimenter taps a number of blocks on a board containing nine blocks and the participant has to recall this block-tapping sequence in reverse order. The length of the sequence gradually increases from two to eight blocks, with two trials per sequence length. The working memory score is equal to the total number of correct trials (1 point per correct trial). The attention-concentration index of the Children's Memory Scale (CMS; Cohen, 1997) was also measured. This is also an index of working memory, but is referred to as an attention-concentration index because it requires dynamic/continuous monitoring and

updating of the content of working memory (Riccio, Garland, & Cohen, 2007). Previous studies have shown that participants' scores on this index were better predictors of temporal performance in bisection than the scores on a memory span test (e.g., Zélandi & Droit-Volet, 2011). Indeed, the attention-concentration index is based on two subtests. The first, called number, measures forward and backward digit span. The second, called sequence, assesses 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 in fours. The total raw score is 114 points, and the higher the attention-concentration index is, the greater the participant's attention/concentration capacities are. To measure selective attention, we used the selective visual attention test from a developmental neuropsychological assessment scale (NEPSY; Korkman, Kirk, & Kemp, 1998), which assesses participants' ability to selectively focus their attention on a visual target (i.e. a cat or a specific face) located in an array of 96 different items. The score is the time in seconds needed to complete the task divided by the number of correct visual targets found. Consequently, high scores on this test correspond to poor selective attention capacities (see Table 1). To assess selective attention with an inhibitory dimension, we used a Stroop test adapted for use with children (Albaret & Migliore, 1999). In this task, the participant initially reads 50 colour words (e.g. blue, yellow, green, red) printed in black and white. He/she then names the colours of 50 squares and, finally, he/she must read a colour word printed in a colour different from that of the word. The score is the time taken to complete this last phase: The higher it is, the lower

Table 1. Mean and error standard of scores on the neuropsychological tests for the 5-year-olds, the 8-year-olds, and the adults

Neuropsychological scores	5 years		8 years		Adults	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Working Memory	4.40	0.36	6.23	0.30	8.38	0.33
Att. Concentration	34.80	1.87	58.23	1.67	88.62	1.68
Selective Attention	8.72	0.50	5.68	0.25	2.98	0.13
Att. Inhibition	46.10	3.87	48.22	2.77	18.63	0.94
Processing Speed	37.79	3.34	25.76	1.29	11.22	0.67

the attention inhibition capacities are (Table 1). Finally, we measured information processing speed, which is a major measure of cognitive efficiency (Grégoire, 2007), by using the well-known Trail Making Test part A (TMT-A, Reitan, 1992). In TMT-A, the participant is presented with 25 circles, each of which contains a number, which are distributed randomly on a sheet of paper. He/she has then to connect these circles in ascending numerical order, as quickly as possible. The score is the amount of time required to complete this task. The higher the score on the TMT-A, the slower the information processing speed is (Table 1). The mastery of numbers was previously verified in the children we tested.

Results

Temporal performance

Temporal Bisection. Figure 1 shows the proportion of “long” responses ($p(\text{long})$) plotted against test stimulus durations for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition. To examine the participants’ temporal performance in bisection,¹ two indices were calculated: the Bisection Point (BP) and the Weber Ratio (WR). The BP is the point of subjective equality, i.e., the stimulus duration where $p(\text{long}) = .50$. The WR is a sort of coefficient of variation. It is the Difference Limen ($[D(p(\text{long}) = .75) - D(p(\text{long}) = .25)] / 2$) divided by the BP. The higher the WR, the flatter the psychometric function, and the more variable the temporal discrimination is. In other words, the higher the WR, the lower the sensitivity to time is. The BP and the WR were obtained by approximating each participant’s bisection function using the statistical linear function from the SPSS program. This linear function produced the best fits for all participants. For each of these temporal indexes, an ANOVA was performed with duration range (0.4/0.8-s vs. 8/16-s) as within-subjects factor and age as between-subjects factor.

Bisection point. The ANOVA on the BP did not reveal either a significant main effect of age, $F(2, 65) = 0.15, p > .05$, or any significant age \times duration interaction, $F(2, 65) = 0.21, p > .05$ (Figure 2). There was only a significant main effect of duration, $F(1, 65) = 1569, p < .05$, indicating that the BP was higher for the long than for the short durations.

Weber ratio. In contrast to the BP, there was a significant main effect of age for the WR, $F(2, 65) = 10.67, p < .05$, revealing a developmental improvement in sensitivity to time. The 5-year-olds ($M = .48, SE = .03$) exhibited a higher WR, indicating lower sensitivity to time, than the 8-year-olds ($M = .37, SE = .03$) and the adults ($M = .26, SE = .03$) (Scheffé test, all $p < .05$). The WR did not differ significantly between the 8-year-olds and the adults ($p = .06$). In addition, the main effect of duration, $F(1, 65) = 36.73, p < .05$, as well as the age \times duration interaction, $F(2, 65) = 3.27, p < .05$, reached significance. The main effect of age was always significant whatever the duration condition (0.4/0.8-s: $F(2, 65) = 7.77, 8/16$ -s: $F(2, 65) = 6.77$, all $p < .05$). However, as illustrated in Figure 2, the sensitivity to time was lower in the long ($M = .48, SE = .04$) than in the short duration condition ($M = .25, SE = .01$), even though the magnitude of the difference in time sensitivity between the two duration conditions decreased with increasing age. Indeed, the adults produced similar WRs in the 8/16-s and in the 0.4/0.8-s duration condition, $t(20) = 1.96, p > .05$, whereas the 5-year-olds and the 8-year-olds produced higher WRs in the long than in the short duration condition [$t(20) = 4.99; t(25) = 3.33$, respectively, $p < .05$]. In fact, as far as the children are concerned, this significant effect of duration ranges on the WR revealed a violation of Weber’s law (i.e., the scalar property of variance) that postulates that WR values should remain constant for different duration ranges. This violation of the scalar property of variance is clearly illustrated in Figure 3 which shows that

¹The initial ANOVA run on $p(\text{long})$ is not reported because it provided results close to those obtained for the Bisection Point and the Weber Ratio.

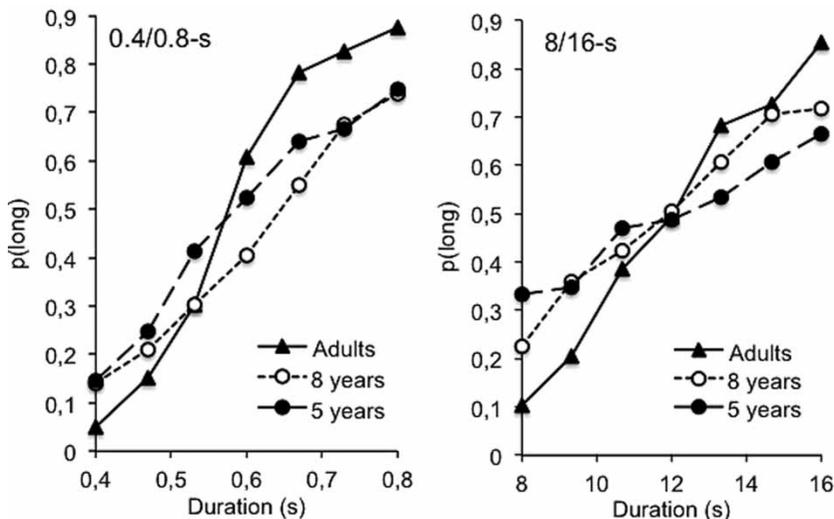


Figure 1. Temporal Bisection. Proportion of long responses ($p(\text{long})$) plotted against stimulus durations for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

the children's psychometric functions derived from different duration ranges did not superimpose well when plotted on the same relative scale. This illustrates children's difficulties in processing long durations in bisection.

Temporal Generalization

The mean generalization gradients for each age group are presented in Figure 4, which plots the proportion of "yes" responses (judgments that the just-presented stimulus had the same duration as the standard) against the stimulus duration. Temporal discrimination seems poorer in the generalization task than in the bisection task, with temporal gradients being particularly flat in the two groups of children. However, to further examine generalization performance, we calculated two temporal indices: (1) the peak time of the generalization gradient, which is the stimulus duration which gives rise to the highest proportion of yes responses and (2) the width of the generalization gradient at half of its maximum height (full width at half maximum, FWHM). The FWHM divided by the peak time is also a sort of coefficient of variation. The higher

its value, the larger the width of the generalization gradient, and the lower the sensitivity to time. The peak time and the FWHM were obtained by approximating each participant's generalization gradient using the Gaussian (*Amplitude*) function from the PeakFit program (PeakFit version 4.2 for Windows) that provided the best fit for the temporal gradients of most of the participants. For one 5-year-old child, it was impossible to obtain a peak time because his/her temporal gradient was totally flat. The maximum value of FWHM/peak time (1.0) was thus attributed to this participant (for this method, see e.g., Droit-Volet, 2008; Droit-Volet & Zélanti, 2013a) and her/his peak time was not included in the subsequent statistical analysis.

Peak time. An ANOVA² on the peak time with the same factorial design as that reported in bisection found a significant main effect of duration, $F(2, 64) = 3235$, $p < .05$, but neither a main effect of age, $F(2, 64) = 1.95$, $p > .05$, nor an age \times duration interaction, $F(2, 64) = 1.84$, $p > .05$ (Figure 5). Consequently, there was no significant developmental difference in temporal accuracy.

²The initial ANOVA run on $p(\text{yes})$ is not reported because it provided results close to those obtained based on peak time and the width of the generalization gradient.

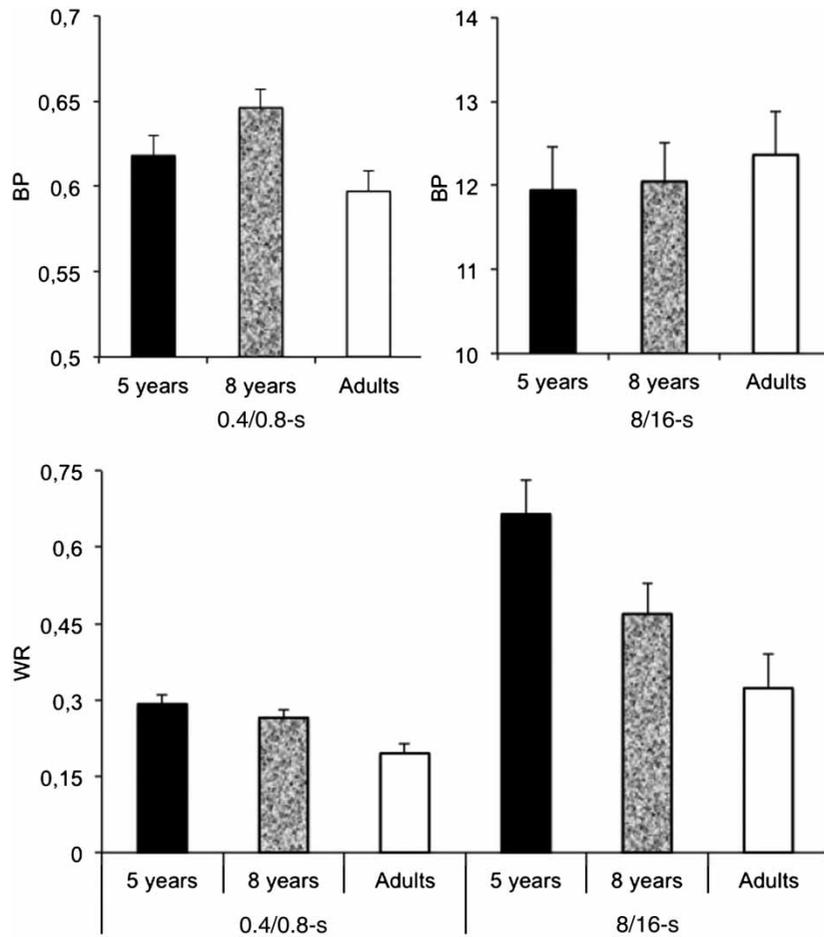


Figure 2. Temporal Bisection. Mean (standard error) Bisecting Point (BP) and Weber ratio (WR) for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

FWHM/peak time. As in the temporal bisection task, the index of time sensitivity (FWHM/peak time) in the generalization task changed with the age. However, in generalization, the age-related difference did not increase with the length of the durations judged. Indeed, the ANOVA showed a significant main effect of age, $F(2, 65) = 5.51$, $p < .05$, without a significant interaction between age and duration, $F(2, 65) = 1.43$, $p > .05$. As suggested by the particularly flat generalization gradients, sensitivity to time was particularly low in the 8-year-olds (.59) and was at a level close to that observed in the 5-year-olds (.54) (Scheffé test, $p > .05$), whereas it was higher in the 8-year-olds

than in the 5-year-olds in the bisection task. However, the only significant difference revealed by the results was between the adults and the youngest children (.46 vs. .59, $p < .05$). The time sensitivity index (FWHM/peak time) in generalization thus suggested a slower age-related improvement in performance on the generalization task than on the bisection task. The ANOVA also showed a significant main effect of duration, $F(1, 65) = 7.68$, $p < .05$, demonstrating that variability in temporal discrimination was greater for the long than for the short durations (.58 vs. .48). This finding is consistent with the violation of Weber's law found in bisection.

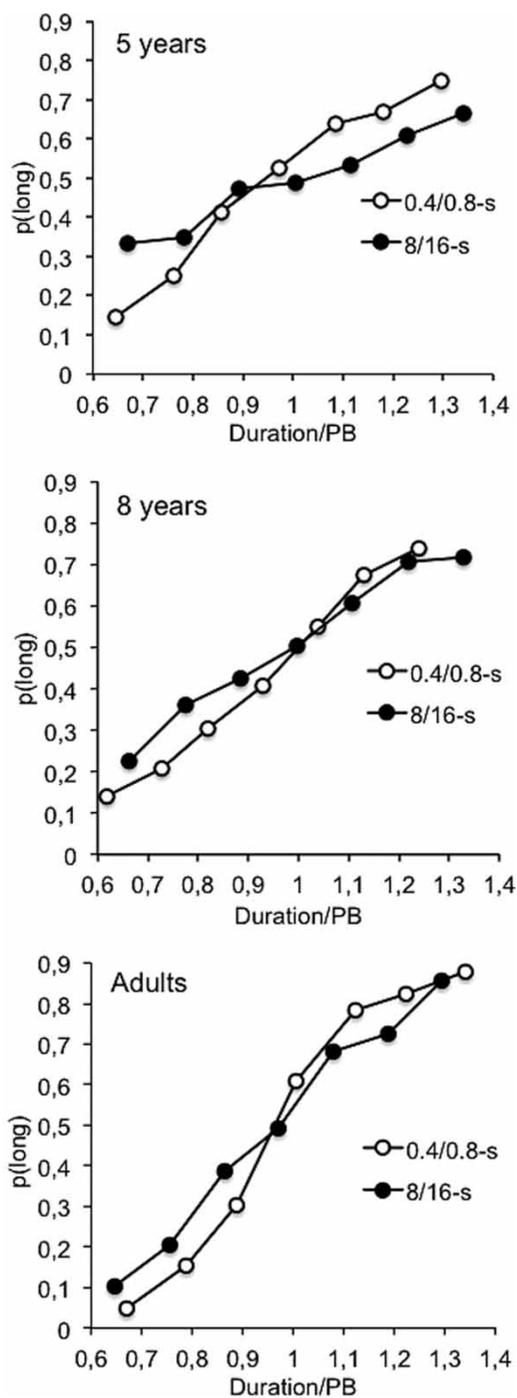


Figure 3. Temporal Bisection. Psychometric functions for the short (0.4/0.8-s) and the long (8/16-s) duration condition plotted against the same relative scale for the 5-year-olds, the 8-year-olds and the adults.

Temporal reproduction

Mean reproduced duration. In the temporal reproduction task, the mean reproduced durations increased on average in an orderly way as a function of stimulus duration both in the children and in the adults (Figure 6). However, there was a systematic bias in the reproduced durations in the younger children compared to the older participants, with the 5-year-olds producing longer durations in the 0.4/0.8-s condition and shorter durations in the 8/16-s condition. An ANOVA was conducted on the mean reproduced durations with stimulus duration and duration range as within-subjects factor and the age as between-subjects factor. The stimulus duration, $F(6, 390) = 76.74, p < .05$, the duration range, $F(1, 65) = 1756, p < .05$, and the interaction between these 2 factors, $F(6, 390) = 49.28, p < .05$, were all significant. More interestingly, the main effect of age was also significant, $F(2, 65) = 3.44, p < .05$, and age interacted significantly with duration and duration range, $F(2, 65) = 7.33, p < .05$. The other interactions were not significant. In the 0.4/0.8-s condition, the 5-year-olds ($M = 1.13, SE = .08$) produced longer durations than did the 8-year-olds ($M = 0.82, SE = .03$) and the adults ($M = 0.82, SE = 0.06$) (Scheffé test, both $p < .05$), while the mean reproduced durations were similar between the 8-year-olds and the adults ($p > .05$). In contrast, in the 8/16-s condition, the 5-year-olds reproduced durations ($M = 8.75, SE = .04$) shorter than those of the adults ($M = 10.43, SE = 0.03$) ($p < .05$), with the length of durations reproduced by the 8-year-olds ($M = 9.45, SE = .04$) lying between those reproduced by the 5-year-olds and the adults. In sum, while temporal “accuracy” was similar across age groups in the temporal discrimination tasks, in temporal reproduction, temporal accuracy was lower in the youngest children because they produced greater overestimations and underestimations of the short and the long durations, respectively.

Variability of durations reproduced. The ANOVA on the coefficient of variation of temporal reproductions (SD/M) also showed a main effect of duration range, $F(1, 65) = 30.97, p < .05$, with

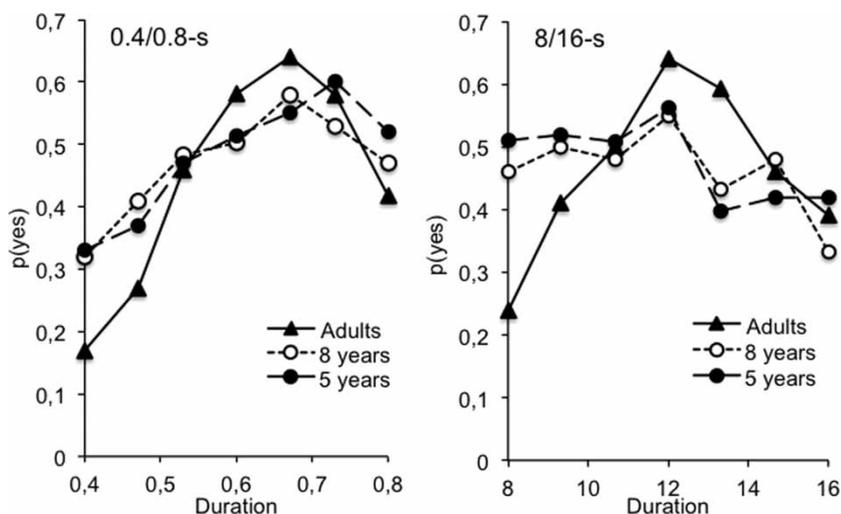


Figure 4. Temporal Generalization. Proportion of yes responses ($p(\text{yes})$) plotted against stimulus durations for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

no interaction involving this factor ($p > .05$). This therefore pointed to a violation of Weber's law in the temporal reproduction task as in the other temporal discrimination tasks. However, in contrast to these discrimination tasks, temporal variability assessed by coefficient of variation was greater in the reproduction task for the short than for the long durations (.46 vs. .34) and not the reverse (Figure 7). There was also a main effect of age, $F(2, 65) = 35.71$, $p < .05$, which revealed an increase between each age group in the sensitivity to time (5 years: $M = .52$, $SE = .02$; 8 years: $M = .38$, $SE = .02$; Adults: $M = .29$, $SE = .02$, Bonferroni tests for all comparisons, $p < .05$). The age \times stimulus duration interaction was also significant, $F(12, 390) = 2.11$, $p < .05$. The statistical analyses nevertheless revealed that this significant interaction was linked to the effect of stimulus durations on SD/M that tended to be significant in the 5-year-olds, $F(6, 120) = 2.16$, $p = .08$. However, no difference in the coefficient of variation between the stimulus durations reached significance.

Correlation between the timing measures and neuropsychological scores

Table 1 presents the mean and the standard error of scores obtained by the children and the adults on the different neuropsychological tests.³ For each neuropsychological test, the effect of age was significant: Working memory, $F(2, 64) = 34.70$; Attention concentration, $F(2, 64) = 222.07$; Selective attention, $F(2, 64) = 76.66$; Attention inhibition, $F(2, 57) = 42.36$; Processing speed, $F(2, 64) = 42.16$ (all $p < .05$), with all pairwise comparisons between age groups being significant (Scheffé, all $p < .05$).

Table 2 shows, for the 3 temporal tasks, the correlations between the timing measures for the short (0.4/0.8-s) and the long (8/16-s) duration condition and the z-scores on neuropsychological tests calculated for the 3 age groups. When there were significant correlations between the timing measures and scores on several neuropsychological tests, we entered these different scores into the equation and ran hierarchical regression analyses to identify which factor was the best predictor of

³Among the twenty-one 5-year-olds, one child did not perform the different neuropsychological tests. The attention inhibition scores for 8 children were not included in Table 1 because they were unable to read the color name correctly.

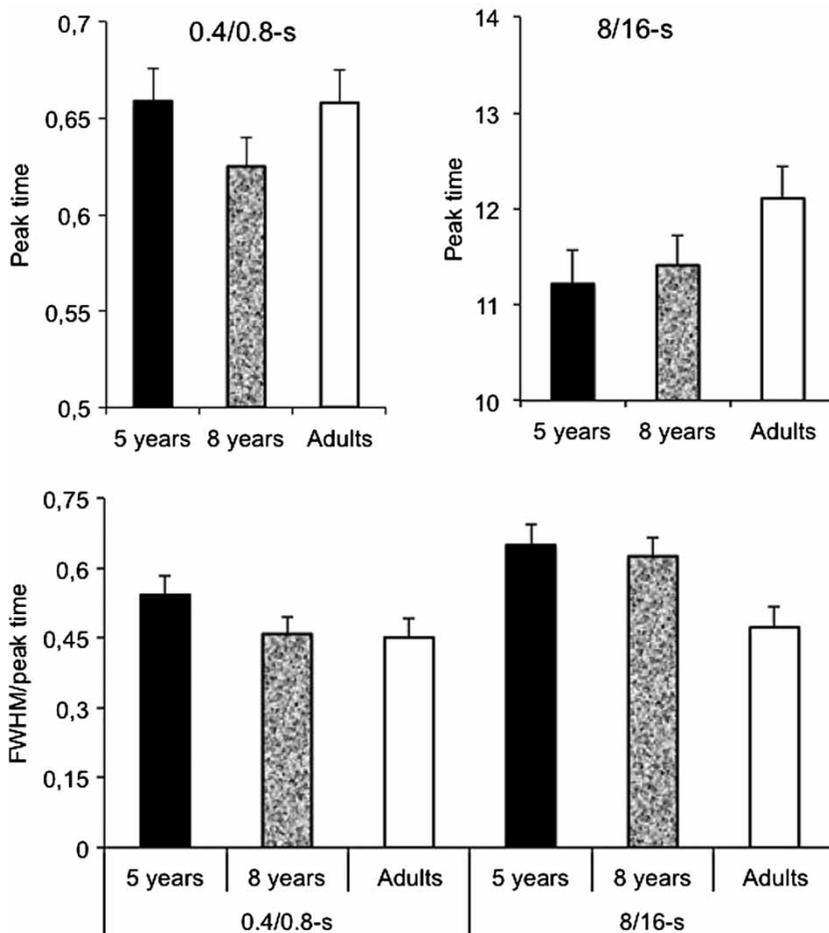


Figure 5. Temporal Generalization. Peak time and FWHM/peak time for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

individual variance in these timing measures for each type of task.

Temporal Bisection

Bisection point. In line with the absence of an age effect on the BP, there was no correlation between the BP and the scores on the neuropsychological tests (Table 2), with the exception of the BP in the short duration condition, in which we observed a significant correlation between the BP and the scores on the attention inhibition test, $R = .30$, $p < .05$. This result suggests that when the attention inhibition capacities decreased, the

BP for the short durations shifted toward the right (lower BP values), a finding which is consistent with a shortening effect.

Weber ratio. Table 2 shows that the WR for the short and the long duration were significantly correlated with 5 and 4, respectively, of the different neuropsychological scores. The various significant scores were therefore entered into the equation of the hierarchical regression analyses. This analysis revealed that the only reliable predictor of individual variances in time sensitivity was the scores on the attention-concentration test and that this

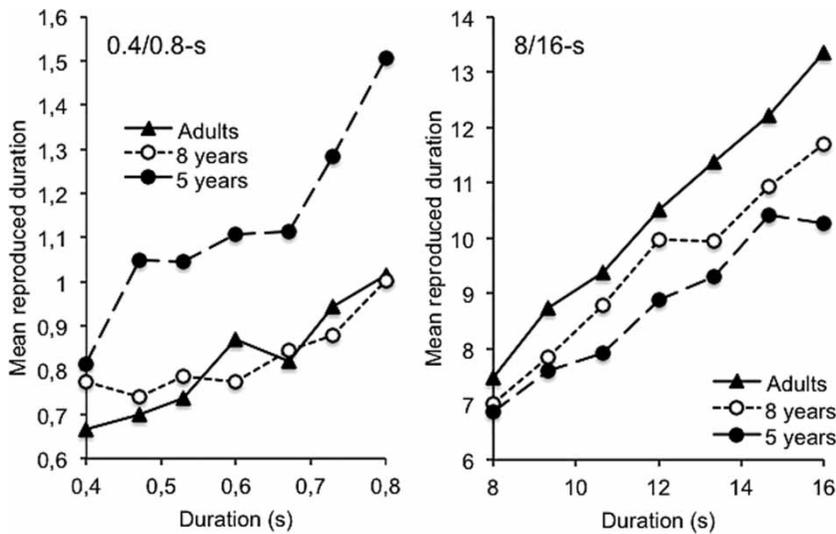


Figure 6. Temporal reproduction. Mean reproduced duration for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

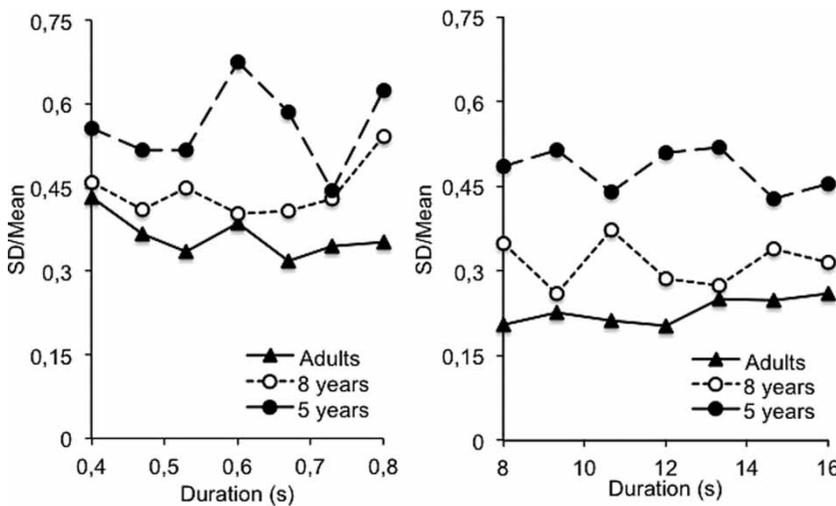


Figure 7. Temporal reproduction. Coefficient of variation (SD/M) of reproduced duration for the 5-year-olds, the 8-year-olds and the adults in the short (0.4/0.8-s) and the long (8/16-s) duration condition.

was true both for the short ($\beta = -.49, R^2 = .24, p < .05$), and for the long duration condition ($\beta = -.56, R^2 = .31, p < .05$). The higher the attention-concentration scores, the lower the WR and the higher the sensitivity to time was. This finding is entirely consistent with that

obtained in previous bisection studies using neuropsychological tests in children that showed that the improvement in time sensitivity depends on working memory capacities assessed by this neuropsychological test (Zélanti & Droit-Volet, 2011).

Table 2. Correlation between neuropsychological scores and timing measures on bisection, generalization, and reproduction for the 0.4/0.8 and the 8/16-s duration condition?

Neuropsychological scores	Bisection				Generalization				Reproduction			
	PB		WR		Peak Time		FWHM/Peak		Mean		SD/Mean	
	S	L	S	L	S	L	S	L	S	L	S	L
Working Memory	-.04	.03	-.36**	-.38**	.02	.30*	-.14	-.18	-.37**	.33**	-.49**	-.62**
Att. Concentration	-.16	.01	-.48**	-.40**	.09	.31*	-.18	-.31*	-.38**	.31*	-.50**	-.63**
Selective Attention	.11	-.06	.43**	.21	.07	-.20	.08	.33**	.40**	-.22	.47**	.59**
Att. Inhibition	.30*	-.09	.40**	.39**	-.26*	-.11	.27*	.26*	.02	-.17	.30*	.36**
Processing Speed	.17	.19	.46**	.34**	-.05	-.12	.16	.31*	.45**	-.23	.50**	.64**

Note: Underlined numbers = significant predictors resulting from the hierarchical regression analyses. Neuropsychological scores = z-scores. Duration condition: S (short) = 0.4/0.8 s; L (long) = 8/16 s.

* $p < .05$; ** $p < .01$.

Temporal Generalization

Peak Time. In the generalization task, temporal accuracy was significantly correlated with attention inhibition scores for the short durations, $R = .26$, $p < .05$ (Table 2). When the attention inhibition capacities decreased, the peak time also decreased, a finding that is consistent with the shortening effect observed in bisection. However, concerning the long durations, the peak time value was correlated with both the working memory scores, $R = .30$, $p < .05$, and the attention-concentration scores, $R = .31$, $p < .05$. The hierarchical regression analyses with these two scores nevertheless revealed that the attention-concentration scores were better predictors of individual variance in the peak time value, irrespective of the order in which the factors were entered into the equation ($\beta = .30$, $R^2 = .09$, $p < .05$), although the amount of variance explained remained low. In other words, the temporal gradient tended to peak at a shorter value when the individuals' attention-concentration capacities decreased.

FWHM/peak time. The attention components of cognitive functions were also related to differences in the width of the temporal generalization gradient (FWHM/peak time). There was a significant correlation between this index of temporal variability and the scores on the attention inhibition test in the short duration condition, $R = .27$, $p < .05$

(Table 2). For the long duration condition, the hierarchical regression analyses revealed that participants' scores on selective attention were the only reliable predictor of individual differences in the width of the generalization gradient ($\beta = .29$, $R^2 = .08$, $p < .05$). The variability in time judgments in generalization therefore increased when the attentional components of executive functions decreased.

Temporal Reproduction

Mean reproduced duration. An initial inspection of the results in Table 2 shows that a great number of cognitive factors significantly interacted with the performance indices calculated for the temporal reproduction task compared to those calculated for the temporal discrimination tasks. The hierarchical regressions performed with the significant neuropsychological scores nevertheless indicated that the scores for information processing speed were the only reliable predictor of individual differences in the mean reproduced duration for the short durations ($\beta = .45$, $R^2 = .20$, $p < .05$), whereas this role was played by the working memory scores in the case of the long durations, ($\beta = .33$, $R^2 = .11$, $p < .05$). There was therefore a lengthening effect on estimates of short durations when the information processing speed slowed down. Furthermore, estimates of long durations also shortened with decreasing memory capacities.

Variability of durations reproduced. The hierarchical regressions also revealed that, taken together, the scores for information processing speed and working memory helped explain individual differences in the variability of reproduced durations ($SD/Mean$) for the long durations ($\beta = .69$, $R^2 = .48$, $p < .05$), although processing speed appeared to be the best predictor of this performance index ($\beta = .64$, $R^2 = .41$, all $p < .05$). For the short durations, processing speed was the only reliable predictor ($\beta = .50$, $R^2 = .25$, $p < .05$). The increase in variability of time estimates was thus associated with a slowing down of information processing speed.

Modeling of Data

Model description. As mentioned in the introduction, we modelled each participant's data for the 3 temporal tasks by selecting two parameters of scalar timing-consistent models used to account for temporal performance on both the bisection and the generalization task (see Wearden & Jones, 2013). The first parameter, C , is a variability parameter applied to the reference durations: The higher its value, the fuzzier the representation of reference durations is. The second parameter, K , is a distortion parameter, which was applied to reference durations. If K is 1.0, the reference duration value is remembered correctly. If K is $<$ or $>$ 1.0, it is remembered as shorter or longer, respectively, than it really is.

Applied to the bisection task, the model calculated two absolute differences – $abs[D(s^*K, t)]$ and $abs[D(l^*K, t)]$ – between the stimulus duration to be judged, t , and s^* or l^* . s^* or l^* (s for the short reference duration, and l for the long reference duration) differed from trial to trial and were drawn from Gaussian distributions with means equal to s and l , and some coefficient of variation, C (for an illustration of this model, see Delgado & Droit-Volet, 2007). K was a multiplier of the short or long reference duration. This K value was drawn from a large list of K values. Finally, the model assumed that the participant responded “short” when $abs[D(s^*K, t)] < abs[D(l^*K, t)]$ and “long” when $D(s^*K, t) > D(l^*K, t)$.

The same C and K parameters were used in the generalization model, except that they were applied to one reference duration, g . In addition, in the

generalization task, a decision parameter was required to fit the individual data correctly. Based on the decisional values found in other studies (e.g., Droit-Volet et al., 2001; McCormack et al., 1999), we decided to set this decisional parameter value to .20 for all the participants (for an illustration of the effect of this parameter in the model, see Droit-Volet et al., 2001). A lower value did not produce significant fits with our data. When $abs[(g^*K) - t]/t < .20$, then the model assumed that the participant responds “yes”.

In the reproduction task, after unsuccessfully testing a series of models related to the complexity of this task, we decided to simply consider that the participant uses the remembered reference duration, r , in working memory and responds when he/she judges that the reference duration is ended. The C and K parameters were thus applied to r values (the 7 reference durations) using the previously described procedure (r^*K).

For each task, the model, which was implemented in a computer programme written in Visual Basic 6.0 (Microsoft Corporation), was run for 1000 trials, and C and K were varied over a wide range to obtain the best-fitting simulation for data from each individual participant in terms of mean absolute deviation (MAD), the sum of the absolute deviations between the predictions of the simulation and the individual data, divided by 7, the number of stimulus durations to be judged (t). Table 3 gives the mean individual values of parameters obtained with our modelling, with the mean MAD. The MAD, equal or smaller than 0.10 for each task revealed that our model fitted the data reasonably well, although the fit was poorer for the generalization task than for the other tasks, especially in children.

Analyses of age and task effects on K (reference duration distortion) and C (reference duration variability) parameters

Distortion in temporal reference (K parameter). As illustrated Figure 8, the magnitude of the distortion of reference durations was larger in the temporal reproduction task in terms of shortening for the long durations and of lengthening for the short durations than in the discrimination tasks. An ANOVA

Table 3. Mean and standard deviation of the K parameter and the C parameter resulting from modelling of individual data for the 5-year-olds, the 8-year-olds and the adults in the temporal bisection, generalization and reproduction tasks for the short and the long duration conditions

Group	Task	Duration condition	K		C		MAD	
			M	SD	M	SD	M	SD
5-year-olds	Bisection	Short	0.95	0.02	0.50	0.04	0.06	0.01
		Long	0.86	0.05	0.70	0.05	0.07	0.01
	Generalization	Short	1.03	0.03	0.35	0.03	0.08	0.01
		Long	0.91	0.03	0.40	0.03	0.09	0.01
	Reproduction	Short	1.65	0.09	0.82	0.03	0.07	0.01
		Long	0.68	0.03	0.78	0.04	0.02	0.01
8-year-olds	Bisection	Short	0.98	0.02	0.49	0.03	0.06	0.01
		Long	0.87	0.05	0.63	0.05	0.07	0.01
	Generalization	Short	1.02	0.03	0.37	0.03	0.08	0.01
		Long	0.92	0.03	0.40	0.03	0.08	0.01
	Reproduction	Short	1.21	0.08	0.80	0.03	0.05	0.01
		Long	0.74	0.03	0.77	0.03	0.02	0.01
Adults	Bisection	Short	0.97	0.02	0.26	0.04	0.01	0.01
		Long	0.98	0.05	0.37	0.05	0.04	0.01
	Generalization	Short	1.05	0.03	0.30	0.03	0.04	0.01
		Long	0.99	0.03	0.32	0.03	0.06	0.01
	Reproduction	Short	1.25	0.09	0.82	0.03	0.04	0.01
		Long	0.83	0.03	0.73	0.04	0.01	0.01

Note: K parameter = reference duration distortion; C parameter = reference duration variability; MAD = mean absolute deviation, the sum of the absolute deviations between the data and the model fit divided by the number of data points. Duration condition: short = 0.4/0.8 s; long = 8/16 s.

was run on the K parameter, with task and duration as within-subjects factor and age as between-subjects factor. This ANOVA revealed a significant main effect of task, $F(2, 130) = 10.85$, $p = .0001$. However, there was also a significant 3-way interaction between task, duration and age, $F(4, 130) = 5.83$, $p = .0001$, which subsumed a significant main effect of duration, $F(1, 65) = 209.16$, $p = .0001$, and significant 2-way interactions between task and age, $F(4, 130) = 3.77$, $p = .02$, and task and duration, $F(2, 130) = 68.09$, $p = .0001$. Only the main effect of age did not reach significance, $F(2, 65) = 2.37$, $p = .10$, although age significantly interacted with duration, $F(2, 65) = 14.10$, $p = .0001$.

To examine this significant 3-way interaction, we conducted ANOVAs on the K parameter for each age group taken separately. For each age group, there was a significant task \times duration interaction [5 years, $F(2, 40) = 31.39$; 8 years,

$F(2, 50) = 18.11$; adults, $F(2, 65) = 16.29$, all $p < .001$]. To further analyze our results in terms of a shortening or lengthening of the reference duration for the two ranges of durations, we calculated the difference between K and 1 and ran a series of one-sample t -tests.

For the long durations, the analyses of this value ($K - 1$) revealed that the reference durations were systematically distorted in the reproduction task in line with a shortening effect [all one-sample t -tests²: 5 years, -0.31 , $t(20) = -11.63$; 8 years, -0.26 , $t(25) = -7.01$; adults, -0.17 , $t(20) = -5.66$, $p < .05$]. In the generalization task, this shortening effect for the reference durations disappeared in the adults, $t(20) = -0.50$, $p > .05$, but was still observed in the 5-year-old, $t(20) = -2.82$, and 8-year-old children, $t(25) = -3.32$, both $p < .05$. Similarly, the adults remembered the reference durations correctly in the bisection task,

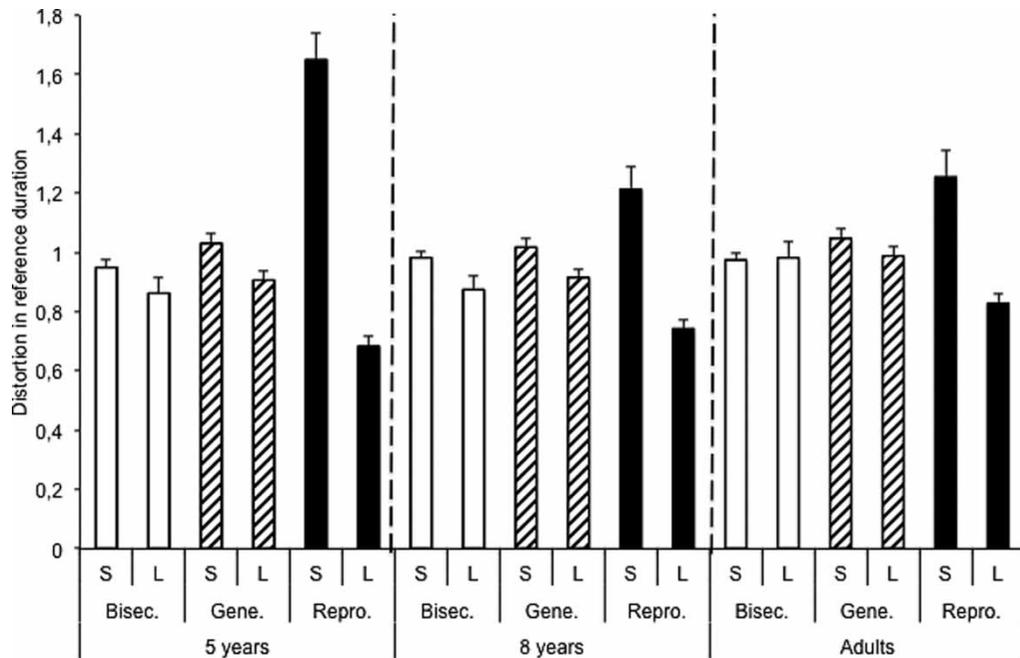


Figure 8. Reference duration distortion parameter, K , resulting from our modelling of individual data for the 5-year-olds, the 8-year-olds and the adults in the temporal bisection, generalization and reproduction tasks, for the 0.4/0.8 (S) and the 8/16-s (L) duration conditions.

$t(20) = -0.66$, $p > .05$, whereas the children remembered or tended to remember these durations as being shorter than they actually were at 8 and 5 years of age [$t(25) = -3.18$, $p < .05$; $t(20) = -1.87$, $p = .07$].

For the short durations, in the reproduction task, the $K - 1$ difference was significantly greater than zero in all age groups, indicating a lengthening rather than a shortening effect on the reference durations [all one-sample t -tests²: 5 years, 0.65, $t(20) = 6.22$; 8 years, 0.21, $t(25) = 3.70$; adults, 0.25, $t(20) = 2.71$, $p = .01$]. This lengthening effect was nevertheless greater in the 5-year-old children than in the 2 older age groups (Bonferroni tests, all $p < .05$) for which similar memory distortion values were observed ($p > .05$). Unlike in the reproduction task, for the short durations, no significant distortion of the reference duration was found in any age group in the generalization task, suggesting that both the children and the adults accurately remembered the short reference duration in generalization (all $p > .05$).

Similarly, the $K - 1$ difference differed from zero in the bisection task only in the youngest children. In other words, the 8-year-old children and the adults remembered the reference durations correctly in the short condition, whereas the 5-year-olds remembered the reference durations as shorter than they actually were [-0.5 , $t(20) = -2.09$, $p = .049$]. However, for the short durations, the magnitude of the temporal memory distortions did not significantly differ between age groups in the two discrimination tasks (all pairwise comparison using the Sheffé tests, $p > .05$), whereas it was greater in the 5-year-olds than in the 8-year-olds and the adults in the reproduction task ($p < .05$), with no difference being observed between these two older age groups.

Variability in temporal reference (C parameter). In the same way as for the results for the distortion parameter, those for the variability parameter, C , revealed important differences between the temporal reproduction task and the other

discrimination tasks (Figure 9). The ANOVA run on the C parameter, using the factorial design described above, showed a significant main effect of task, $F(2, 130) = 197.80$, $p = .0001$, indicating that the variability in the representation of reference durations was higher in the reproduction task than in the generalization and the bisection task (Bonferroni tests, all $p < .05$). Although not expected, the C parameter value was also higher in the bisection task than in the generalization task ($p < .05$). However, there was a significant task \times age interaction, $F(4, 130) = 7.72$, $p = .0001$, as well as a significant main effect of age, $F(2, 65) = 17.86$, $p = .0001$, which suggested that the variability in the memory representation of reference durations was lower in the adults than in the children (Scheffé tests, $p < .05$), with no difference being observed between the two groups of children ($p > .05$). No other interaction involving age was significant. For each age group

taken separately, the task effect was significant [5 years, $F(2, 40) = 61.20$; 8 years, $F(2, 50) = 45.85$; adults, $F(2, 40) = 161.46$, all $p = .0001$]. This indicated that the proportion of noise in the representation of reference durations was greater in the reproduction task than in the two temporal discrimination tasks (bisection and generalization) in all age groups (Bonferroni tests, $p < .05$). However, the C parameter values were similar in the two discrimination tasks for the adults, ($p > .05$), whereas they were higher in the bisection than in the generalization task for the 5-year-olds and for the 8-year-olds ($p < .05$). In sum, the time judgment in the reproduction task resulted in part from the fact that the representation of reference durations was more variable than in the temporal discrimination tasks, although the variability in temporal memory appeared to be higher in the bisection than in the generalization task.

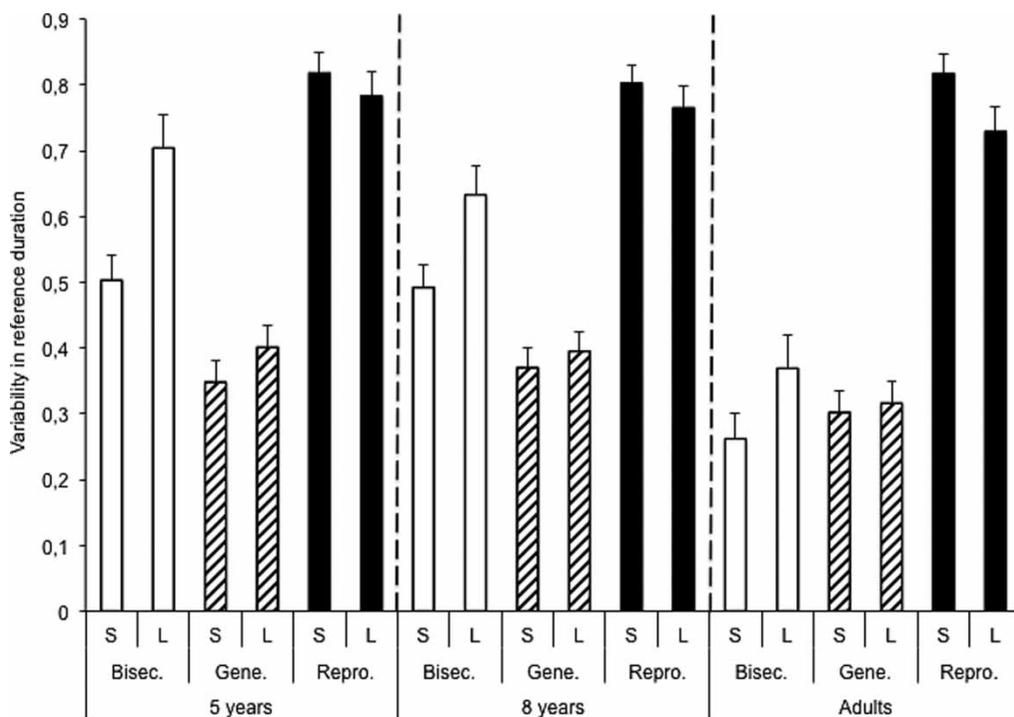


Figure 9. Reference duration variability parameter, C , resulting from our modelling of individual data for the 5-year-olds, the 8-year-olds and the adults in the temporal bisection, generalization and reproduction tasks, for the 0.4/0.8 (S) and the 8/16-s (L) duration conditions.

In addition, the overall ANOVA run on the *C* parameter showed a significant main effect of duration, $F(1, 65) = 8.72, p = .004$, and a significant interaction between duration and task, $F(4, 130) = 12.22, p = .0001$. This revealed that the memory variability parameter was similar for both the short and the long durations in the generalization task ($p > .05$), whereas it was higher for the long than for the short duration in the bisection task ($p < .05$). At the same time, the *C* parameter was higher for the short than for the long durations in the reproduction task ($p < .05$).

Moreover, the analyses of correlation between the *C* and the *K* parameters for each task taken separately revealed significant correlations between these two parameters, except for the reproduction of short durations (Bisection: Short, $R = -.42$, Long, $R = -.46$, both $p < .01$; Generalization: Short, $R = -.47$, Long, $R = -.42, p < .01$; Reproduction: Short, $R = -.13, p > .05$, long, $R = -.32, p < .01$). These results suggest that the shortening of reference durations was related to “noise” introduced into their representation, as discussed later.

Correlation between *K* and *C* parameters and neuropsychological scores

Table 4 shows correlations between the z-scores on the different neuropsychological tests and the memory parameter values resulting from the

modelling of our data for bisection, generalization and reproduction. In line with the statistical analyses reported above, we ran hierarchical regression analyses by entering into the equation the significant neuropsychological scores in order to identify which factor was the best predictor of individual variances in these memory parameters.

Distortion in reference memory (K parameter). There was no significant correlation between cognitive abilities and the distortion of reference duration for the short durations in bisection and generalization, with the reference durations being remembered correctly. It was only for the long durations, when a shortening effect occurred for the reference durations, that the *K* values were significantly correlated with the attention inhibition scores in the bisection task, $R = .27, p < .05$, as well as with the working memory, $R = .31, p < .05$, and attention concentration scores, $R = .35, p < .05$, in the generalization task (Table 4). However, in the generalization task, the best predictor of individual variance in the memory distortion parameter was attention concentration ($\beta = .34, R^2 = .12, p < .05$). Consequently, the distortion of reference durations decreased as attention inhibition capacities and attention-concentration capacities increased in the bisection and the generalization task, respectively.

Table 4. Correlations between neuropsychological scores and both the reference duration distortion parameter, *K*, and the reference duration variability parameter, *C*, derived from modelling of data for the 0.4/0.8 and the 8/16-s duration conditions

Neuropsychological scores	Distortion parameter (<i>K</i>)						Variability parameter (<i>C</i>)					
	Bisection		Generalization		Reproduction		Bisection		Generalization		Reproduction	
	<i>S</i>	<i>L</i>	<i>S</i>	<i>L</i>	<i>S</i>	<i>L</i>	<i>S</i>	<i>L</i>	<i>S</i>	<i>L</i>	<i>S</i>	<i>L</i>
Working Memory	.13	.16	-.09	.31*	-.28*	.27*	-.37**	-.46**	-.11	-.11	.03	-.11
Att. Concentration	.13	.14	-.01	.34**	-.30*	.27*	-.50**	-.50**	-.14	-.21	-.13	-.08
Selective Attention	-.15	-.11	-.09	-.17	.34**	-.21	.47**	.31*	.25*	.09	.03	.16
Att. Inhibition	-.07	-.27*	-.20	-.25	-.03	-.20	.58**	.53**	.20	.28*	.10	.06
Processing Speed	-.16	.07	.02	-.07	.37**	-.22	.50**	.37**	.02	.05	.04	-.02

Note: Underlined numbers = significant predictors resulting from the hierarchical regression analyses. Neuropsychological scores = z-scores. Duration condition: *S* (short) = 0.4/0.8 s; *L* (long) = 8/16 s.

*Significant at .05. **Significant at .01.

As far as the reproduction task is concerned, the scores on several tests assessing different neuropsychological scores were significantly correlated with the memory distortion parameters for both the short and the long durations (Table 4). The hierarchical regression analyses nevertheless revealed that the only reliable predictor of distortions in temporal memory was the information processing speed score in the case of short durations ($\beta = .37$, $R^2 = .14$, $p < .05$), and the attention-concentration score in that of long durations ($\beta = .27$, $R^2 = .07$, $p < .05$), although the variance explained was low. In other words, when the participants had to reproduce short durations, the reproduced reference durations lengthened as information processing speed slowed down. In contrast, when they had to reproduce long durations, the representation of reference durations shortened with decreasing working memory capacities.

Variability in reference duration (C parameter). The correlational analyses (Table 4) and the hierarchical regression analyses with the significant neuropsychological scores entered into the equation revealed that the same factor accounted for inter-individual variance in the memory variability parameter for the bisection and the generalization task, namely the score on the attention inhibition test (Bisection-Short, $\beta = .58$, $R^2 = .33$, Bisection-Long, $\beta = .53$, $R^2 = .28$, Generalization-Long, $R = .28$, all $p < .05$), except in the case of the short duration in the generalization task where the only significant correlation found was with the selective attention score, $R = .25$, $p < .05$. However, for the bisection task, the selective attention and working memory scores increased the proportion of variance explained for the short durations ($\Delta = 0.5$, $\beta = .63$, $p < .05$), and the long durations ($\Delta = 0.7$, $\beta = .59$, $p < .05$), respectively. For reproduction, as discussed below, none of the scores on the neuropsychological tests used in our study accounted for the individual differences in the memory variability parameter.

DISCUSSION

In the present study, children and adults were given 3 different temporal tasks: a temporal bisection, generalization, and reproduction task. The results showed a difference in temporal performance and developmental course between these 3 temporal tasks. Indeed, no age-related effect was observed on the accuracy of temporal judgments for the two temporal discrimination tasks, while the younger children's temporal judgments were less accurate in the reproduction task. In contrast, the variability of time judgment decreased with age in all temporal tasks. The speed of improvement in the sensitivity to time was nevertheless greater in the two discrimination tasks than in the reproduction task, and also greater in the bisection than in the generalization task. As reported in the introduction, temporal performance results from the combination of different cognitive processes related to executive functions (e.g., updating, inhibition) that are required to a greater or lesser extent as a function of the task in question. In our study, by analyzing the correlations between the indices of temporal performance and scores on a wide battery of neuropsychological tests and then modeling our data, we have been able to provide findings allowing us to gain a better understanding of the processes involved in the variations in time judgments as a function of temporal task.

Distortion in the representation of reference durations

As regards the "accuracy" of temporal judgment (BP, Peak Time, Mean Duration), our study revealed age differences in the reproduction task but not in the two discrimination tasks. Indeed, the bisection point and the peak time of the generalization gradient did not significantly vary between age groups in the bisection and the generalization task. The 5-year-old children were thus as accurate as the adults in their temporal judgments in the temporal discrimination tasks. In contrast, there was a general tendency for participants to

overestimate short durations and underestimate long durations in the reproduction task, and the magnitude of this temporal over- or underestimation was larger in the younger children. Consequently, the children found it more difficult to make adult-like judgments in the reproduction task than in the other tasks. The modelling of our data suggests that the temporal distortions in reproduction were linked to a distortion of the reference durations (K parameter). In addition, the analyses of regressions revealed that this distortion of reference durations was related to young children's limited cognitive capacities, i.e. to their slower speed of information processing in the case of short durations, and to their lower working memory capacities in that of long durations. Consequently, our study with participants of different ages suggested that the representation of reference durations are more distorted (K parameter) in the temporal reproduction task than in the other discrimination tasks because the former task is more demanding in terms of cognitive resources, although the processes involved in the reproduction of short and long durations differ, as discussed below.

Independently of the age effect, our modelling of the data also suggested that the cognitive processes involved in the representation of short and long reference durations differed. Indeed, when the durations were short (< 1 s), no temporal distortion was found in the representation of reference durations (K parameter) in the temporal discrimination tasks, i.e. either the bisection or the generalization task and only a lengthening effect occurred in the reproduction task. In contrast, when the durations were long (> 8 s), a shortening effect occurred in the representation of reference durations in all the temporal tasks, although this was more pronounced in the reproduction task than in the other discrimination tasks. In addition, the predictor of individual differences in the representation of reference durations (K parameters) changed as a function of duration, taking the form of the scores on the information processing speed test for the reproduction of short durations and those on the attention-concentration test for the judgment of long durations in all the temporal

tasks, with the exception of the bisection task as we discuss later.

For the lengthening of short durations (< 1 s) only observed in the temporal reproduction task, the significant role of information processing speed suggests that the young children took longer to implement their motor responses in reproduction, which necessarily affected the value of reproduced durations. In her model of temporal reproduction, Droit-Volet (2010) considered that motor dexterity plays a critical role in the reproduction of short durations of a few hundred milliseconds, when the time required to initiate a motor response is particularly long. Recently, we showed that the durations reproduced by children with poor motor dexterity due to lesions of the cerebellum were longer than those of healthy control children in response to short (< 1 s), but not to long durations (< 4 s) (Droit-Volet et al., 2013). It is therefore possible that the motor component of temporal reproduction was responsible for the fact that over-estimations of short durations were more frequent in the children than in the adults.

With reference to the shortening of long durations, which was observed in all the temporal tasks, our regression analyses emphasized the critical role of scores on the attention-concentration test for the temporal reproduction and the generalization task. Contrary to what was assumed, the cognitive components related to inhibition or selective attention did not appear to be reliable predictors of shortening effect observed in the reproduction task. Consequently, the children's difficulty in inhibiting their response is not the major cause of their underestimation of time in reproduction. Indeed the attention-concentration test assesses working memory capacities rather than attentional control capacities. It is, however, referred to as attention-concentration because it requires the continuous manipulation and updating of the content of working memory. Our data thus demonstrated that major causes of time distortions for long reference durations (> 8 s) were related to individual capacities in the updating and monitoring of reference durations in working memory during time judgments (see also Ogden et al., 2011). The lack of resources in working memory

would therefore result in a shortening of the representation of long reference durations. However, our analyses also revealed a significant correlation between the distortion (K parameter) and the variability (C parameter) of reference durations. It is therefore likely that a poor working memory capacity results in fuzzier representations of reference durations, that in turn produces a shortening effect. In the case of the reproduction of long durations, when the children have fuzzier (noisier) representation of reference durations, they necessary terminate their reproduction more quickly, because the duration of reproduced durations reaches the point of subjective equality more quickly (Riemer, Trojan, Kleinböhl, & Hölzl, 2012). As explained further later, our model thus suggests that the major parameter of age-related differences in time judgment is a mis-representation of reference durations.

For the bisection task, surprisingly enough, the shortening of long reference durations (8/16-s duration condition) was not significantly correlated with scores on the working memory tests, as was the case for the reproduction and the generalization task, but with those on attention inhibition. A similar correlation was also found in bisection between attention-inhibition and the variability of time judgment (i.e., C parameter). The attention inhibition test (Stroop test) assesses the deliberate suppression of automatic or prepotent responses (Miyake & Shah, 1999; Miyake et al., 2000). In bisection, we can suppose that the prepotent response is the verbal response “short”. The “short” response is indeed activated in working memory before the “long” response. Individuals perceive a short duration before they realize that it is a long one. Using a partition task without reference durations, Droit-Volet and Rattat (2007) showed that children do indeed tend to respond “short” in a bisection task more often than adults do. The difficulties children experience in inhibiting the automatically activated “short” response could thus go some way to explaining the shortening effect observed in bisection. Finally, this suggests that the nature of the verbal response required in a temporal task (temporal categorization strategy) should also interfere with the

representation of durations in memory. However, our bisection model does not take account of decision processes, unlike other models of temporal bisection (Wearden & Jones, 2013) that assume that there is a tendency to respond “long” more often in ambiguous cases, i.e. when $D(s^*, t)$ is close to $D(l^*, t)$. In fact, it is difficult to dissociate memory and decision processes in bisection because they both produce a shifting of the BP in the same direction (left-shifting). However, this shifting of the BP is greater for distortions of temporal memory than for biases in decision processes (see Delgado & Droit-Volet, 2007). It is nevertheless possible that the decision to respond “short” or “long” might be, in part, related to this capacity to inhibit the “short” response. In this case, taking account of decision processes in our model would have perhaps produced a better fit of our model to our individual participant data, but to the detriment of a good between-task comparison.

Variability of time judgment

Unlike the results on the accuracy of temporal judgment (BP, Peak Time, Mean Duration), which demonstrated that the age effect varied as a function of the temporal task and the duration used, those on the variability of time judgment (WR, FWHM/Peak Time, SD/Mean) revealed a general effect of age irrespective of temporal task and duration. Our study using a within-subject factorial design thus provides convincing evidence of an improvement in time sensitivity during childhood on all temporal tasks. However, our results also showed different patterns of age-related improvement in time sensitivity as a function of the type of temporal task used. In the reproduction task, there was a systematic improvement in time sensitivity between ages, i.e. from 5 to 8 years and from 8 years to adulthood. In the bisection task, a difference in time sensitivity was observed between 5 and 8 years, whereas the older children reached a level of performance similar to that of adults. In the generalization task, the age differences in sensitivity to time were somewhat less clear since the temporal gradients were particularly flat in the 5-year-olds and the 8-year-olds. In this case, it is likely that the lack of

an age-related difference was due to the older children's poorer performance in the generalization task. Consequently, the results showed that the 8-year-olds exhibited similar levels of temporal sensitivity to those found in younger children. Overall, these findings indicate that age-related differences in time sensitivity are smaller in the two discrimination tasks than in the reproduction task, and are probably smaller in bisection than in generalization.

Our model confirmed that the variability of the representation of reference durations (*C* parameter) was higher in the reproduction task than in the two discrimination tasks. However, no score on the different neuropsychological tests explained individual differences in the *C* parameter values (Table 4), except for attention inhibition in the bisection and the generalization tasks. In contrast, scores on numerous neuropsychological tests were significantly correlated with the indices of variability of time judgment (i.e., WR, FWHM, SD) in the 3 temporal tasks. Consequently, we can argue that this reveals that the major source of individual differences in the variability of time judgment does not lie in the representation of reference durations, but rather in the encoding of time. In their model, McCormack et al. (1999) introduced a parameter representing the amount of "noise" added to the perceived duration and achieved a good fit with their data by revealing a higher proportion of noise in perceived time in children than in adults. By manipulating variability in the sample durations used as references in a bisection task, Delgado and Droit-Volet (2007) also demonstrated that the source of noise in temporal reference memory, as measured by the *C* parameter, derives from initial noise introduced during the encoding of time.

In our models, we have implicitly considered that the encoding of time is similar in the 3 temporal tasks. Consequently, contrary to our initial hypothesis, variations in the encoding of time would occur as a function of the temporal task used. Our regression analyses, conducted with the different indices of time sensitivity (WR, FWHM, SD) (Table 2), showed that the attention-concentration scores were the best predictors of individual differences in sensitivity to time

(WR) in the temporal bisection task (also see Zélandi & Droit-Volet, 2011). In the generalization task (FWHM) the best predictor was selective attention, and in the reproduction task (SD) both working memory and information processing speed fulfilled this role. The relationships between information processing speed, working memory and attention are difficult to understand because none of these cognitive dimensions represents a uniform set of processes (Fougnie, 2008). This is the major problem that is often discussed in the literature on executive functions (Brown et al., 2012; Packwood, Hodgetts, & Trembaly, 2011). Nevertheless, models of the development of intelligence suggest that cognitive development results from a cascade of related processes in which age-related changes in the speed of information processing play a critical role (Camos & Barouillet, 2014; Case, 1985; Demetriou, Mouyi, & Spanoudis, 2008; Fry & Hale, 1996). According to Demetriou et al. (2008), the changes in information processing speed would be "followed in time" by changes in working memory and, later, by changes in selective attention.

Finally, our study suggests that the improvement in time sensitivity in the reproduction task required the development of greater cognitive abilities than were required for the bisection and generalization tasks. Individual differences in time sensitivity were indeed linked to the development of both information processing speed and working memory capacities in the reproduction task, while they were linked only to working memory or to selective attention in the case of the bisection and the generalization tasks, respectively. Since the encoding of current durations is theoretically similar for these two discrimination tasks, this suggests that the nature of the required judgment (e.g., identity or categorization judgment) influences the encoding of time. A judgment of identity between current durations and a reference duration would therefore be more cognitively demanding than a judgment categorizing current durations as either short or long. Indeed, some bisection studies have demonstrated that participants are able to categorize current durations as short or

long without the initial presentation of two anchor reference durations (Jones & McAuley, 2005; Killeen, Fetterman, & Bizo, 1997; Wearden & Ferrara, 1995, 1996).

In conclusion, our study, conducted with both children and adults, provides evidence that the age-related differences in explicit time judgments depend on the cognitive demands imposed by the temporal task used. Our study thus demonstrated that age-related differences in time judgment are greater in a reproduction task than in a temporal discrimination task, because this task is more demanding in terms of working memory and information processing speed. At the same time, we found that the bisection task was easier for the children than the generalization task in terms of time judgment, whereas these tasks were similar for the adults. Temporal performance in the bisection task was associated with a greater variability in the representation of durations in reference memory than was the case in the generalization task. However, this latter task required more attention to be paid to the processing of current durations in order to judge the similarity between these durations and the reference duration. In conclusion, our study suggests that it is better to use a temporal bisection than a generalization task in children, whereas these tasks are equivalent for adults. Whatever the case, researchers should avoid using the complex task of temporal reproduction for all ages, and more particularly in participants with limited cognitive resources and motor dexterity for the short durations.

Original manuscript received 21 February 2014

Accepted revision received 13 January 2015

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