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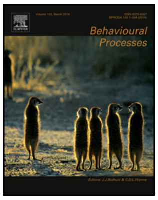

Time dilation in children and adults: The idea of a slower internal clock in young children tested with different click frequencies

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This experiment examined the effect of a train of regular repetitive clicks of different frequencies (8 Hz, 20 Hz) on time judgment in a bisection task in children aged 5 and 8 years old and adults with two duration ranges (200/800 and 400/1600 ms). Participants' scores on neuropsychological tests assessing memory, information processing speed and different components of attention control were also measured. The results showed that a train of clicks produced a time dilation in the children as well as in the adults, with the result that the perceived duration was judged to last longer with than without clicks. However, the time dilation reached a maximum level at a lower click frequency value (8 Hz) in the children than in the adults (20 Hz). In addition, beyond this click value (8 Hz), a reversal effect was observed in the youngest children, who responded "long" less often, while the time dilation was extended in the adults. In addition, while the differences in the time dilation between the click and the no-click condition were not correlated with the individual cognitive capacities, those that occurred when the click frequency increased from 8 to 20 Hz were significantly correlated with individual capacities in terms of attention and working memory. The hypothesis of a slower internal clock in the younger children is discussed as are the attentional interference processes involved in the click effect on time judgment.

1. Introduction

The accurate measurement of time in humans is often explained by the existence of a putative internal clock-like system that would provide the raw material for the representation of time (for recent reviews, see Allman et al., 2014; Van Rijn et al., 2014). In this theoretical framework, the debate is rather on the nature of this material: pulses emitted by a pacemaker (Church, 1984; Gibbon et al., 1984; Treisman, 1963), or neural oscillations distributed in the brain (Buhusi and Oprisan, 2013; Matell and Meck, 2004; Miall, 1989; Treisman et al., 1992). However, whatever the proposed mechanism, the results predicted at the behavioral level are similar: The longer objective time is, the longer the temporal estimates will be because a greater number of ticks (pulses, oscillations, regular spikes) are accumulated.

The results of studies in infants and children suggest that this internal clock system would be functional at an early age and that the increase in cognitive capacites (working memory, attention) accounts for most of the age-related differences in time judgments (for a review, see Droit-Volet, 2013, 2016; Droit-Volet and Coull, 2016). However, alhough the clock system allows early time measurement in infants, it is possible that some age-related changes occur in its functioning. Indeed, its functioning should be closely linked to the brain maturation (Menon, 2013; Rubia, 2013; Vogel et al., 2010). There is ample evidence of a gradual increase in the white matter in different parts of the brain during childhood and this continues in late adolescence in associative regions of the prefrontal cortex (e.g., BDCG, 2012; Faria et al., 2010; Lebel and Beaulieu, 2011; Giedd, 2004; Sowell et al., 1999). The role of the white matter in the brain is to ensure coordination between different brain regions and to speed up information transmission between regions such as in the striatal-prefrontal circuit, which underpins our sense of time (Coull et al., 2011; Merchand et al., 2013). Consequently, it is possible that the internal clock system is less efficient in young children, i.e., it is slower and noisier, characterized by a lower frequency, poor oscillatory synchronization, and a broader network of less integrated oscillators (Droit-Volet, 2016). Low-frequency bands (delta and theta <7 Hz) have been shown to be predominant in young children, while higher EEG frequencies (alpha, 8–13 Hz) predominate in mature brain rhythms (Eisermann et al., 2013; Michels et al., 2013). In addition, a significant correlation has been found between brain wave frequency

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and information processing speed (Survillo, 1961, 1963). Individuals with lower EEG frequencies exhibit slower and more variable response times than those with higher EEG frequencies. Recently, Droit-Volet and Zélanti (2013) showed a significant correlation between information processing speed and variability in time judgment: the slower the information processing speed, the lower the sensitivity to time. These authors thus suggested that their results might reflect an age-related increase in the clock speed that accompanies the general acceleration of information processing during childhood. However, there is as yet no direct evidence, i.e., at the behavioral level, of a slower and noisier clock in younger children. This is mainly due to the difficulty of capturing subtle age-related effects in the clock speed because human beings quickly adapt to their new clock rate (clock recalibration, Meck, 1983). The purpose of this experiment was to try to explore this idea that the internal clock runs more slowly in young children via the immediate effects of the manipulation of the internal clock in response to repetitive external stimuli.

In 1990, to “speed up the internal clock”, Treisman, Faulkner, Naish, and Brogan invented a method that consists in presenting a train of repetitive auditory clicks or visual flickers either before or at the same time as the to-be-timed stimulus. Using this method, they showed that a click frequency between 2.5 and 27.5 Hz changes time judgments in such a way that stimulus durations are judged longer with than without a click train, and that the magnitude of the click effect increases with click frequency (Treisman et al., 1990, 1994; Treisman and Brogan, 1992). Treisman and his colleagues explained these results by a transient increase in the tick rate of the internal clock under the influence of an external rhythm (clicks). The effect of click trains on time judgment has been replicated in numerous studies using different temporal tasks, thus demonstrating that this is a robust phenomenon (e.g., Herbst et al., 2013; Jones, 2014; Jones et al., 2011; Jones and Odgen, 2016; Kanai et al., 2006; Makin et al., 2012; Palumbo et al., 2015; Penton-Voak et al., 1996; Ortega and Lopez, 2008; Ortega et al., 2012; Plomp et al., 2012; Wearden et al., 1999, 2008).

To date, only one study, conducted by Droit-Volet and Wearden (2002), has examined the effect of visual flickers on children’s time judgments. This study replicated in children aged from 3 to 8 years the time dilation effect observed in adults. This finding therefore demonstrates that the rapid change in clock speed in response to changes in the environment is a fundamental property of timing. However, Droit-Volet and Wearden (2002) did not find any age-related variation in the effect of repetitive stimuli on the judgment of time. The authors thus concluded that the click effect on temporal performance is automatic, that is to say independent of the development of cognitive capacities, although this has not been directly tested by assessing children’s cognitive capacities. In sum, the similarity across ages of the effect of the entrainment of the internal clock by an external rhythm would suggest that the rate of the internal clock does not change from 3 to 8 years old. However, in this study, the lack of an age-related difference in the click effect is likely to be due to the tested age range, namely between 3 and 8 years, a range which is not large enough to permit the detection of developmental changes. The authors also used repetitive stimuli in the visual modality (flickers) and these are less efficient than auditory stimuli (clicks) in producing time dilations (e.g., Treisman and Brogan, 1992; Ortega and Lopez, 2008). In addition, Kanai et al. (2006) showed that the time dilation observed with the increase in the frequency of the flickers saturates rapidly; in other words, it did not increase beyond a threshold (click frequency). It is thus likely that time dilatation saturates early in children due to their slower clock rate. As explained by Jones (1976), entrainment by an external rhythm is more efficient when this rhythm is close to the intrinsic preferred period of oscillation. When the rhythm is too fast, and therefore too distant from the preferred one, the system returns to its preferred period. Consequently, in the present study, children aged 5 and 8 years but also adults were given a temporal task (bisection) with or without a 5-s click train preceding the stimulus to be timed. In addition, two click frequencies were used: a slower (8 Hz) and a faster (20 Hz) click frequency. We also assessed the participants’ individual cognitive capacities in terms of working memory, attention (selective attention, divided attention) and processing speed in order to determine whether the developmental variations in the click effect on the perception of time are due or not to an automatic speeding up of the internal clock that is not related to individual cognitive capacities.

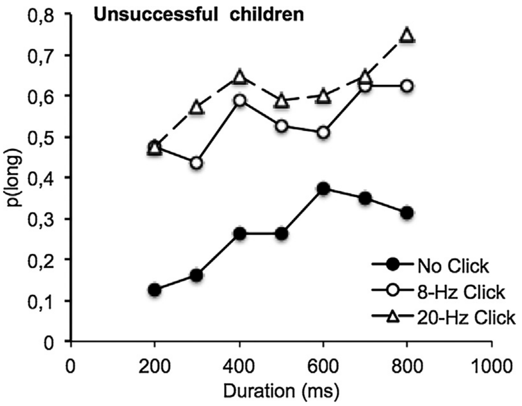

Fig. 1. Proportion of long responses plotted against stimulus durations for unsuccessful children, i.e. excluded from the statistical analyses.

2. Method

2.1. Participants

The sample consisted of 115 participants: Thirty-eight 5-year-olds (Mean age = 5.42, *SD* = 0.28), thirty-seven 8-year-olds (Mean age = 8.17, *SD* = 0.50) and forty adults (Mean age = 22.67, *SD* = 3.085). Eleven additional children (ten 5-year-olds and one 8-year-old) participated in this experiment. However, their data were excluded from the final sample because the fit between the pseudo-logistic function and the individual data that make it possible to calculate a Bisection Point (see below) was not significant. As Fig. 1 illustrates, these children almost always responded short on the no-click trials and long on the click trials, thus producing flat psychophysical functions[1] (for a similar phenomenon observed with the filled duration illusion, see also Droit-Volet, 2008). The children were attending nursery and primary schools in Chamalière and Clermont-Ferrand, and the adults were students at Clermont Auvergne University, all in the Auvergne region of France. The children’s parents and the students all gave their informed consent for participation in this experiment. The procedure was validated by the local committee of the French National Education Authority.

2.2. Material

The children and the adults were tested individually in a quiet room in their schools and in our laboratory, respectively. A computer controlled the experimental events and recorded the data using E-prime (Psychology Software tools Inc.). The children gave their “short” vs. “long” responses orally, whereas the adults pressed on the *D* and *K* keys of the computer keyboard. The stimulus to be

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[1] Additional analyses revealed that the “unsuccessful” 5-year-old children had significantly lower scores on the different neuropsychological tests than the “successful” 5-year-old children.

timed was a blue circle (6 cm in diameter) presented in the center of the screen. The repetitive auditory stimuli, i.e. a click train with a regular rhythm of either 8 Hz or 20 Hz, were played through the computer's loudspeakers. The clicks were 10-ms tones delivered at about 60 dB.

2.3. *Procedure*

2.3.1. *Bisection task*

The participants were assigned to a short (200/800-ms) or a long (400/1600-ms) duration group. In the 200/800-ms condition, the short and long standard durations were 200 and 800 ms and the comparison durations were 200, 300, 400, 500, 600, 700, and 800 ms. In the 400/1600-ms condition, the standard durations were 400 and 1600 ms and the comparison duations 400, 600, 800, 1000, 1200, 1400 and 1600 ms. In both groups, the participants were given a bisection task consisting of a training and a test phase. In the training phase, the participants were trained to respond short and long after the short and the long standard stimulus durations, respectively, on 10 randomly presented trials (5 Short, 5 Long), with an intertrial interval varying from 0.5 to 1 s. Each trial started with the word "ready/prêt" displayed on the computer screen. Then, if the participant was ready, the experimenter pressed the spacebar and the stimulus duration appeared after a 5-s interval of silence. The test following the training phase used the same experimental conditions except in the case of the click-train trials and the comparison durations. The experimenter told the participants that they would sometimes hear sounds but that they should ignore these, their task being to judge whether the duration of the blue circle was more similar to the short or to the long standard duration. The test consisted of 10 blocks of 21 trials (7 × 3) for the 7 comparison durations, preceded by either 5 s of silence (no-click trials) or 5 s of repetitive clicks (click trials) played at a frequency of 8 Hz or 20 Hz. The 21 trials were randomly presented within each block.

2.3.2. *Neuropsychological test*

After the bisection task (the next day), the participants were administered a series of neuropsychological tests to assess their individual cognitive abilities in terms of working memory, attention and information processing speed. Their short-term and working memory capacities were assessed using the forward and the backward digit span tests from the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003). In these tests, the experimenter reads out a sequence of numbers and the participants repeat this sequence in the same order (short-term memory) and in the reverse order (working memory). One other neurospsychology subtest from the Developmental Neuropsychological Assessment (NEPSY; Korkman et al., 1998) was used to assess selective attention in the auditory modality ("auditory attention and response set" subtest). In this subtest, the participants listen to a sequence of words at a rate of one per second and must respond to each target word (yellow, red, blue) by selecting the right color square (yellow, red, blue, black) and putting it in a box. One other attention subtest was taken from the Test of Everyday Attention for children (TEA-ch; Manly et al., 1999) to assess divided attention ("listening to two pieces of information at the same time"). In the divided attention subtest, participants perform two tasks simultaneously: counting the number of gunshots and recalling the name of an animal heard in an audio recording. The information processing speed index from age-appropriate Wechsler intelligence scales was also measured. This index comprised the sum of the raw scores from the Coding and Symbol Search subtests.

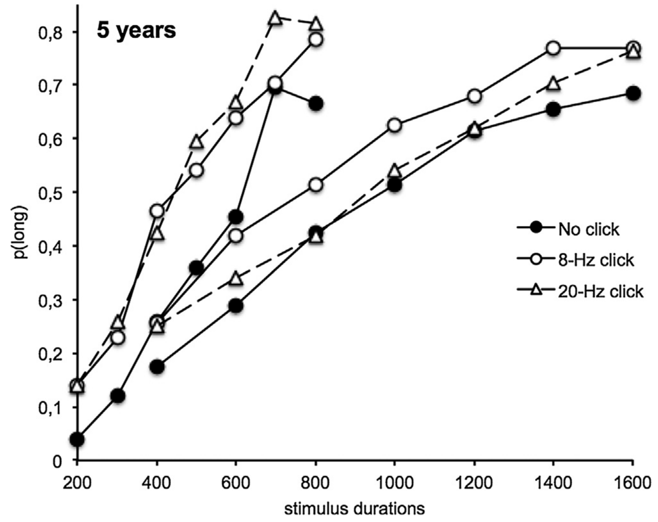

Fig. 2. Proportion of long responses plotted against stimulus durations in the two duration ranges (200/800-ms, 400/1600-ms) for the 5-year-old children.

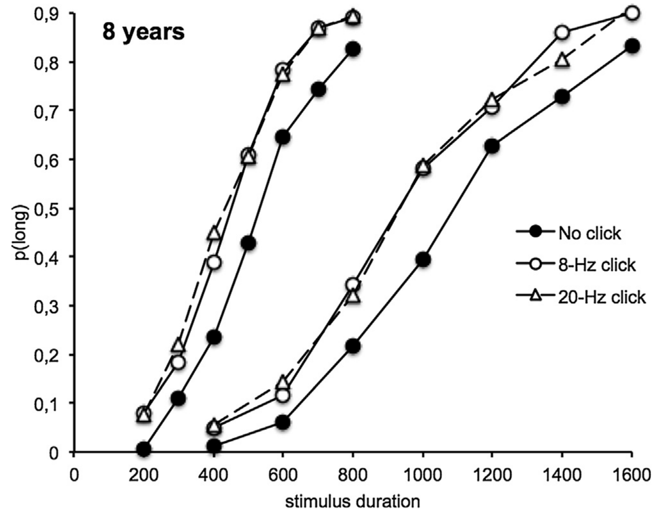

Fig. 3. Proportion of long responses plotted against stimulus durations in the two duration ranges (200/800-ms, 400/1600-ms) for the 8-year-old children.

3. Results

3.1. *Temporal bisection*

The bisection functions plotting the proportion of long responses (p(long)) against the stimulus durations in the 3 click conditions are presented in Fig. 2 for the 5-year-olds, Fig. 3 for the 8-year-olds, and Fig. 4 for the adults. The bisection functions appear to be shifted towards the left with the clicks compared to without the clicks, indicating a time dilation with the clicks. In addition, this time dilation seems to increase significantly with the click frequency in the adults. By contrast, a reversal effect was observed for the youngest children, at least when the stimulus durations were longer.

To examine this bisection performance, two indexes were calculated: the Bisection Point (BP) and the Weber Ratio (WR) (Table 1). The BP is the point of subjective equality, i.e. the stimulus for which the participants respond long as often as short (p(long) = 0.5). The WR is a measure of time sensitivity (Difference limen ([p(long)=0.75 − p(long)=0.25]/2) divided by the BP): the lower the WR value, the greater the time sensitivity and the steeper the psychophys-

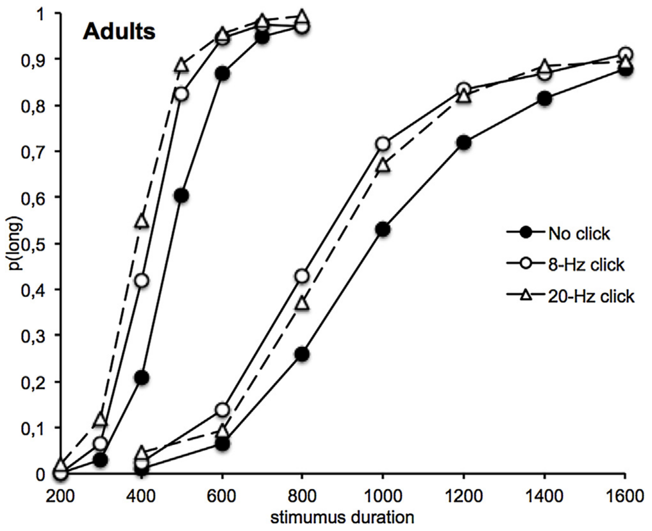

Fig. 4. Proportion of long responses plotted against stimulus durations in the two duration ranges (200/800-ms, 400/1600-ms) for the adults.

Table 1
Bisection Point and Weber Ratio for the 5-year-olds, the 8-year-olds and the adults in the trials without click or with a train of clicks of 8- or 20-Hz frequency in the short (200/800-ms) and long (400/1600-ms) duration range.

	Bisection Point				Weber Ratio			
	200/800		400/1600		200/800		400/1600	
	M	SE	M	SE	M	SE	M	SE
5-year-olds								
No click	637.87	50.51	888.52	50.51	0.43	0.08	0.69	0.09
8-Hz click	468.98	38.82	708.77	38.82	0.50	0.12	0.95	0.12
20-Hz click	444.51	44.23	860.86	44.23	0.39	0.07	0.72	0.08
8-year-olds								
No click	522.72	50.51	1102.58	51.89	0.28	0.08	0.27	0.09
8-Hz click	426.28	38.82	926.29	39.88	0.28	0.12	0.25	0.12
20-Hz click	414.05	44.23	941.83	45.44	0.27	0.07	0.23	0.08
Adults								
No click	474.38	49.23	1041.61	49.23	0.22	0.08	0.26	0.08
8-Hz click	414.84	37.83	860.48	37.83	0.10	0.11	0.20	0.11
20-Hz click	384.70	43.11	877.77	43.11	0.10	0.07	0.21	0.07

ical function. These two indexes were derived from the fit of the pseudo-logistic function with the individual psychophysical functions (Killeen et al., 1997) (5 years, Mean $R^2 = 0.84$, $SD = 0.09$; 8 years, Mean $R^2 = 0.92$, $SD = 0.10$; adults, Mean $R^2 = 0.97$, $SD = 0.01$). An ANOVA was then run using SPSS on each index with two between-subjects factor (age, duration) and one within-subjects factor (click). In addition, the Bayes factors (BF_{10}) were measured with JASP software (Love et al., 2015).

The ANOVA on the WR did not reveal neither significant effect of click, $F(2, 214) = 1.16$, $p = 0.32$, $\eta^2_p = 0.01$, $BF_{10} = 0.083$, $(1-\beta) = 0.25$, nor click x age, $F(4, 214) = 1.8$, $p = 0.13$, $\eta^2_p = 0.03$, $BF_{10} = 0.249$, $(1-\beta) = 0.55$, nor other effect involving the click factor (all $p > 0.05$). There was only a significant interaction between age and duration, $F(2, 107) = 3.35$, $p = 0.04$, $\eta^2_p = 0.06$, $BF_{10} = 1.627$, $(1-\beta) = 0.62$, with significant main effects of age, $F(2, 107) = 19.08$, $p = 0.0001$, $\eta^2_p = 0.26$, $BF_{10} = 41488.945$, $(1-\beta) = 1.0$, and duration, $F(1, 107) = 4.98$, $p = 0.03$, $\eta^2_p = 0.05$, $BF_{10} = 0.902$, $(1-\beta) = 0.60$, although Bayes Factors provided anecdotal evidence for the effects involving the duration range on the WR. The time judgment was thus more variable in the 5-year-olds than in the 8-year-olds and the adults ($t(77) = 9.32$, $p = 0.001$, Cohen's d (d) = 1.06, $BF_{10} = 780.6$, $t(79) = 8.34$, $p = 0.001$, d = 0.932, $BF_{10} = 40619$), with no significant difference being observed between the two older age groups ($t(76) = 1.89$, $p = 0.06$, d = 0.428, $BF_{10} = 2.08$).

Unlike the WR, the ANOVA on the BP showed a significant main effect of click, $F(2, 218) = 44.13$, $p = 0.0001$, $\eta^2_p = 0.29$, $BF_{10} > 13670$, $(1-\beta) = 1.0$. Click also interacted with age and duration, as indicated by the significant 3-way click x age x duration interaction, $F(4, 218) = 2.75$, $p = 0.03$, $\eta^2_p = 0.05$, $BF_{10} = 2.341$, $(1-\beta) = 0.75$. The click x duration interaction, $F(2, 218) = 3.71$, $p = 0.03$, $\eta^2_p = 0.03$, $\eta^2_p = 0.03$, $BF_{10} = 1.30$, $(1-\beta) = 0.68$, was also significant (but the Bayes factor suggested anecdotal evidence in favor of this interaction), as was the main effect of duration, $F(1, 109) = 207.86$, $p = 0.001$, $\eta^2_p = 0.66$, $BF_{10} > 7680$, $(1-\beta) = 1.0$, and the age x duration interaction, $F(2, 109) = 5.48$, $p = 0.01$, $\eta^2_p = 0.09$, $BF_{10} = 9.05$, $(1-\beta) = 0.84$.

In each age group taken separately, a significant effect of click was found (5 years, $F(2, 72) = 9.30$, $\eta^2_p = 0.21$, $BF_{10} = 73.164$, $(1-\beta) = 0.97$; 8 years, $F(2, 70) = 27.98$, $\eta^2_p = 0.44$, $BF_{10} > 4764$, $(1-\beta) = 1.0$; adults, $F(2, 76) = 26.43$, $\eta^2_p = 0.41$, $BF_{10} > 1325$, $(1-\beta) = 1.0$, all $p < 0.001$). There was also a main effect of duration (5 years, $F(1, 36) = 21.99$, $\eta^2_p = 0.38$, $BF_{10} = 526.487$, $(1-\beta) = 1.0$; 8 years, $F(1, 35) = 121.41$, $\eta^2_p = 0.78$, $BF_{10} > 1124$, $(1-\beta) = 1.0$; adults, $F(1, 38) = 117.04$, $\eta^2_p = 0.76$, $BF_{10} > 1816$, $(1-\beta) = 1.0$, $p = 0.0001$). However, the click x duration range interaction reached significance in the adults, $F(2, 76) = 4.87$, $p = 0.01$, $\eta^2_p = 0.11$, $BF_{10} = 4.351$, $(1-\beta) = 0.79$, but not in the 5-year-olds or the 8-year-olds ($F(2, 72) = 2.93$, $p = 0.08$, $BF_{10} = 1.104$, $(1-\beta) = 0.55$, $F(2, 70) = 1.88$, $p = 0.16$, $BF_{10} = 0.499$, $(1-\beta) = 0.38$). In all age groups, there was systematically a time dilation with the clicks compared to without the clicks whatever their frequency: 8 Hz (5 years, $t(38) = 4.65$, $p = 0.001$, $d = 0.744$, $BF_{10} = 1137$; 8 years, $t(36) = 5.736$, $p = 0.001$, $d = 0.93$, $BF_{10} = 24561$; adults, $t(39) = 5.22$, $p = 0.001$, $d = 0.825$, $BF_{10} = 3110$) or 20 Hz (5 years, $t(38) = 2.204$, $p = 0.03$, d = 0.352, $BF_{10} = 2.918$; 8 years, $t(36) = 5.503$, $p = 0.001$, d = 0.905, $BF_{10} = 11669$; adults, $t(39) = 5.46$, $p = 0.001$, d = 0.864, $BF_{10} = 6220$). However, the effect of the click frequency on time perception changed as a function of the age group. In the 5-year-olds, there was not an increase but a decrease in time dilation between 8 Hz and 20 Hz, as the fact that the BP was lower for 8 Hz than for 20 Hz indicates (588.87 vs. 652.68, $t(37) = -2.20$, $p = 0.03$, d = 0.36, $BF_{10} = 2.913$). Post-hoc analysis revealed that, in this age group, there is very strong evidence for this decrease in BP for the long duration range, $t(18) = -3.329$, $p = 0.004$, d = 0.764, $BF_{10} = 23.70$. In contrast, in the 8-year-olds, no difference in the BP was observed between these two click frequencies (676.29 vs. 677.94, $t(36) = -0.08$, $p = 0.93$, d = 0.014, $BF_{10} = 0.166$). Finally, in the adults, time dilation was greater with a click frequency of 20 Hz than with a frequency of 8 Hz, but only in the short duration range condition. Indeed, the BP was significantly lower at 20 Hz than at 8 Hz (384.7 vs. 414.84, $t(19) = 2.74$, $p = 0.01$, d = 0.61, $BF_{10} = 12663$) for the short durations, while it was similar for these two frequencies for the longer durations (877.77 vs. 860.48, $t(19) = 0.68$, $p = 0.51$, d = 0.152, $BF_{10} = 0.15$).

Finally, and in line with these results, when we measured an index of the difference in the BP between each click condition (no-click/8-Hz click, no-click/20-Hz click, 8-Hz/20-Hz click) averaged on the two duration range conditions, no significant effect of age was found for no-click/8-Hz click and no-click/20-Hz click ($F(2, 114) = 1.15$, $BF_{10} = 0.208$; $F(2, 113) = 0.06$, $BF_{10} = 0.085$, both $p > 0.05$). Only an effect of age tended to be observed for the difference in the BP between 8 and 20 Hz, $F(2, 112) = 3.53$, $p = 0.03$, $\eta^2_p = 0.06$, $BF_{10} = 1.457$, $(1-\beta) = 0.65$, suggesting a reduction in the magnitude of the time dilation with the increase in click frequency (−63.81) in the 5-year-olds compared to the adults (6.43), $t(76) = -2.21$, $p = 0.015$, d = 0.50, $BF_{10} = 1.88$. The 8-year-olds (−1.3) obtained an intermediate value that did not significantly differ from

Table 2
Correlations between the age, the z-scores on neuropsychological tests and the bisection point and the Weber Ratio in each click condition and for the difference between (1) no-click and 8-Hz click, (2) no-click and 20-Hz click and (3) 8-Hz click and 20 Hz click condition.

	Bisection Point						Weber Ratio					
	No	8 Hz	20 Hz	No/8 Hz	No/20 Hz	8 Hz/20 Hz	No	8 Hz	20 Hz	No/8 Hz	No/20 Hz	8 Hz/20 Hz
Age	−0.12	−0.05	−0.11	−0.14	−0.01	0.19*	−0.30**	−0.34**	−0.38**	−0.15	−0.08	0.11
S-T memory	−0.11	−0.07	−0.16	−0.09	0.07	0.24*	−0.29**	−0.32**	−0.36**	−0.14	−0.07	0.08
Working memory	−0.33**	−0.28**	−0.35**	−0.18	0.02	0.26**	−0.28**	−0.40**	−0.37**	−0.23*	−0.11	0.19*
Selective Attention	−0.38**	−0.34**	−0.39**	−0.18	−0.01	0.25**	−0.37**	−0.41**	−0.42**	−0.19*	−0.05	0.17
Divided Attention	−0.03	0.03	−0.06	−0.10	0.05	0.23*	−0.37**	−0.44**	−0.48**	−0.22*	−0.12	0.16
Processing speed	0.01	0.06	0.01	−0.08	0.02	0.14	−0.26**	−0.34**	−0.36**	−0.18	−0.12	0.13

* $p < 0.05$.
** $p < 0.01$.

Table 3
Scores on neuropsychological tests for the 5-year-olds, the 8-year-olds and the adults.

	5 years		8 years		Adults	
	M	SE	M	SE	M	SE
Short-term memory	5.10	0.25	8.11	0.24	10.08	0.24
Working memory	3.54	0.27	5.08	0.27	7.18	0.26
Selective Attention	54.64	3.26	81.34	3.31	100.7	3.22
Divided Attention	8.79	0.35	14.18	0.35	19.6	0.34
Processing speed	30.08	2.4	45.63	2.4	110.74	2.4

Table 4
For each age group taken separately, correlations between the raw scores on neuropsychological tests and the bisection point in each click condition and for the difference between (1) no-click and 8-Hz click, (2) no-click and 20-Hz click and (3) 8-Hz click and 20 Hz click condition.

	No	8 Hz	20 Hz	No/8 Hz	No/20 Hz	8 Hz/20 Hz
5 years						
S-T memory	0.02	−0.25	−0.16	0.26	0.20	−0.03
Working memory	−0.30	−0.39*	−0.50**	0.01	0.26	0.40*
Selective Attention	0.34*	0.19	0.10	0.23	0.24	0.11
Divided Attention	0.22	0.12	0.06	0.17	0.14	0.07
Processing speed	0.36*	0.39*	0.37*	0.06	−0.04	−0.13
8 years						
S-T memory	−0.21	−0.20	−0.18	−0.07	−0.08	−0.05
Working memory	−0.45**	−0.40*	−0.35*	−0.21	−0.23	−0.12
Selective Attention	−0.60**	−0.47**	−0.41*	−0.42**	−0.43**	−0.06
Divided Attention	−0.32*	−0.20	−0.20	−0.34*	−0.28	0.04
Processing speed	−0.38*	−0.31	−0.27	−0.23	−0.24	−0.06
Adults						
S-T memory	−0.27	−0.28	−0.38*	−0.16	0.04	0.32*
Working memory	−0.50**	−0.53**	−0.56**	−0.26	−0.17	0.13
Selective Attention	−0.61**	−0.64**	−0.70**	−0.34*	−0.18	0.26
Divided Attention	−0.18	−0.16	−0.17	−0.16	−0.13	0.04
Processing speed	0.22	0.21	0.23	0.16	0.11	−0.08

** $p < 0.01$.
* $p < 0.05$.

the 5-year-olds, $t(73) = 1.90$, $p = 0.06$, d = 0.438, $BF_{10} = 1.105$, and the adults, $t(75) = -0.37$, $p = 0.71$, d = 0.085, $BF_{10} = 0.318$.

3.2. Correlation between temporal bisection and scores on neuropsychological tests

To examine whether the age differences in the click effects as a function of their frequency were related to developmental differences in cognitive abilities, we analyzed the correlations between the indexes of difference in the BP between each condition (no-click/8-Hz click, no-click/20-Hz click, 8-Hz/20-Hz click) (duration range averaged), the participants' age and their scores (*z*-scores) on the neuropsychological tests (Table 2). Previous analyses showed that the raw scores on the different neuropsychological tests changed with the age groups (short-term memory, $F(2, 114) = 105.94$, $\eta^2_p = 0.65$, working memory, $F(2, 114) = 47.49$, $\eta^2_p = 0.45$, selective attention, $F(2, 114) = 50.75$, $\eta^2_p = 0.47$, divided attention, $F(2, 114) = 245.89$, $\eta^2_p = 0.81$, information processing speed, $F(2, 114) = 245.79$, $\eta^2_p = 0.82$ (all $p = 0.0001$) (for all between-age groups differences, Bonferroni test, $p < 0.0001$)) (Table 3).

The correlations presented in Table 2 suggest that the individual differences in the magnitude of the time dilation induced by the presence of clicks were not correlated with the scores on any of the tests assessing cognitive abilities (all $p < 0.05$). However, the individual differences in time dilation between the two click frequencies (8-Hz *vs*. 20-Hz) were significantly correlated with age ($R = 0.19$), as well as with the scores on the tests assessing attention (selective attention, $R = 0.25$, divided attention, $R = 0.23$, $p < 0.05$) and working memory capacities ($R = 0.26$, $p < 0.05$). No significant correlation with information processing speed was found (R = 0.14, $p > 0.05$). The hierarchical regression analysis with age and the significant neuropsychological scores revealed that the best predictor of inter-individual differences in time dilation with increasing click frequency was the working memory scores, although the proportion of variance explained remained low (B = 32.96, SE B = 11.94; ß = 0.25, $R^2 = 0.06$, $p = 0.01$). Adding the other factors into the regression model did not change the R^2 value. Therefore, the dilation of time with the increase in click frequency from 8 to 20 Hz was greater when working memory capacity was higher. Additional analyses were performed on the correlations between the raw cognitive scores and the 8-Hz/20-Hz difference in the BP for each age group taken separately (Table 4). As for the previous analyses, a significant correlation was observed between the magnitude of the time dilation with the increase in click frequency from 8 to 20 Hz and the increase in memory capacities at all ages (5 years, $R = 0.40$, adults, $R = 32$, both $p < 0.05$), except at the intermediate age of 8 years ($R = 0.12$, $p > 0.05$). The correlation with the other cognitive dimensions did not reach significance (all $p > 0.05$). For the 8-year-olds and the adults, we nevertheless observed a significant correlation between the selective attention scores and the no-click/8-Hz click difference in the BP ($R = -42$, $R = -34$, $p < 0.05$). This suggests that the attentional capacities also contributed to the time distortion in the presence of a click train. No other correlations were significant.

There was no effect of clicks on the WR. However, since the ANOVA showed a significant effect of age, we decided to analyze the correlations between the WR and the individual cognitive scores in all the click conditions (Table 2). In line with the results of most developmental studies (Droit-Volet, 2013, 2016), this index of time sensitivity appeared to be significantly correlated with age and individual cognitive capacities. However, the stepwise regression analysis revealed that age *per se* was no longer a reliable predictor of individual differences in the WR values ($p < 0.05$). The most reliable predictor of individual differences in the sensitivity to time in a bisection task with click trials was the divided attention scores ($R = 0.51$, $R^2 = 0.26$, $p = 0.0001$). However, adding the selective attention scores increased the proportion of variance explained ($R = 0.54$, $R^2 = 0.29$, $p = 0.0001$).

4. Discussion

Numerous studies have shown that the presentation of external rhythmic stimuli (clicks, flickers) produces a dilation of perceived time in adults. The results of our study using clicks replicated this finding in participants aged from 5 to 25 years. This therefore confirmed that time dilation in the presence of repetitive stimuli is a robust phenomenon observed at an early age (also see Droit-Volet and Wearden, 2002). However, the originality of our study was to test different click frequencies in children of different ages. First of all, our results showed that difference in the magnitude of the time dilation was lower between 8 and 20 Hz than it was between the click condition (8 or 20 Hz) and the no-click condition. This is consistent with the results of studies in adults showing that sensitivity to click frequency is at its highest between 7 and 20 Hz (e.g., Treisman et al., 1990; Treisman and Brogan, 1992), despite the fact that maximum sensitivity is lower for flickers than for clicks (Kanai et al., 2006). Therefore, there is no linear relation between time dilation and the objective rate of the external repetitive stimulus. In other words, the perceived duration does not simply depend on the number of changes perceived (click frequency) (Herbst et al., 2013). Then, and more interestingly, in our study, we found three new specific developmental findings. Firstly, our results showed that the click frequency value at which the time dilation reached a maximum level (threshold) was lower in the children than in the adults. Indeed, an increase in time dilation was observed between 8 and 20 Hz in the adults (at least in the 200/800-ms condition), whereas it did not increase beyond 8 Hz in the children aged 5 or 8 years. Secondly, beyond this threshold, time dilation remained at a plateau value regardless of increasing click frequency in the adults and the 8-year-olds, whereas a decrease (reversal effect) tended to be observed in the youngest children aged 5 years. Thirdly, the individual differences in time dilation with the increase in the click frequency from 8 to 20 Hz were significantly correlated with individual cognitive capacities in terms of attention and working memory.

The developmental results obtained in our study must be replicated in future experiments to be able to conclude. However, this raises the question: what is the cause of developmental differences in these click effects on time judgment? A first suggestion is that the click effects depend on the speed of the internal clock system (for a review, see Wearden, 2016). However, Eagleman and Pariyadath (2009) consider that the representation of time does not depend on an internal clock system but an amount of neural response (firing rates) (brain energy expenditure). The neural response level would increase with the stimulus intensity (click, brightness, size, numerosity), thus leading to duration dilation (p. 1843). Kaufmann et al. (2000) showed a linear relation between the increase in striate cortex activity and the increase in flicker frequency (measured from 0 to 22 Hz) up to 8 Hz. Whatever the neural system that underpins time representation (pulses, oscillators, neural activity) and the terms used, the fact that time dilation peaked in the children at a lower click frequency value than in the adults could be due to the underlying system that saturated earlier in the younger children. This earlier saturation could thus result from the clock system that works more slowly and less efficiently in children than in adults.

In the same way, the reversal effect observed in the younger children could be also explained by the external rhythm, which was too dissimilar from the rhythm of their own internal clock, with the result that the system picked up and quickly returned to its spontaneous internal rhythm. This hypothesis is supported by the results of developmental studies on sensory-motor synchronization (Provasi and Bobin-Bègue, 2003; McAuley et al., 2006; Monier and Droit-Volet, 2016). Indeed, young children find it difficult to synchronize their taps with an external tempo that is very different from their spontaneous motor tempo and quickly return to their spontaneous tempo when the external tempo is removed. The entrainment by an external rhythm is thus more efficient when the external rhythm is close to the intrinsic preferred tempo (Jones, 2014). When it is too distant, the system returns to its preferred period. Consequently, the decrease in time dilation with increasing click frequency in younger children might be explained by their slower and/or less flexible internal clock system.

However, surprisingly enough, our results suggested that the individual differences in the extension of time dilatation when the click frequency increases from 8 to 20 Hz were significantly related to individual capacities in terms of attention and working memory. In other words, the increase of time distortion with the click frequency tended to be lower in participants with low cognitive capacities. These results are unexpected and difficult to explain. However, they suggest that the effects of click on time judgment cannot be reduced to a clock-related effect and involved attentional processes. In her dynamic attending theory, Mari Jones did not explain the click effect in terms of changes in clock speed but through attentional processes that also work in an oscillatory manner (Jones, 1976; Jones and Boltz, 1989). She explained that attentional oscillations could be synchronized with an external rhythm though entrainment (for a recent review, see Henry and Herrmann, 2014).

In line with this attention hypothesis, our results revealed that, in the children, the click effect on time judgment was additive with the range of stimulus durations (no click × duration interaction) rather than multiplicative. An additive effect between click and duration suggests a constant distortion of time, related to the earlier closure of the attentional switch, rather than a distortion due to oscillatory mechanisms (clock speed) during the processing of time (Lejeune, 1998). In addition, and perhaps more convincing, our results showed that the click frequency-dependent magnitude of the time dilation (8 Hz vs. 20 Hz) was significantly correlated with the individual attention and working memory capacities. The higher the working memory capacity, the greater the extent of the time dilation in response to changes in the click frequency. However, in the adult group, a significant correlation was also observed between selective attention scores and the extent of the time dilation in the 8-Hz click condition compared to the no-click condition. Overall, these results suggested that cognitive resources play a role in the click effect on time judgments when the click frequency increases from 8 to 20 Hz, especially in young children.

Recently, Herbst et al. (2013) studied the effect on perceived duration of the increase of flicker frequency beyond the flicker fusion threshold, i.e. when the frequency is so rapid that no change is perceived (30 Hz–82 Hz). They found that time dilation no longer occurred beyond this threshold, even though the EEG recordings continued to show a significant frequency-specific neural response. The authors thus concluded that duration is affected more by the subjective saliency of changes than by the amount of neural energy induced by repetitive stimuli or their objective rate. However, they did not further develop the theoretical argument. The idea of saliency is related to attention. Given that the increase in time dilation in response to the click frequency effect was lower in the children with limited cognitive capacities, we can assume that the presence of a rapid train of clicks produces attentional interference during the processing of time. In children with low cognitive capacities, this would delay the closure of the attentional switch at the beginning of time processing. When the attentional switch closes later, fewer pulses are accumulated and the duration is judged shorter. The reversal effect with the highest click frequency and the additive click effect observed in the young children are consistent with this attention-related hypothesis. In adults, some studies have also provided evidence of an additive click effect on time judgment (Makin et al., 2012; Jones and Odgen, 2016; Palumbo et al., 2015). This additive click effect has thus also been explained in terms of attention, i.e., an increase in alertness that results in more efficient switch operation (Jones and Odgen, 2016). However, most studies have found a multiplicative click effect rather than an additive effect on adults' time judgments. This suggests that, depending on the click frequency, both clock-speed and attention-related processes could contribute to time judgment in click conditions. Consequently, we may assume that, beyond a threshold at which the maximum rate of the internal clock is reached, the increase in click frequency disrupts time processing, at least in children who have limited attention capacities and who find it difficult to ignore the clicks. Further experiments using a wider range of click frequencies are nevertheless required to test this new hypothesis.

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