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High levels of time contraction in young children in dual tasks are related to their limited attention capacities

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ABSTRACT

Numerous studies have shown that durations are judged shorter in a dual-task condition than in a simple-task condition. The resource-based theory of time perception suggests that this is due to the processing of temporal information, which is a demanding cognitive task that consumes limited attention resources. Our study investigated whether this time contraction in a dual-task condition is greater in younger children and, if so, whether this is specifically related to their limited attention capacities. Children aged 5–7 years were given a temporal reproduction task in a simple-task condition and a dual-task condition. In addition, different neuropsychological tests were used to assess not only their attention capacities but also their capacities in terms of working memory and information processing speed. The results showed a shortening of perceived time in the dual task compared with the simple task, and this increased as age decreased. The extent of this shortening effect was directly linked to younger children's limited attentional capacities; the lower their attentional capacities, the greater the time contraction. This study demonstrated that children's errors in time judgments are linked to their cognitive capacities rather than to capacities that are specific to time.

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Introduction

During recent decades, many researchers have spent much time demonstrating that humans, like all animals, possess an internal clock system that allows them to accurately measure time. However, humans often experience a dilatation or a contraction of time, with time being judged longer or shorter than it really is. Among the factors responsible for these time distortions, one can mention the attention allocated to the processing of time (Nobre & Coull, 2010). Time is indeed judged shorter when our attention is distracted away from the passage of time.

The contraction of time as a function of attention has been widely studied in human adults by means of the dual-task paradigm (for a meta-analysis, see Block, Hancock, & Zakay, 2010). In the dual-task paradigm, participants need to judge the duration of a stimulus while they perform a secondary non-temporal task. The non-temporal task has taken the form of a memory task (e.g., Champagne & Fortin, 2008; Fortin & Breton, 1995; Fortin, Rousseau, Bourque, & Kirouac, 1993), a Stroop task (Brown & Perreault, 2017; Zakay & Fallach, 1984), and another specific task (e.g., Casini & Macar, 1997, 1999; Coull, 2004; Fortin & Rousseau, 1998; Grondin & Macar, 1992; Hicks, Miller, & Kinsbourne, 1976; Kladopoulos, Hemmes, & Brown, 2004; Macar, Grondin, & Casini, 1994). Whatever the non-temporal task used, the results systematically show that the stimulus duration is judged shorter in the dual task than in the simple task when participants need only to judge time.

The resource-based theory of time perception suggests that this is linked to the processing of temporal information, which is a demanding cognitive task that consumes limited attention resources (Block et al., 2010; Brown, 1997; Thomas & Weaver, 1975; Zakay, 1989, 1992, 1993). According to the internal clock models (Gibbon, 1977; Gibbon, Church, & Meck, 1984; Treisman, 1963), the raw material for the representation of time consists of a number of pulses that are emitted by a pacemaker and transferred into an accumulator via an attention-controlled switch that closes at the beginning and opens at the end of the stimulus to be timed. Temporal shortening, thus, would result from a loss of temporal units (pulses) that underlie the representation of time. Lejeune (1998) explained this loss of pulses in terms of an attentional switch that would close early when the participant needs to perform a second task and/or would flicker more often between the onset and offset positions. This latter proposal is consistent with the idea of a succession of alternating attention phases between the non-temporal and temporal tasks. However, this explanation in terms of an "all-or-nothing" switch mechanism does not take into account the performance in a dual task when there is a continuous "sharing" of attention resources between two tasks rather than "a single excursion away from the timing of a duration while a non-temporal task is carried out" (Wearden, 2016, p. 90). Indeed, the judgment of time in a dual task also depends on the degree of attention allocated to temporal information. Thus, in their attentional gate model, Zakay and Block (1996), Zakay and Block (1998) extended the clock system to include an attentional gate that controls the quantity of attentional resources allocated to time processing. The opening of the attentional gate, thus, would be smaller in the dual-task condition than in the single-temporal-task condition, thereby limiting the number of pulses passing into the accumulator.

Regardless of the way in which these authors conceive of attention (e.g., switch, gate), all of them consider that the time contraction in the dual task would occur at an early stage of temporal processing, namely during the online accumulation of pulses. However, other authors place the source of this time distortion at a later stage, at the level of memory, when temporal information (pulses) is maintained, or rehearsed, in short-term memory in order to make temporal decisions or temporal predictions (for discussions, see Fortin & Schweickert, 2016; Ivry & Schlerf, 2008; Taatgen, Van Rijn, & Anderson, 2007). For example, Fortin et al. (1993) showed that the accuracy of temporal reproduction decreased as the short-term memory requirements of concurrent tasks increased, and they concluded that the interference of the non-temporal task on temporal processing "may not be a matter of non-specific general purpose attentional resources, but rather of concurrent short-term memory processing demands" (p. 536). Several studies have indeed found a shortening of estimated durations as the retention interval in memory increases (e.g., Church, 1980; Rattat & Droit-Volet, 2010; Spetch & Grant, 1993). This is also explained by a loss of pulses during the retention interval (Spetch & Wilkie, 1983). In sum, the contraction of time may be due to specific attentional control processes that limit the amount of pulses entering the accumulator (accumulation process per se), to memory processes that erode the amount of already accumulated pulses, or to both. The aim of our study was to investigate this question by testing children in an age range between 5 and 7 years in which there are considerable inter-individual differences in attention and memory capacities (Gathercole, 1998; Gathercole, 2002). The aim was to examine which is the best predictor (attention, memory, or processing speed) of individual differences in the shortening effect in a dual-task paradigm during childhood.

Surprisingly enough, only three studies on time judgment have tested typically developing children in a dual-task paradigm (Arlin, 1986; Gautier & Droit-Volet, 2002; Rattat, 2010), and none has investigated the link between children's temporal performance in this paradigm and their individual cognitive capacities. In Arlin's (1986) study, children aged 6–12 years were asked to reproduce the duration of tones (2, 10, and 5 s) while they performed a second non-temporal task such as naming a series of pictures. In Gautier and Droit-Volet (2002) and Rattat's (2010) studies, younger children (5–8 years) were asked to reproduce a visual stimulus of 6 or 12 s with different interfering tasks: picture naming, sound discrimination, digit, and visuospatial memory tasks. In all of these studies, the reproduction of the duration was always shorter in the dual task than in the single task, a finding that is consistent with the shortening effect found in adults. However, and more interesting, this shortening effect was greater in 5-year-olds than in the older children (8 years). Thus, the authors concluded that this developmental effect in the contraction of time in a dual task is due to attentional capacities, which are more limited in the youngest children. It is indeed well established that the total quantity of mental resources available to process a given task increases as children grow older (Dempster & Brainerd, 1995; Towse, Hitch, & Horton, 2007). However, the direct link between attentional capacities and the magnitude of the shortening effect has not yet been demonstrated in children because their individual attention levels have not been measured. Furthermore, the greater shortening in young children may be related to their low ability to retain temporal information in short-term memory.

Numerous neuropsychological tests have been validated in children to assess their cognitive capacities. These have been widely used for clinical purposes but also to examine the relationships between individual cognitive differences and performance in different tasks (Muris et al., 2008; Savage, Cornish, Manly, & Hollis, 2006), including simple temporal tasks (e.g., Droit-Volet, Wearden, & Zélanti, 2015; Droit-Volet & Zélanti, 2013a, 2013b; Ogden, Wearden, & Montgomery, 2014; Rammsayer & Brandler, 2007; Ulbrich, Churan, Fink, & Wittmann, 2007; Zélanti & Droit-Volet, 2011, 2012). Among these tests, some are used to measure the short-term memory span (i.e., Corsi block-tapping test) that accounts for the ability to keep information active in memory until the task is completed (Corsi, 1972). Others focus more on attention control capacities. The Test of Everyday Attention for Children (TEA-Ch) is composed of a series of subtests that provide an objective measure of available attentional resources (Manly, Robertson, Anderson, & Nimmo-Smith, 1999). Among these subtests, the "Sky search" test was designed to measure selective attention capacities, whereas the "Listen to two things at once" test measures divided and sustained attention. The aim of our study, thus, was to examine the reproduction of stimulus durations (6 and 12 s) in a dual-task paradigm in children aged 5–7 years. We also used different neuropsychological tests to assess their attentional capacities (selective attention and divided attention) as well as their short-term and working memory capacities. A processing speed index was also calculated. Indeed, the faster the information is processed, the greater the number of time units that can be treated and the smaller the shortening effect will be (Droit-Volet & Zélanti, 2013a). In addition, the faster the information is processed, the lower the interference effects are (Vernon, 1987). Our assumptions, therefore, were that the time estimates should be shorter and more variable in the dual task than in the single task, especially in the case of the youngest children. According to the resource-based theory of time perception, the extent of the shortening effect should be significantly related to individual capacities of attention rather than to those of short-term memory, although all increase with age.

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Method

Participants

A total of 57 children aged 5–7 years took part in this experiment: 25 5-year-olds (11 girls and 14 boys; M_{age} = 5.44 years, SD = 0.24), 15 6-year-olds (5 girls and 10 boys; M_{age} = 6.48 years, SD = 0.36), and 17 7-year-olds (7 girls and 10 boys; M_{age} = 7.68 years, SD = 0.31). The 5-year-olds were recruited from a kindergarten (Philippe Arbos school, Clermont-Ferrand), and the 6- and 7-year-olds were recruited from an elementary school (Félix Thonat school, Cournon), all in the Auvergne region of France. The children's parents signed written informed consent for participation in this study. The study was carried out according to the principles of the Helsinki Declaration and was approved by both the inspector of the academy of the French National Education Ministry and the Clermont-Ferrand Sud-Est VI Statutory Ethics Committee (Comité de Protection des Personnes [CPP], Sud-Est VI, France).

Materials

In a quiet neutral room, the children sat in front a computer that controlled the experimental event and recorded the responses using E-Prime 2.1 software (Psychology Software Tools, Pittsburgh, PA, USA). For the temporal reproduction task, the children's responses were presses on the computer mouse. For the non-temporal task, children gave their responses aloud and the experimenter pressed on the corresponding button on the computer keyboard. In the non-temporal task (color discrimination task), small blue squares (4 cm) of two different colors (light blue and dark blue) were displayed at the center of the computer screen on a black background, each presented for a duration of 200 ms. In the temporal task, the stimulus to be timed was a larger blue square with 15-cm sides that was also presented at the center of the computer screen on a black background. In the dual task, a sequence of different small squares (those used in the non-temporal task) was presented in the large square to be timed.

Procedure

Temporal and non-temporal tasks

Each child performed three successive tasks: a simple non-temporal task, a simple temporal task, and a dual task. Each of these tasks was preceded by six learning trials consisting of three demonstrations and three training trials. After an inter-trial interval randomly selected between 500 and 1000 ms, each trial began with the word "ready". When the child was genuinely ready, the experimenter pressed the spacebar that triggered the stimulus presentation after a fixed time of 250 ms. In the non-temporal task, the child was given 16 random trials, with one square per trial (i.e., 8 light blue squares and 8 dark blue squares. The child needed to say whether the blue color of each small square was "light" or "dark" (color discrimination task). In the simple temporal task, the child saw the large blue square that was presented for 6 or 12 s. This stimulus then reappeared, and the child needed to produce a press response when he or she judged that the duration of this second stimulus was similar to that of the first one. The child was given 16 trials, 8 trials for each duration, presented in a random order. In the dual task, the child needed to simultaneously perform the temporal task with the large blue square and the non-temporal task with the small squares of different colors presented inside the large square. There were 16 random trials: 8 trials for the 6-s duration with a sequence of 3 different small squares and 8 trials for the 12-s duration with a sequence of 6 different small squares. The presentation duration of each small square was 200 ms, with an inter-squares interval randomly taken from a temporal window from 500 to 1300 ms. The first small square of the sequence was presented 500 ms after the onset of the large square to be timed. The order of the small squares of different colors was randomized. In this dual task, therefore, the child needed to estimate the presentation duration of the large square while saying the color (light vs. dark) of each small square in the sequence. The large square then reappeared, but without the small squares, and the child pressed when its duration was judged to be similar to the first one.

Neuropsychological tests

Each child was given five neuropsychological tests. The order of presentation was random. The first test used to assess short-term memory and working memory was the Corsi block-tapping test (Corsi, 1972). This test consists of repeating immediately in forward order (short-term memory) and backward order (working memory) the block-tapping sequence presented by the experimenter. There were 8 block-tapping sequences going from 2 to 9 blocks, with two trials per block sequence. The test was halted when the child failed on two trials in the same block sequence. To measure an index of information processing speed, the child also performed two subtests of the Wechsler Intelligence Scale for Children: "Code A" and "Symbol A" (Wechsler, 2005). In the first test, the child was initially presented with 5 figures, each of which was associated with a specific code. The child then drew the right code for a series of 64 figures in a given time of 120 s. In the second test, also limited in time (120 s), the child was presented with 45 symbols and needed to judge whether or not each of them was present in a series of 5 different symbols. The last two tests were subtests of the TEA-Ch (Manly et al., 1999). The first test, called "Listen to two things at once," measures divided and sustained attention; the second test, called "Sky search," measures selective attention. In the first test, the child needed to simultaneously address two distinct sources of relevant stimuli; the child needed to simultaneously listen to a series of stories in order to recall the names of the animals cited in each story and to count the number of shots that occur randomly during each story. In the second test, the child was presented with a sheet containing 130 pairs of spaceships consisting of five different types. The child's task was to circle all pairs of identical spaceships as quickly as possible.

Results

Temporal performance

Preliminary statistical analysis led us to exclude 6 children (3 5-year-olds and 3 7-year-olds) from the subsequent statistical analyses because their mean temporal reproduction was outside of the ±3 standard deviations range, although their inclusion did not change the results. Fig. 1 shows the mean durations reproduced by the other children aged 5, 6, and 7 years for the target durations of 6 and 12 s in both the simple temporal task and the dual task. An analysis of variance (ANOVA) was performed on this measure with two within-participants factors (duration vs. task) and one between-participants factor (age). This ANOVA[1] showed a main effect of duration, $F(1,50) = 55.54$, $p = .0001$, $\eta_p^2 = .54$, $(1 - \beta) = 1.0$, indicating that the children reproduced shorter durations for 6 s than for 12 s, although the 6-s duration tended to be overestimated and the 12-s duration tended to be underestimated (see Discussion). The main effect of age did not reach significance, $F(2,50) = 1.86$, $p = .17$, and neither did the Duration × Age interaction, $F(2,50) = 1.42$, $p = .25$. This suggests that age per se did not explain differences in temporal reproductions.

More interesting, a significant effect of the task was obtained, $F(1,50) = 70.23$, $p = .0001$, $\eta_p^2 = .59$, $(1 - \beta) = 1.0$, with the reproduced durations being shorter in the dual task than in the simple task. This finding is consistent with a time contraction effect in the dual task. Moreover, the Task × Duration interaction was significant, $F(2,50) = 12.94$, $p = .001$, $\eta_p^2 = .21$, $(1 - \beta) = .94$, indicating that the time contraction in the dual task compared with the simple task was greater for the longer stimulus duration. There was also a significant Task × Age interaction, $F(2,50) = 4.15$, $p = .022$, $\eta_p^2 = .15$, $(1 - \beta) = .71$. The three-way Age × Task × Duration interaction was not significant, $F(2,50) = 0.51$, $p = .60$. When we calculated the difference in reproduced durations between the dual task and the simple task, we found that the magnitude of this difference was higher in the 5-year-olds ($M = 9949$ ms) than in the 7-year-

[1] An analysis of covariance (ANCOVA) was also performed with age in month as a covariate and found similar results with a significant Task × Age interaction, $F(1,56) = 9.62$, $p = .003$, and a non-significant Age × Task × Duration interaction, $F(1,56) = 1.06$, $p = .31$.

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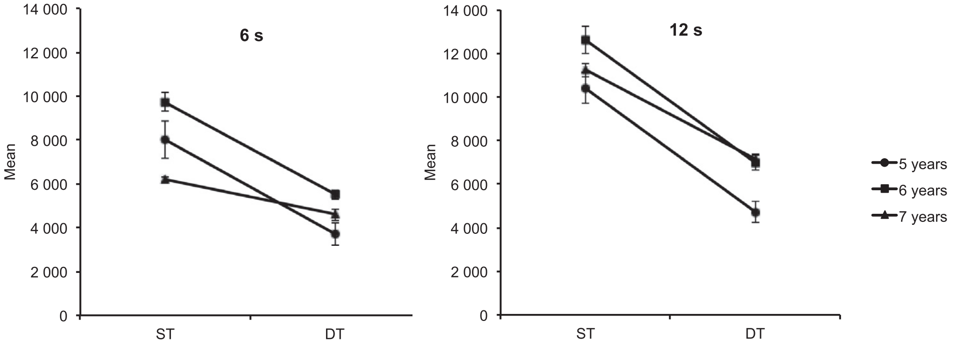

Fig. 1. Mean reproduced durations in children aged 5, 6, and 7 years for the simple task (ST) and the dual task (DT) for the 6-s and 12-s target durations.

olds (M = 5689 ms), $t(36) = 2.33$, $p = .026$. No difference was found between these two ages and the intermediate age of 6 years (M = 9874 ms), $t(35) = 0.025$, $p = .98$ and $t(29) = 1.34$, $p = .20$, respectively.

The same ANOVA was performed on the standard deviation of reproduced durations (Fig. 2). Significant main effects of duration, $F(1,50) = 17.63$, $p = .0001$, $\eta_p^2 = .27$, $(1-\beta) = .98$, and age, $F(2,50) = 5.79$, $p = .006$, $\eta_p^2 = .194$, $(1-\beta) = .85$, as well as a significant Duration $\times$ Age interaction, $F(2,50) = 7.88$, $p = .001$, $\eta_p^2 = .25$, $(1-\beta) = .94$, were found. Consequently, the reproduced duration was more variable for the 12-s duration than for the 6-s duration, especially among the young children. Furthermore, there was no main effect of task, $F(1,50) = 4.00$, $p = .051$, Task $\times$ Age interaction, $F(2,50) = 0.622$, $p = .54$, Task $\times$ Duration interaction, $F(1,50) = 0.054$, $p = .82$, or Time $\times$ Task $\times$ Age interaction, $F(2,50) = 0.13$, $p = .88$. In summary, although the variability of temporal reproductions was higher in the younger children and for the longer duration, the task did not affect the variability of temporal reproductions.

Correlations between the single-/dual-task difference in reproduced durations and cognitive abilities

Table 1 shows the raw scores for the different neuropsychological tests. An analysis of covariance (ANCOVA) was initially performed on these neuropsychological scores, with the child's age in months taken as a covariate. The statistical results systematically showed a significant age effect: short-term memory, $F(1,50) = 14.88$, $p = .0001$, $\eta_p^2 = .23$, $(1-\beta) = .97$; working memory, $F(1,50) = 26.23$, $p = .0001$, $\eta_p^2 = .35$, $(1-\beta) = .99$; processing speed, $F(1,50) = 18.52$, $p = .0001$, $\eta_p^2 = .27$, $(1-\beta) = .99$; selective attention, $F(1,50) = 36.83$, $p = .0001$, $\eta_p^2 = .43$, $(1-\beta) = 1.0$; divided attention, $F(1,50) = 53.83$, $p = .0001$, $\eta_p^2 = .53$, $(1-\beta) = 1.0$. In summary, the older the children were, the higher their scores on the different neuropsychological tests were.

Table 2 shows the correlations between the scores of the different neuropsychological tests. This table shows a high level of correlation between the different neuropsychological scores (all $ps < .01$), although the correlation was lower between the short-term memory scores and the attention-related scores (selective and divided attention), with a non-significant correlation between short-term memory and divided attention ($r = .25$, $p > .05$).

We then calculated the differences in temporal reproduction between the simple task and the dual task for each participant and each stimulus duration (6 or 12 s). A preliminary statistical test of collinearity was performed to test the reproduction-related multicollinearity among our five variables. Tolerance was greater than .10, and the variance inflation factor obtained was less than 10 for each of our variables, indicating that multicollinearity was not a concern (selective attention scores: tolerance = .47, VIF = 2.14; divided attention scores: tolerance = .72, VIF = 1.38; processing speed scores: tolerance = .48, VIF = 2.07; working memory scores: tolerance = .32, VIF = 3.14; short-term memory scores: tolerance = .48, VIF = 2.08). A correlation analysis was then run among the difference index (6 and 12 s), age, and scores on the different neuropsychological tests (Table 3). Although most of

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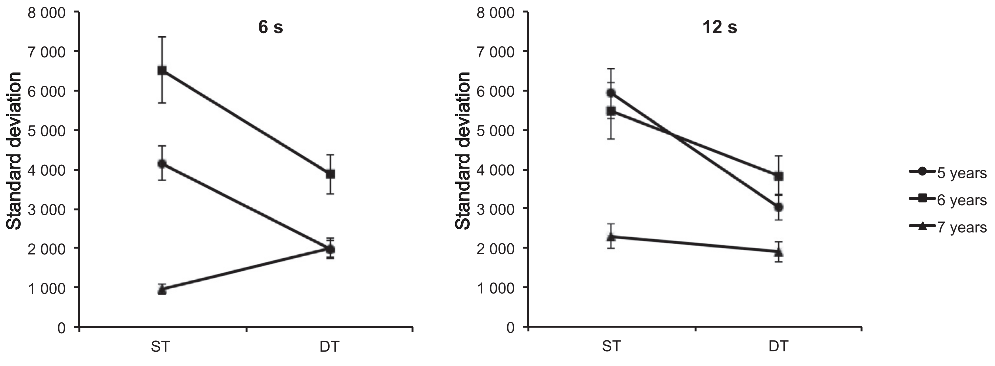

Fig. 2. Standard deviations of reproduced durations in children aged 5, 6, and 7 years for the simple task (ST) and the dual task (DT) for the 6-s and 12-s target durations.

Table 1
Means, standard deviations, and minimums and maximums of raw scores for different neuropsychological tests.

	5 years			6 years			7 years		
	M	*SD*	[Min; Max]	*M*	*SD*	[Min; Max]	*M*	*SD*	[Min; Max]
Short-term memory	4.18	1.56	[2; 8]	5.40	1.72	[3; 10]	6.57	2.03	[4; 12]
Working memory	2.68	2.06	[0; 9]	4.73	1.58	[2; 8]	6.21	1.18	[4; 8]
Processing speed	49.23	18.10	[26; 102]	75.13	14.16	[47; 100]	76.14	14.67	[50; 96]
Selective attention	42.48	20.81	[14; 87]	17.56	10.31	[8; 50]	12.86	4.07	[7; 22]
Divided attention	6.33	3.44	[1; 11]	9.47	2.92	[4; 14]	13.71	2.78	[10; 19]

Table 2
Correlation matrix between age and the raw scores of neuropsychological tests.

	1	2	3	4	5
1. Age in months	1				
2. Short-term memory	.48**	1			
3. Working memory	.59**	.71**	1		
4. Processing speed	.52**	.51**	.61**	1	
5. Selective attention	−.66**	−.42**	−.65**	−.62**	1
6. Divided attention	.73**	.25	.41**	.44**	−.50**

** Correlation significant at .01 level.

Table 3
Correlations between simple-/dual-task differences in reproduction durations, ages, and scores on neuropsychological tests.

	6-s Difference	12-s Difference	Overall
Age	−.21	−.13	−.18
Short-term memory	.11	.05	.08
Working memory	−.12	−.09	−.11
Processing speed	−.12	−.14	−.14
Selective attention	.31*	.42*	.40*
Divided attention	−.31*	−.22	−.28*

* $p < .05$.

the neuropsychological scores correlated, for the 6-s duration there was a significant correlation only between the single-/dual-task difference and the attention scores (divided attention: $r = .31$, $p = .031$; selective attention: $r = .31$, $p = .026$). The correlations with the age and memory scores did not reach

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significance, $p > .05$. Similarly, for the 12-s duration, the only significant correlation was between the single-/dual-task difference and the attention scores, in particular the selective attention score ($r = .45$, $p = .002$), given that the correlation with divided attention did not reach significance ($r = -.22$, $p = .13$). Finally, when we averaged the two stimulus durations together, we found a significant correlation only between this overall temporal difference index and the scores on the two attention tests (divided attention: $r = -.28$, $p = .047$; selective attention: $r = .40$, $p = .004$).

When we ran a simple linear regression on this overall single-/dual-task temporal difference index with age as a factor, the model was not significant, $F(1,50) = 2.17$, $p = .15$ ($B = -1991.04$, $SE = 1351.35$, $\beta = -.206$, $R^2 = .042$). However, when we extended our model to include the scores on the two tests of attention in addition to age, the model became significant, $F(3,48) = 3.70$, $p = .018$. The age variable became even less significant ($B = 2373.12$, $SE = 2074.56$, $\beta = .243$, $p = .26$, $R^2 = .043$), whereas the model explained more variance. In this current model, selective attention reached significance ($B = 181.28$, $SE = 70.75$, $\beta = .445$, $p = .014$, $R^2 = .19$), whereas divided attention did not ($B = -437.96$, $SE = 352.42$, $\beta = -.233$, $p = .22$, $R^2 = .08$).

We then ran a hierarchical regression on the overall single-/dual-task differences, including the scores on the two attention tests (selective and divided attention), to identify which component of attention was the best predictor of time contraction in the dual task. The results revealed a greater effect of selective attention ($B = 142.61$, $SE = 62.36$, $\beta = .350$, $R^2 = .17$, $p = .027$), whereas the effect of divided attention was no longer significant ($B = -204.12$, $SE = 288.02$, $\beta = -.108$, $R^2 = .08$, $p = .48$). In other words, the selective attention capacities explained the largest part of the variance in the shortening of time between the simple task and the dual task.

Finally, we compared the correlation obtained between the selective attention scores and the overall single-/dual-task difference ($r = .40$, $p = .04$) as well as between the divided attention scores and the overall single-/dual-task difference ($r = -.28$, $p = .47$). It appears that the correlations were significantly different from each other, $t(51) = 3.05$, $p < .01$), thereby confirming that the link between the magnitude of time contraction and selective attention capacities was the strongest.

Non-temporal performance

A first ANOVA was performed on the correct response rate in the dual task, with one within-participants factor (duration) and one between-participants factor (age) (Fig. 3). There was neither an effect of duration, $F(1,50) = 0.80$, $p = .38$, nor an Age $\times$ Duration interaction, $F(2,50) = 0.23$, $p = .80$. However, the effect of age was significant, $F(1,56) = 7.92$, $p = .001$, $\eta^2_p = .25$, $(1 - \beta) = .94$. Therefore, the duration of stimulus presentation did not affect performance in the non-temporal task.

A second ANOVA was performed on the correct response rate, with task as a within-participants factor (simple vs. dual task) and age as a between-participants factor. The results again revealed a significant effect of age, $F(2,50) = 8.53$, $p = .001$, $\eta^2_p = .26$, $(1 - \beta) = .96$, suggesting that younger children make more mistakes than older children independently of the task. More interesting, however, the effect of task now also reached significance, $F(1,50) = 11.48$, $p = .001$, $\eta^2_p = .19$, $(1 - \beta) = .91$. Thus, the children made more mistakes in the dual task than in the simple task. However, there was no significant interaction between age and task, $F(2,50) = 2.21$, $p = .12$. When we calculated the difference in the total correct responses between the simple task and the dual task, we found that the magnitude of this difference was higher in the 5-year-olds ($M = -4.09$) than in the 7-year-olds ($M = -0.93$), $t(36) = -3.53$, $p = .002$. We also found a difference between the 5-year-olds and the 6-year-olds ($M = -1.07$), $t(35) = -3.24$, $p = .003$. However, no significant differences were found between the 7-year-olds and the 6-year-olds, $t(29) = -0.29$, $p = .775$.

Correlations between the single-/dual-task difference in non-temporal performance and cognitive abilities

A correlation analysis was carried out among the difference index calculated above, age, and the scores on the different neuropsychological tests. Unlike for time judgment, the single-/dual-task difference in the non-temporal task was significantly correlated not only with age ($r = .39$, $p = .01$) but also with all of the neuropsychological scores, that is, both those for memory (short-term memory: $r = .36$, $p = .01$; working memory: $r = .41$, $p = .003$) and those for attention (divided attention:

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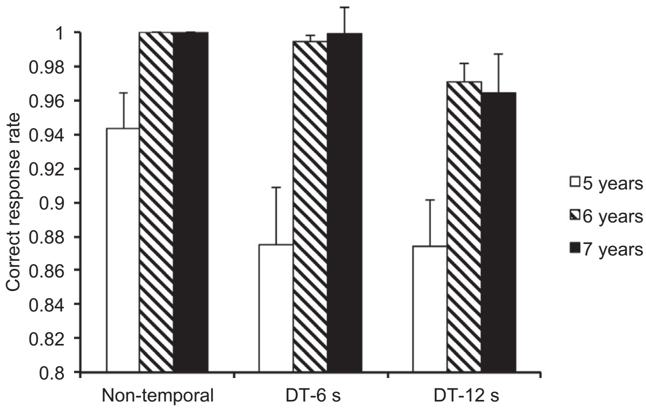

Fig. 3. Correct response rates in the non-temporal task for the single task and dual task (DT) when the stimulus durations were 6 s and 12 s in children aged 5, 6, and 7 years.

r = −.46; selective attention: *r* = −.49; all *ps* < .001). There was also a significant correlation with processing speed (*r* = .60, *p* = .0001). A hierarchical analysis of regression on this single-/dual-task difference index with the different scores in the neuropsychological tests was then run. This regression showed a significant result for the processing speed scores (*B* = .434, *SE* = .03, *p* = .01), indicating that an increase of 1 point in correct responses caused an increase of 0.432 point in the processing speed score. The effect of divided attention was also significant (*B* = .345, *SE* = .124, *p* = .047). No other variables reached significance (i.e., age, working memory, short-term memory, and selective attention, all *ps* > .05).

Finally, we ran a last hierarchical regression to examine whether selective and divided attention scores were still significant predictors of the single-/dual-task difference in the time estimates when the non-temporal results were included in the model. The selective attention always tended to be significant (*B* = 126.67, *SE* = 65.17, β = .311, R^2 = .16, *p* = .05), whereas the other variables were not significant (for divided attention: *B* = −113.45, *SE* = 307.17, β = −.06, R^2 = .08, *p* = .71; for correct response rate in non-temporal task: *B* = −354.14, *SE* = 408.82, β = −.138, R^2 = .09, *p* = .39). This suggests that the selective attention capacities remained the main factor explaining the individual differences in time contraction in a dual task and not the level of performance on the secondary non-temporal task.

Discussion

Children aged 5–7 years were given a temporal reproduction task in a simple-task condition and a dual-task condition involving a non-temporal color discrimination task. In the simple temporal task, the children tended to overestimate the shortest stimulus duration (6 s) and tended to underestimate the longest stimulus duration (12 s), as predicted by Vierordt's (1868) law for adults. According to this law, the shortest durations are reproduced longer and the longest durations are reproduced shorter than they actually are (Lejeune & Wearden, 2009). However, our results suggest that there is a greater temporal bias in the younger children, at least for the shortest duration. A similar temporal bias has been observed in other studies in children (Droit-Volet, 2010; Droit-Volet et al., 2015). This has generally been explained in terms of the effect on temporal reproduction of the slower initiation of the motor response in young children. However, this did not affect the interference effect observed in our dual-task paradigm, showing that a concurrent non-temporal task produced a shortening of reproduced time in children similar to that observed in adults (Brown & Perreault, 2017). However, the interest of our study was to show that this time contraction in the dual task was greater in the youngest children and decreased with increasing age. In addition, our results demonstrated that the age-related decrease in the shortening effect was specifically related to the improvement of individual attention capacities; the more limited the attentional capacities, the shorter the reproduced time

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was. In sum, our study demonstrated that the contraction of time in the dual task depends directly on the individual attentional resources available for the processing of time. Thus, it provides support for the resource-based theory of time perception according to which the representation of time depends on attentional resources allocated to time (Block et al., 2010; Brown, 1997; Thomas & Weaver, 1975; Zakay, 1989, 1992, 1993).

Our results also showed a bidirectional effect on performance between the temporal and non-temporal tasks. Indeed, the color discrimination task affected time judgment by shortening reproduced durations, and the judgment of time affected color discrimination by increasing the number of discrimination errors. The mutual interference between these two tasks suggests that common processes exist for the processing of temporal and non-temporal information (Navon & Gopher, 1979). The internal clock models specifically designed to account for timing do not include common mechanisms for the processing of different types of information. According to Baddeley and Hitch's (1974) working memory model, all information is processed via a central administrator with limited capacity that controls and allocates attentional resources to the different types of information to be processed. The processing of temporal and non-temporal information, therefore, could call on the same attentional resource pool managed by this central processor. The shared mechanisms for the processing of both temporal and other information, therefore, would be restricted to general attention mechanisms. This view is consistent with our results showing that both temporal and non-temporal performance in the dual-task condition depended on individual attentional capacities. However, our results revealed that, for time judgment, the magnitude of the time contraction produced by the secondary task depended only on individual attentional capacities. In contrast, for color judgment, the decrease in non-temporal performance in the dual task was linked not only with attention scores (selective and divided attention) but also with short-term memory, working memory, and processing speed scores. This suggests that the processing of temporal information involves only the central processor, whereas that of non-temporal information (color discrimination) involves other mechanisms, including the visuospatial sketchpad, which is involved in the short-term retention of visual information. This is consistent with the idea that, for long durations (>500 ms), the processing of time does not depend on modality-specific mechanisms and that this one involves a central executive system that manages attentional resources (see Rammsayer, Borter, & Troche, 2015). It is also consistent with the developmental studies showing that the age-related differences in time sensitivity are mainly due to the development of general cognitive capacities in terms of attention and working memory (for reviews, see Droit-Volet, 2013, 2016). Similarly, brain imaging studies have identified the prefrontal cortex as a key brain structure in explicit time judgments, whereas this structure also plays a critical role in executive control functions (e.g., Coull, Cheng, & Meck, 2011).

Some researchers hold that the interference effects on timing are due to "concurrent short-term memory processing demands" rather than to competition for the consumption of attentional resources (for a discussion, see Fortin & Schweickert, 2016). Our results showed that the magnitude of the shortening effect was not linked to individual short-term memory or working memory capacities. In other words, the contraction of time was not higher in the children with low memory capacities, that is, those who found it difficult to actively retain information in memory. Similarly, Fortin and Massé's (1999) study showed that the amount of non-temporal information maintained in short-term memory did not have a significant effect on concurrent time production. Rather than memory capacities, our study demonstrated that selective attention capacities are the only reliable predictors of individual differences in time contraction in a dual task. Therefore, time contraction is mainly related to children's difficulties in keeping track of the flow of temporal information in the presence of a secondary task. This provides support for the attention-based theory of time perception according to which a concurrent task operates at the level of the process of accumulation of temporal units (pulses) before their storage in memory (Lejeune, 1998; Rousseau, Picard, & Pitre, 1984; Zakay & Block, 1996). In other words, the concurrent task would lead to a loss of pulses during their accumulation in the timer.

The question raised now is the nature of the mechanism that produces this loss of pulses during the accumulation process. As mentioned in the Introduction, Lejeune (1998) explained time contraction in dual tasks in terms of the all-or-nothing operation of the switch located between the pacemaker and the accumulator. To account for time contraction in dual tasks, Zakay and Block (1996) added to this switch system an attentional gate, the size of opening of which controls the amount of pulses transferred into the accumulator. Our results did not allow us to settle the question of the nature of the attentional mechanisms involved in time judgments in a dual-task condition, and further experiments will be necessary. In addition, the effect on time judgment of other concurrent non-temporal tasks, namely those with different types of non-temporal tasks that produce larger differences between age groups, must be examined. Nevertheless, our results revealed that the best predictor of individual differences in time contraction in a dual task was selective attention, although divided attention also played also a significant role. Selective attention refers to the ability to focus on one item of information while ignoring the rest of the items, whereas divided attention refers to the ability to process two or more items of information simultaneously by allocating a quantity of attentional resources to each item (Pashler, 1998). These two modes of attention are related, with both depending on executive control functions and the maturation of the prefrontal cortex during childhood (Casey, Tottenham, Liston, & Durston, 2005; Sowell et al., 1999; Tsujimoto, 2008). Nevertheless, it is conceivable that the most critical cognitive operation for the perception of time in a dual task lies in the capacity to control the switch-like system, that is, to close the attentional switch just at the onset of the to-be-timed stimulus and to keep it closed during its presentation. Consequently, children's low capacities in terms of selective attention would produce a malfunction of the switch system that would close later or that would flicker more frequently in a dual task. This is consistent with the developmental studies showing that time contraction is greater with than without an attention distracter in a reproduction task (Zakay, 1992) and a bisection discrimination task (Gautier & Droit-Volet, 2002).

However, our results suggest that time estimates in a dual task are also related in part to the development of divided attention capacities (albeit to a lesser extent). This would indicate that the switch system is insufficient to account for time contraction in a dual task. As argued by Zakay and Block (1996), Zakay and Block (1998), a second mechanism is required, a mechanism that manages the quantity of attentional resources devoted to time at any given moment. In another words, the quantity of attentional resources allocated to time processing can differ even if the switch closure duration remains the same. However, there are few studies in adults, and none in children, that have gathered data allowing us to specifically validate the existence of a gate in the internal clock system. Macar et al. (1994) nevertheless showed that the magnitude of the shortening effect depends on the degree of attention allocated to time by telling adults to allocate a given percentage of their attention to time (e.g., 100%, 75%, 25%, 0%). Thus, future experiments are needed in children to dissociate between the effects related to the switch and the gate in the internal clock system.

In summary, our study examined the direct connection between individual attention capacities and explicit time reproduction in a dual-task paradigm. The results demonstrated that the explicit judgment of time was directly linked to the capacity to allocate attentional resources to time. This provides convincing support for the hypothesis according to which the explicit processing of time involves a general information processor. The issue is now to successfully describe the link between a putative internal clock and general information processing systems.

Uncited references

Block et al. (1998), Brainerd and Dempster (1995), Brown et al. (2013), Case (1987) Cowan (1997), Davidson et al. (2006), MacLeod (2007), Packwood et al. (2011), Spetch (1987).

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