The different contribution of executive control to temporal comparison and reproduction in children and adults

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Abstract

The present study investigated the role of executive functions in the development of two aspects of timing: temporal reproduction and comparison. Children aged 7 and 10 years and young adults were asked to either reproduce target durations (i.e., reproduction task) or judge the similarity of two target durations (i.e., comparison task). These temporal tasks were performed in isolation (single-task condition) or in conjunction (dual-task condition) with an executive task tapping inhibitory control (i.e., Stroop-like interference in animals size task). The results showed that the concurrent executive task degraded temporal performance to a greater extent at the age of 7 years than in older children and adults, and that it had much less influence on temporal comparison than on temporal reproduction. Conversely, regardless of age group, the concurrent timing of stimuli decreased response accuracy in the inhibitory control task in both temporal tasks, but to a greater extent in the comparison than the reproduction task. Furthermore, the dual-task condition reduced response time in the executive task, but only in children aged 7 years -and not in older children and adults. Thus, both duration reproduction and comparison relate to executive functions, although the relation is stronger for reproduction. Importantly, timing progress during childhood stems at least partly from more efficient executive functions (more specifically inhibitory control).

Keywords: inhibitory control; temporal comparison; temporal reproduction; children; timing; interference effects

Introduction

As time is one of the dimensions that govern much of human behavior, for instance, cooking, speaking, playing, playing music or sport, it is critical for individuals to be able to measure it. The human brain is equipped to adapt to the dynamic temporal environment, that is, to capture time and process temporal information (Buonomano, 2017). Although the ability to measure time is present from birth (Brannon et al., 2004; De Hevia et al., 2014), suggesting a primitive, early emerging sense of time, time measurement becomes more efficient during childhood (for reviews see Droit-Volet, 2013, 2016). However, it is still unclear whether age-related progress stems from more efficient processes per se or more efficient executive functions.

Classical internal-clock timing models (Gibbon, 1977; Gibbon, Church & Meck, 1984; Treisman, 1963; for a review, see also Wearden, 2003) state that perceived time depends on the number of pulses emitted continuously by a pacemaker (i.e., a time-base or oscillator) and transferred into an accumulator through an attention-controlled switch which closes at the beginning and opens at the end of the stimulus to be timed. In other words, the number of pulses counting during a given time interval is the internal representation of this interval (the more pulses are accumulated, the longer is the perceived duration). Diverting attention from the temporal accumulation process (timekeeping), in particular by distractors or concurrent non-temporal tasks, would result in a loss of temporal pulses that underlie the representation of time, and consequently in time contraction. Timekeeping thus requires directing and maintaining attention focused on time, which in turn depends on executive functions, in other words, the goal-directed regulation of attention and actions (e.g., Diamond, 2013). As executive functions develop from early childhood to late adolescence (e.g., Carlson, 2005; Cragg & Nation, 2008; Davidson, Amso, Anderson, & Diamond, 2006; Nigg, 2017; Pennequin, Nanty, & Khomsi,

2004; Tillman, Thorell, Brocki, & Bohlin, 2008; Wright, Prescott, & Murdoch-Eaton, 2003; see also Chevalier, 2010; Fourneret & des Portes, 2016, for reviews), age-related progress in timekeeping during childhood may reflect better executive abilities rather than changes in temporal accumulation per se with age.

Consistently, at younger ages, children are more subject to time distortions, in particular in dual task conditions where parallel processing of a temporal task and a non-temporal task are required (Arlin, 1986; Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017; Rattat, 2010), hence speaking to the role of executive functions development in better timing during childhood. Specifically, Arlin (1986) asked 6-12-year-olds to reproduce 2-, 5- and 10-sec stimulus durations in both single- and dual-task condition with a secondary task consisted of naming a series of pictures presented at regular intervals. The results showed that the reproduction of the durations was systematically shorter in the dual- than the single-task condition, as classically observed in adults (for a meta-analysis, see Block, Hancock, & Zakay, 2010). More importantly, this temporal underestimation in dual-task progressively reduced from 6 years to remain stable between 9 and 12 years. It was not until many years later that other researchers have examined again temporal reproduction in dual task condition with children aged 5-8 years (Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017; Rattat, 2010). These three studies confirmed that the dual task condition led children to underestimate durations (6 and 12 sec) compared to single task one, and that this temporal underestimation decreased with age between 5 and 8 years, irrespective of the concurrent non-temporal task used (i.e., picture naming, sound or color discrimination, digit or visuospatial memory tasks).

However, these previous studies have targeted temporal reproduction, while completely overlooking another essential aspect of timing measurement, that is time estimation. It is

therefore unclear whether executive functions are fundamental to timing in general or only for temporal reproduction. In particular, executive functions may support cognitive operations specifically involved in temporal reproduction or specific demands of tasks tapping temporal reproduction. In temporal reproduction tasks, participants are exposed to a sample duration and asked to reproduce it by pressing a key and only releasing it when they judge that the same time as the stimulus duration has elapsed. As preparing and executing a motor action take time and executive resources, participants have to consider this motor delay in order to reproduce the sample duration as accurately as possible. In children, the motor delay is longer and more variable than in adults, partly explaining their poorer accuracy in a temporal reproduction task (Droit-Volet, 2010). In contrast, time estimation tasks do not require participants to integrate in their temporal productions the motor components of responses. Instead, participants have to judge whether two stimuli presented successively lasted for the same duration or not (comparison task), to categorize a stimulus duration as short or long (bisection task), or even to identify whether or not a duration was the same as a previously-presented standard (generalization task). In all cases, responses just consist of a single press of the corresponding key, hence imposing much lower executive functions demands. In addition to the motor components of the task, it is very likely that the nature of the required temporal judgment is also a critical factor contributing to explaining age-related differences in timing performance. For example, children may need to engage more attentional resources to process a duration (i.e., timekeeping) in order to judge its similarity with the standard one than to simply categorize it as being short or long, resulting in lower temporal performance in generalization than in bisection in children (Droit-Volet, Wearden, & Zelanti, 2015). Therefore, progress in executive functions may influence greater changes in time reproduction than time estimation during childhood.

Consistent with a greater role of executive functions in temporal reproduction than estimation, studies with adults have systematically shown that dual tasks tapping executive functions, and in particular inhibitory control, hinder temporal production performance (Brown, 2006; Brown, Collier, & Night 2013; Brown, Johnson, Sohl, & Dumas, 2015; Brown & Perreault, 2017; Lovas & Kacmar, 2016; Ogden et al., 2011). Only one study found no interference between concurrent timing and inhibition processing (Ogden et al., 2011), which may reflect the lower difficulty of the dual task relative to other studies. In line with this, the bidirectional interference effect between temporal production and inhibitory control tasks has recently been shown to increase with inhibition demands (Brown & Perreault, 2017). Thus, executive functions (specifically inhibitory control in this case) are likely recruited during temporal processing, especially when task difficulty is high.

Unlike studies addressing time (re)productions, those addressing the effect of executive function dual tasks on time estimation have reported mixed findings in adults. Adults' inhibition performance in a random number-letter generation task correlates with temporal performance in bisection (Ogden et al., 2017) but not in reproduction, verbal estimation and generalization (Ogden et al., 2014). In the random number-letter generation task, the participants had to verbalize a continuous series of numbers in a random sequence, thus requiring to inhibit the production of numbers in either ascending or descending order (both orders being familiar for most adults). The only study in children found that 7 to 11-year-olds with attention deficit hyperactivity disorder (ADHD) showed larger errors under dual-tasks than control children in a temporal reproduction task but not in a temporal verbal estimation task (Bauermeister et al., 2005). More precisely, on the latter task, the control and ADHD children did not differ from each other on their performance. The measure of inhibitory control via a Stroop task

significantly correlated with time reproduction performance but not with verbal time estimation performance. Therefore, children's inhibition performance may have a stronger relation with temporal reproduction performance than with verbal temporal estimation.

The present study aimed to examine the role of executive functions, and more specifically inhibitory control, in different aspects of temporal performance in children and adults. Critically, we directly compared the effect of a dual task tapping inhibitory control (i.e., Stroop-like interference in animals size task, Catale & Meulemans, 2009) on both temporal reproduction and time estimation performance. More precisely, children aged 7 and 10 years old and young adults either reproduced target durations or judged the similarity of two target durations; this task being performed in isolation (single-task condition) or in conjunction (dual-task condition) with the inhibitory control task. We selected a dual task tapping inhibitory control—the deliberate suppression of goal-irrelevant information and actions (Diamond, 2013; Nigg, 2000), as (1) this particular executive function may be especially involved in selectively attending to temporal aspects of a situation while suppressing attention to other aspects, and (2) a limited but increasing number of studies have shown that inhibitory control supports timing processes in adults (e.g., Brown, 2014; Ogden et al., 2011; Radua et al., 2014).

As previously explained, two findings emerge from the only four studies examining how time judgments develop during childhood in a dual-task paradigm to date: first, the classical temporal underestimation observed in dual-tasks progressively reduced with age between 5 and 8 years, and second it then stabilized between 9 and 12 years of age. Insofar as none of these studies included a group of young adults to directly compare their performance with that of older children, we can not conclude with certainty that the time contraction under dual-task reaches a level comparable to the adults from age 9. In the present study, we therefore decided to select

three groups of different ages: a first group of 7-year-olds, a second group of 10-year-olds, and a third group of young adults. We expected interference in the dual-task conditions, but to a greater extent in the reproduction task than the comparison task. Moreover, these interference effects should reduce between 7 and 10 years of age, and then stabilize until adulthood, that is, no difference should be observed between older children and adults.

Method

Participants

A total of 147 children aged 7 and 10 years old and young adults took part in the present experiment on a voluntary basis. The children were recruited, with parental written consent, from monolingual classes in urban primary schools in or around Albi in southwestern France, and the adults were recruited at the University of Albi. Most families in the catchment areas of these schools have middle SES backgrounds. No children who were behind in their schooling. In each age group, participants were randomly assigned to one of the two temporal task conditions, reproduction (30 adults: 20 women and 10 men; mean age = 21.52, SD = 3.17; 21 children aged 10 years old: 14 girls and 7 boys; mean age = 9.95, SD = 0.56; and 25 children aged 7 years old: 14 girls and 11 boys; mean age = 7.40, SD = 0.61) or comparison (30 adults: 26 women and 4 men; mean age = 22.08, SD = 3.43; 20 children aged 10 years old: 11 girls and 9 boys; mean age = 9.85, SD = 0.62; and 21 children aged 7 years old: 13 girls and 8 boys; mean age = 7.47, SD = 0.80). Note that in each age group, the random assignment of participants in one of the two temporal task conditions have led to the constitution of two groups with similar mean age (t-tests for independent samples, 7-year-olds: t < 1; 10-year-olds: t < 1; adults: $t(58)$ = 1.05, p = .298).

Materials

We used a Macintosh computer, placed approximately 50 cm away from the participant, to control all the experimental tasks and record data via the PsyScope program (Cohen, MacWhinney, Flatt, & Provost, 1993). For the two temporal tasks, the visual stimulus to be timed was a 4.5×4.5 cm blue square displayed against a white background in the center of the computer screen. Each presentation of the temporal stimulus was preceded by a black fixation cross (4 mm). Participants responded by pressing the S or L key of the computer keyboard for the comparison task, and the spacebar twice, once at the beginning and once at the end, for the reproduction task. For the Stroop-like interference in animals size task, we used eight different color drawings of animals (four large animals: a whale, a cow, an elephant and a bear; and four small animals: a duck, a mouse, a cat and an ant) printed as either large (10x9 cm) or small (5x4 cm) drawings and displayed against a white background on the left- and the right-hand sides of the screen. Responses were collected using the A and P keys on the computer keyboard.

Procedure

Participants were tested individually in a quiet room of their school or university for 35-40 min on average. They all completed the three following tasks in the same order: (1) a single temporal task, either reproduction or comparison task (single-task condition), (2) a single inhibitory control task (Stroop-like interference in animals size task, e.g., Catale & Meulemans, 2009; Naglieri & Das, 1997; Pennequin, Nanty, & Khomsi, 2004), and (3) the same temporal task concomitantly with the inhibitory control task (dual-task condition). Before each task, they were given one demonstration trial and three practice trials without feedback (as in test trials). To prevent them from using a counting strategy, they were explicitly told not to count (for this method see Rattat & Droit-Volet, 2012). No performance-related feedback was given in any task.

As illustrated in Figure 1a, in the single temporal reproduction task, a press on the spacebar initiated every trial by triggering the presentation of a fixation cross for 750 ms in the center of the computer screen. The fixation cross was immediately followed by a blue square, which lasted either 6 or 12 sec – the two durations used in the three recent developmental studies on time judgment in a dual-task paradigm. Participants were then asked to reproduce the duration of this stimulus by pressing the spacebar once to mark the start and again when they judged that sufficient time had elapsed. They completed 24 trials (12 for each target duration), the value of the inter-trial interval being randomly chosen between 800 and 1200 ms.

In the single temporal comparison task, the time course of each trial was as follows (Figure 1b): after the participant pressed the spacebar, the fixation cross was presented for 750 ms at the center of the computer screen, followed by the presentation of the first stimulus to be timed. Then, after a variable inter-stimuli interval (800 to 1200 ms), the second stimulus to be timed was presented, also preceded by a 750 ms fixation cross. Participants had to decide whether the two stimulus durations were similar or different by pressing the corresponding key (either S or L, the key order being counterbalanced) on the computer keyboard. In 50% of the trials, the duration of the first stimulus was randomly selected between either 5 and 7 sec or 11 and 13 sec, and this random value was repeated for the second stimulus duration. In 25% of the trials, the first stimulus duration was randomly selected between either 6 and 7 sec or 12 and 13 sec, and the second stimulus duration was systematically 1 sec shorter. Finally, in the remaining 25% of the trials, the first stimulus duration was randomly selected between either 5 and 6 sec or 11 and 12 sec, and the second stimulus duration was systematically 1 sec longer. Thus, for a given target stimulus duration, the correct response corresponded to "similar durations" for half

the trials and "different durations" for the remaining half. There was a total of 24 trials (12 for each target duration), with an inter-trials interval varying randomly from 800 to 1200 ms.

In the single inhibitory control task (Stroop-like interference in animal size task), two color drawings of animals of different sizes (one big and one small) were presented side by side on each trial (Figure 2). Participants were instructed to press a computer key (A or P) on the same side as the animal that was larger in real life. In congruent trials, the larger animal in real life was visually larger on the screen too. In contrast, in incongruent trials, the larger animal was visually smaller, hence creating interference between the real-life size and the visual size. In these trials, participants had to inhibit the salient visual size in order to respond based on the animal's size in real life. The task comprised 48 experimental trials (24 congruent trials and 24 incongruent trials) presented in a random order, with an inter-trial interval of 1500 ms.

In the dual-task conditions, participants were asked to perform the inhibitory control task during the presentation of the stimulus duration to be reproduced in the reproduction task (Figure 3a) or during the presentation of the first stimulus duration in the comparison task (Figure 3b). All the instructions remained the same as those given in the single task conditions. For each short (vs. long) target duration trial, the participants completed four (vs. eight) inhibitory control trials. Each participant completed a total of 24 trials in the dual-task condition, with 12 trials per target duration, presented in random order. A press on the space bar initiated each trial.

Data analysis

In the temporal reproduction task, following many previous studies (e.g., Brown, 2014; Droit-Volet, 2010; Matha, Rattat, & Cegarra, 2014; Rattat, 2010; Rattat & Tartas, 2019; Ulbrich, Churan, Fink, & Wittmann, 2007), we calculated both the mean duration reproduced and the coefficient of variation (CV) for each participant and for each target duration. CV corresponds to the ratio of the target duration to the mean reproduction duration, in both the single- and dual-task conditions. The CV thus represents a relative measure of timing variability. Its value ranged from 0 to 1, with higher values indicating higher variability in the temporal reproductions.

To analyze temporal performance in the comparison task, the participant's responses were converted into two measures used in recent studies (Rattat & Picard, 2012; Bratzke, Quinn, Ulrich, & Bausenhart, 2016), namely the indexes A' for discriminability and B'' for bias (i.e., decision criterion). These were calculated separately for each participant, each target duration and each condition according to the formulas initially provided by Grier (1971) and later amended by Aaronson and Watts (1987) to correct for below-chance performance. These two indices were computed as follows, with y denoting the probability of a hit (i.e., "similar durations" responses when the two stimulus durations were identical) and x the probability of a false alarm (i.e., "similar durations" responses when the two stimulus durations were different):

if $y \geq x$

- $A' = 0.5 + [(y - x)(1 + y - x) / 4y(1 - x)]$
- $B'' = 0.5 + [y(1 - y) - x(1 - x)]/[(y(1 - y) + x(1 - x)]$

if $y < x$

- $A' = 0.5 - [(x - y)(1 + x - y) / 4x(1 - y)]$
- $B'' = 0.5 - [x(1 - x) - y(1 - y)]/[(y(1 - y) + x(1 - x)]$

Accordingly, the A' index ranged from 0 to 1, with 1 representing perfect discrimination performance and 0.5 indicating chance level; and the B'' index ranged from -1 to 1, with -1 indicating a liberal criterion for decision (i.e., participants were biased to answering that the two

stimulus durations were similar) and 1 a conservative criterion for decision (i.e., participants

tended to answer that the two stimulus durations were different).

Finally, to analyze participants' performance in the inhibitory control task, we calculated

the mean response time and accuracy rate. Response times were log-transformed to correct for

skewness and control for age-related baseline differences. In the analyses of single- and dual-

task data, trials in which incorrect responses were provided were dropped from the response time

data set (see Figure 7 illustrating accuracy by condition and age). Outliers (+/- 3 SD from the

participant's mean) were then removed from the data set. In children aged 7 years old, there were

5 (0.23%) outliers of 2208 observations in the single inhibitory control task and 25 (0.38%)

outliers of 6624 observations in the dual-task conditions. In children aged 10 years old, there

were no outlier in the single inhibitory control task and 34 (0.58%) outliers of 5904 observations

in the dual-task conditions. In adults, there were 21 (0.73%) outliers of 2880 observations in the

single inhibitory control task and 111 (1.28%) outliers of 8640 observations in the dual-task

conditions.

To test the influence of the concurrent inhibitory control task on temporal performance,

four separate analyses of variance (ANOVAs) were performed on mean durations reproduced

and on CVs in the reproduction task, and on A' and B'' in the comparison task. These four

ANOVAs included age as between-participants factor and target duration and task condition as

within-participants factors. Conversely, to test the reciprocal influence of the two concurrent

temporal tasks on inhibitory control performance, we conducted an ANOVA including age

(adults vs. children) and temporal task (reproduction vs. comparison) as between-participants

factor and trial type (congruent vs. incongruent) and task condition (single-task vs. 6 sec dual-

task vs. 12 sec dual-task) as within-participants factors on both the mean response time and

accuracy. For all statistical analyses, we set the alpha level at 0.05. We reported partial Eta-square (η^2_p) as a measure of effect size whenever a significant main or interaction effect was revealed by the ANOVAs.

Results

Temporal reproduction task

The ANOVA conducted on the mean durations reproduced revealed significant main effects of target duration, $F(1, 73) = 710.33, p < .0001, \eta^2_p = .91$, and task condition, $F(1, 73) = 43.41, p < .0001, \eta^2_p = .37$, as well as a significant interaction between these two factors, $F(1, 73) = 72.10, p < .0001, \eta^2_p = .50$. The difference between mean durations reproduced in the single- and dual-task conditions was greater for the 12 sec target duration than for the 6 sec target duration, $t(75) = 8.07, p < .0001$, suggesting a greater temporal shortening in the dual-task compared to the single-task condition for the longer target duration (18.18 % of the duration) than for the shorter one (11.08 % of the duration) (Figure 4). There was also a significant interaction effect between target duration and age, $F(2, 73) = 3.98, p = .023, \eta^2_p = .10$, as well as a significant triple interaction effect between target duration, age and condition, $F(2, 73) = 3.95, p = .024, \eta^2_p = .10$. In the dual task condition, the difference between mean durations reproduced for the 6- and 12-sec target durations was greater for the children aged 7 years old than for the adults ($p = .002$), the other between age comparisons failed to reach statistical significance (children aged 7 years old vs. 10 years old: $p = .062$; older children vs. adults: $p = .61$). In contrast, in the single task condition, the difference between mean durations reproduced for the 6- and 12-sec target durations did not differ between age groups, $F < 1$. No other significant main or interaction effect were found.

The ANOVA conducted on the coefficients of variation (CVs) revealed a significant main effect of age, $F(2, 73) = 23.09$, $p < .0001$, $\eta^2_p = .39$, indicating that children aged 7 years old were more variable in their temporal reproduction than children aged 10 years old ($.34 > .26$, $p = .003$), and that the latter were more variable than adults ($.26 > .19$, $p = .023$). The main effect of condition also reached statistical significance, $F(1, 73) = 4.48$, $p = .038$, $\eta^2_p = .06$, revealing that the participants were more variable in their temporal reproduction in the dual- than single-task condition ($.27 > .24$). There was no other significant main or interaction effects (Figure 4).

Temporal comparison task

The ANOVA conducted on A' only revealed a significant main effect of target duration, $F(1, 68) = 3.83$, $p = .05$, $\eta^2_p = .05$, the mean temporal discriminability being higher for the 6 sec than for 12 sec target duration (Figure 5). No other significant main or interaction effect were observed.

As for the index of discriminability A', the ANOVA conducted on B'' revealed a significant main effect of target duration, $F(1, 68) = 16.33$, $p < .0001$, $\eta^2_p = .19$. As shown in Figure 5, mean decision criterion was more negative for the short than the long stimulus duration ($-.098$ vs. $.068$). We also found a significant interaction effect between task condition and age, $F(2, 68) = 3.61$, $p = .033$, $\eta^2_p = .10$. The decision criterion B'' changed as a function of the task condition only in the younger children, $t(20) = -2.11$, $p = .047$, $d = 0.46$, but not in both older children and adults ($t(19) = 0.93$, $p = .362$, and $t(29) = 1.09$, $p = .285$, respectively). More precisely, in 7-year-olds, the mean decision criterion value in the single-task condition was negative, revealing a small bias towards "similar durations" responses, but was positive in the dual-task condition, revealing a small bias towards "different durations" responses. Furthermore,

while the mean decision criterion B'' did not significantly differ between age groups in the single-task condition, $F < 1$, it significantly differed across age groups in the dual-task one $F(2, 20) = 6.24, p = .003, \eta^2_p = .16$. More precisely, its value was positive in 7-year-olds and on the contrary negative in adults; no other between-age comparisons being significant. There was no other significant main or interaction effects.

Inhibitory control task

We first checked whether the two groups (i.e., temporal reproduction task vs. temporal comparison task) of each age matched or not in their inhibitory performance on the single task. To this end, we ran t-tests for independent samples to compare inhibitory performance (i.e., mean response time and mean proportion of accurate responses) for both between the two groups both for both congruent and incongruent trials. At all ages, the two groups matched in their mean response times (all $t < 1$), suggesting that they were well matched. Regarding the mean proportion of accurate responses, while the two groups of adults and children aged 10 years old were similar, the accuracy of younger children appeared lower in the temporal comparison group compared to the temporal reproduction one (84.23 vs. 90.0, $t(44) = -2.39, p = .021, d = 0.72$) (Figure 7). Nevertheless, even at this age, the difference between the mean proportion of accurate response for congruent and incongruent trials did not differ between groups, $t(44) = 1.03, p = .31$.

As expected, the ANOVA conducted on the mean response time revealed a significant main effect of trial type, $F(1, 141) = 230.08, p < .0001, \eta^2_p = .62$, indicating that participants responded faster in congruent than incongruent trials (Figure 6). There were also a significant main effect of age, $F(2, 141) = 99.56, p < .0001, \eta^2_p = .58$, indicating that children aged 7 years old took longer to respond than older children who took longer to respond than adults (a

posteriori comparisons with Bonferroni adjustment, $p < .0001$ and $p = .018$, respectively). The

main effect of task condition, $F(2, 282) = 10.04$, $p < .0001$, $\eta^2_p = .07$, as well as the interaction

between the task condition and age, $F(4, 282) = 4.53$, $p = .001$, $\eta^2_p = .06$, were also significant.

In both older children and adults, the mean response time did not differ across task conditions

$F(2, 80) = 2.46$, $p = .092$, and $F<1$, respectively). In contrast, in children aged 7 years old, the

mean response time was longer in the single-task condition than in both the 6 sec and 12 sec

dual-task ones (a posteriori comparisons with Bonferroni adjustment, $p = .005$ and $p = .001$,

respectively), with no difference between the two dual-task conditions ($p = 1.0$). Another

significant interaction effect was obtained between task condition and trial type, $F(2, 282) =$

7.53, $p = .001$, $\eta^2_p = .05$. While the mean response time for incongruent trials was not affected

by the condition, $F(2, 292) = 1.78$, $p = .171$, that for congruent trials was clearly longer in the

single-task condition than in both the 6 sec and 12 sec dual-task ones (both $p < .0001$), with no

difference between the two dual-task conditions ($p = .82$). The difference score between the

mean response time on congruent and incongruent trials was therefore lower in the single-task

condition than in the two dual-task ones ($p = .006$ and $p = .017$, respectively), with no difference

between the two dual-task conditions ($p = .674$). All other main and interaction effects did not

reach statistical significance.

As also expected, accuracy was significantly higher in congruent than incongruent trials,

$F(1, 141) = 217.54$, $p < .0001$, $\eta^2_p = .61$, and significantly increased with age, $F(2, 141) = 46.14$,

$p < .0001$, $\eta^2_p = .40$. As shown in Figure 7, the children aged 7 years old were less accurate than

older children who were less accurate than adults (a posteriori comparisons with Bonferroni

adjustment, $p < .0001$ and $p = .007$, respectively). Moreover, a significant main effect of temporal task was found, $F(1, 141) = 7.23$, $p = .008$, $\eta^2_p = .05$, indicating that more accurate responses were given with the concurrent temporal reproduction than comparison task ($91.69 > 89.09$). Accuracy was also affected by task condition, $F(2, 282) = 13.43$, $p < .0001$, $\eta^2_p = .09$, more accurate responses being given in the single-task condition than in both the 6 sec and 12 sec dual-task ones (a posteriori comparisons with Bonferroni adjustment, both $p < .0001$), with no difference between the last two conditions ($p = 1.0$). To decompose the trial type x age, $F(2, 141) = 9.29$, $p < .0001$, $\eta^2_p = .12$, the trial type x task condition, $F(2, 282) = 6.84$, $p = .001$, $\eta^2_p = .05$, and the trial type x temporal task, $F(2, 232) = 3.72$, $p = .026$, $\eta^2_p = .03$, significant interaction effects, we calculated for each participant a difference score between congruent and incongruent trials. This difference score was higher in children than in adults (a posteriori comparisons with Bonferroni adjustment, 7 years old: $p = .003$; and 10 years old: $p = .001$), with no difference between the two groups of children ($p = 1.0$). This difference score was also higher in the 6 and 12 sec dual-tasks than the single-task condition ($p = .033$ and $p = .001$, respectively), with no difference between the two dual task conditions ($p = 1.0$). Furthermore, this difference score was higher with the comparison than the reproduction temporal task ($p = .042$).

Discussion

The aim of this study was to investigate the role of executive functions, and more specifically inhibitory control, in time reproduction and comparison performance in children and adults. The results showed that adding a concurrent executive task tapping inhibitory control affected temporal reproduction accuracy by producing a shortening effect (i.e., responses were shorter than the target durations) and an increase in response variability, regardless of age group.

This shortening effect in the dual-task condition was more pronounced for the long target duration, particularly in 7-year-old children. Indeed, the difference between the durations reproduced for the short and the long target durations was clearly reduced between the single- and dual-task conditions, but exclusively in the 7-year-olds, and not in the older children and adults. In contrast, the same concurrent executive task had much less influence on temporal comparison performance. Specifically, it had no effect on temporal discriminability scores, in either children or adults, although it slightly shifted 7-year-old children's (but not older children's and adults') mean decision criterion value towards "different durations" responses.

The less accurate and more variable temporal reproduction performance in dual-task condition compared with single-task condition is in line with previous dual-task studies that showed that adults not only underestimated durations when they had to simultaneously perform an inhibition task but also that timing was more variable (Brown, 2006; Brown et al., 2013, 2015; Brown & Perreault, 2017; Lovas & Kacmar, 2016). Our findings show that the interference effect between tasks tapping timing and inhibitory control is also observed in 7-year-old children and, to a lesser extent, 10-year-olds. In our study, the time contraction in dual task was greater for the 12 s than for the 6 s target duration (see also Rattat, 2010), probably because of the higher executive demand of the former. Timekeeping for a long duration likely requires more sustained attentional effort, which in turn depends on executive functions. Time contraction in dual-task may come from top-down selectivity in attending to both temporal and non-temporal aspects and suppressing attention to irrelevant information or actions, this being even more pronounced for long durations.

Furthermore, from a developmental point of view, as expected, we observed that the interference effect between concurrent temporal reproduction and executive processing was

greater in 7-year-olds than both 10-year-olds and adults. This is consistent with previous

developmental findings using dual tasks tapping executive functions other than inhibitory control

(Arlin, 1986; Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017; Rattat, 2010). Moreover,

we experimentally showed that the magnitude of this interference effect at age 10 is comparable

to that observed in adults. These findings support the idea that the reduction of time distortions

in dual task during childhood reflects the development of executive functions. Due to their less

efficient executive functioning, inhibitory control in this case, younger children struggled more

than older children and adults to keep track of time (for a review, see Fourneret & des Portes,

2016). Consequently, temporal performance was increasingly affected as inhibitory control

demands increased. This explains why in the condition requiring the highest executive function

demand (i.e., 12 s dual task), the time contraction was particularly high at the age of 7 years,

reaching 24%, in other words almost a quarter of the duration, while it was between 16 and 17%

in older children and adults. Then, near the age of 10 years, sufficient executive resources

required for the reproduction of long durations remains within reach of children, thus potentially

explaining why their temporal performance was not more affected than in adults.

Whereas the temporal performance accuracy decrease under dual-task condition in the

reproduction task, this is not the case in the comparison task. Interestingly, concurrent executive

processing nevertheless affected 7-year-old children's mean decision criterion value, leading

them to more often answer that the two stimulus durations were different (i.e., a more

conservative criterion for decision). This more conservative criterion in young children's

temporal comparison responses, but not in older participants', may relate to age-related

differences in metacognition. Specifically, participants who are less confident in their own

knowledge are also more conservative and take less risk when facing an ambiguous case (e.g.,

Chandler, 1994; Koriat & Goldsmith, 1996; Nelson, 1996). Droit-Volet (2002) argued a similar link existed between children's decision threshold in a time discrimination task (generalization task) and how confident they felt in their time knowledge. We therefore suggest that young children are more conservative in the dual-task condition relative to the single-task condition because they have less confidence in their time knowledge under these specific conditions that also required simultaneous executive control processing. The comparison task indeed appeared as relatively more difficult to them under the dual- than the single-task condition, and consequently might have led to a more conservative decision criterion. In contrast, 10-year-olds' and adults' more advanced metacognitive skills may have shielded them from such an effect. Further studies are however needed to directly test this hypothesis.

Moreover, dual-task-related interference was greater in the temporal reproduction than the temporal comparison task. Further, only temporal reproduction increased across age groups in the single-task condition. Together, these findings suggest that executive functions are not similarly involved with all aspects of timing. Instead, temporal reproduction is more executively demanding than temporal comparison (see also, Bauermeister et al., 2005; Droit-Volet et al., 2015; Ogden et al., 2014). Importantly, executive function development plays a more substantial role in age-related differences in temporal reproduction than estimation. In other words, gains in executive function do not seem to lead to more accurate time estimations but instead help children use time estimations to reproduce durations more accurately.

Another open question is whether inhibitory control plays a specific role in time beyond that of executive functions in general. Previous studies have shown that dual tapping aspects of executive functions other than inhibitory control interfere with children's temporal reproduction performance (Arlin, 1986; Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017; Rattat,

2010). In these studies, concurrent tasks were picture naming, sound or color discrimination, verbal or visuospatial memory tasks. None of them included demands on inhibitory control specifically, but rather on more general attentional and/or memory processes, hence suggesting that the interference effect is not limited to inhibitory control. Yet, inhibitory control may be especially critical to selectively attend to timing-relevant information and suppress other information. On the basis of the available data, it seems difficult to draw a definitive conclusion given that (1) we only used a secondary task that mainly recruits inhibitory control, and (2) one might argue that this task also taps some working memory processes insofar as successful performance on incongruent trials also requires generating the expected response based on semantic animal characteristics. Therefore, other dual-task studies with different concurrent executive tasks tapping on different executive processes are needed to deepen our understanding of how timing is moderated by executive processes and how this may change developmentally.

In addition, regardless of age group, the concurrent timing of stimuli yielded lower response accuracy in the inhibitory control task in both temporal tasks, but to a greater extent when the concurrent task was the comparison task than the reproduction task. At first, this may seem to conflict with the conclusion that executive control, in particular inhibitory control, is involved in temporal reproduction to a greater extent than in temporal comparison. However, the fact that the reproduction task is more difficult -and thus requires more inhibitory control- may have led the participants, in the dual-task condition, to focus a little more on the inhibition task in order to maintain a high accuracy level in this task, thus explaining the higher percentage of accurate responses in the inhibition task with the temporal reproduction than comparison. Surprisingly, children aged 7 years old -and not older children and adults- responded faster in the dual- than in the single-task. It is possible that to remedy their less

efficient executive control (inhibitory control in this case), in the dual-task conditions, young

children tried to respond as quickly as they could (even faster than in the single-task condition)

in the executive control task (i.e., they prioritized response speed over accuracy), allowing them

to have sufficient available resources for simultaneously processing temporal information.

Unlike younger children, the dual-task condition may have prioritized 10-year-olds and adults'

maintenance of response speed in the executive control task at the expense of response accuracy.

Nevertheless, despite a similar speed-accuracy trade off in dual-tasks in both groups, 10-year-old

children remained both slower to respond and less accurate in the inhibitory control task.

Finally, although the present study focused on the potential influence of executive control

(and more particularly inhibitory control) on timing, timing may conversely influence executive

functioning. Engagement of executive functions towards specific tasks is thought to reflect

integration of information about the expected reward (i.e., likelihood of success) and cost (i.e.,

cognitive effort) associated with each task (e.g., Shenhav et al. 2013; Westbrook & Braver,

2015). Although children's subjective perception of cognitive effort influences executive

functioning (Chevalier, 2018), children are less likely than adults to avoid unnecessary cognitive

effort (Niebaum et al., 2019). Predictions about how much time a task will take are likely an

integral part of cognitive effort estimation and, if so, age-related progress in timing may

contribute to more adaptive engagement of executive functions during childhood. As such,

further investigation of the links between timing and executive functioning is a promising

avenue to better understand the cognitive underpinnings of both.

In conclusion, our data emphasize the importance of executive control in timing, by

showing that not only inhibitory control are required to accurately process time, and more

especially in the reproduction task, but also that timing progress during childhood likely stems

from more efficient executive functions (more specifically inhibitory control). Thus, greater age-related differences in timing performance in the reproduction than the comparison task could results from greater demands in terms of cognitive (inhibitory) control in the former.

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(b)

Spacebar
press

Key press
(S or L)
S1 = S2 ?

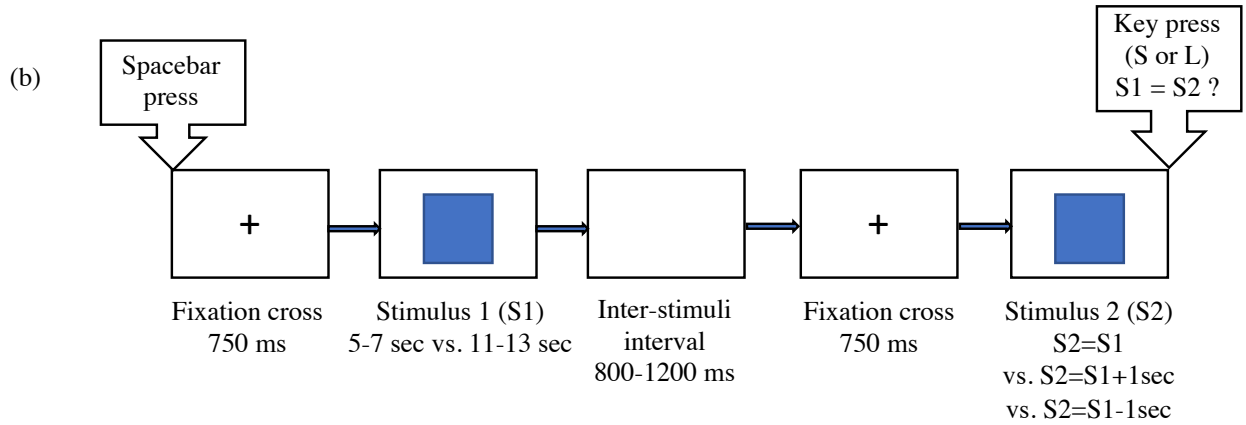| Fixation cross	Stimulus 1 (S1)	Inter-stimuli	Fixation cross	Stimulus 2 (S2)
750 ms	5-7 sec vs. 11-13 sec	interval	750 ms	S2=S1
		800-1200 ms		vs. S2=S1+1sec
				vs. S2=S1-1sec

Figure 1. Schematic illustrations of a trial in the single temporal (a) reproduction and (b) comparison tasks. In the reproduction task (a), participants pressed the space twice to reproduce the duration of the target stimulus. In the comparison task (b), they indicated whether the two stimulus durations were similar or different by pressing one of the two response keys.
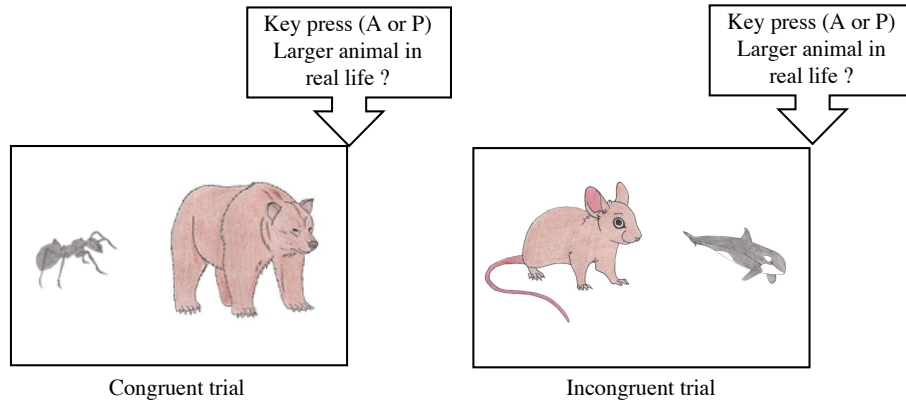
Figure 2. Schematic illustrations of sample congruent and incongruent trials in the single inhibitory control task. Participants had to press on the button on the same side as the animal that was larger in real life.
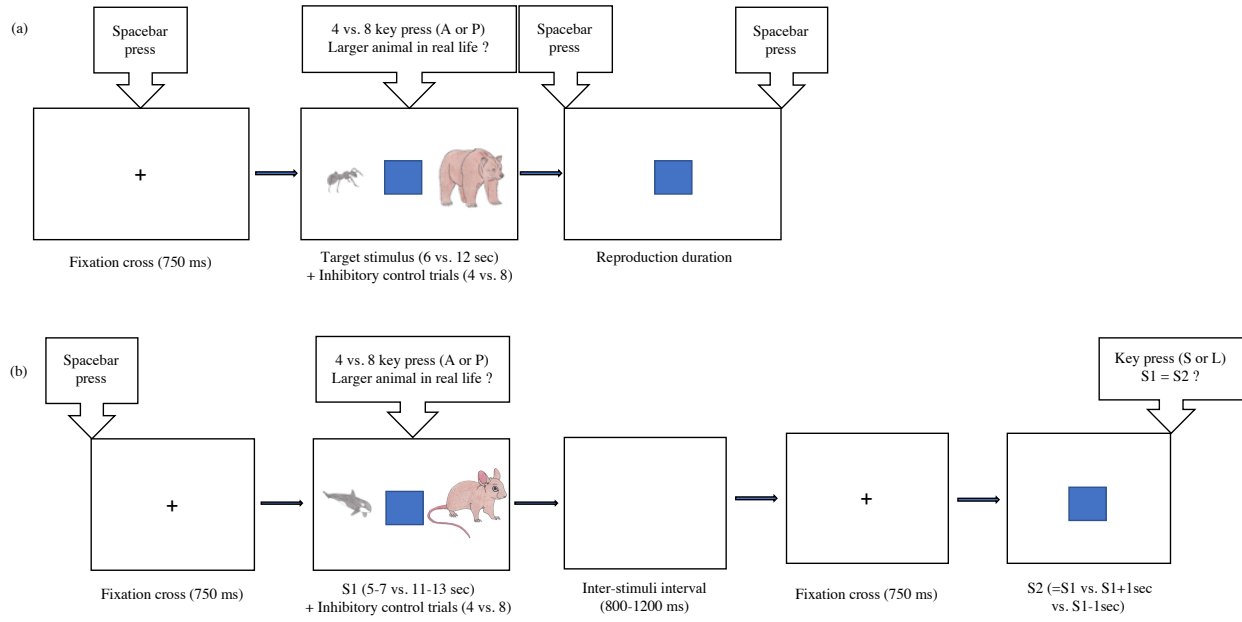
Figure 3. Schematic illustrations of a dual-task trial with the temporal (a) reproduction and (b) comparison tasks.
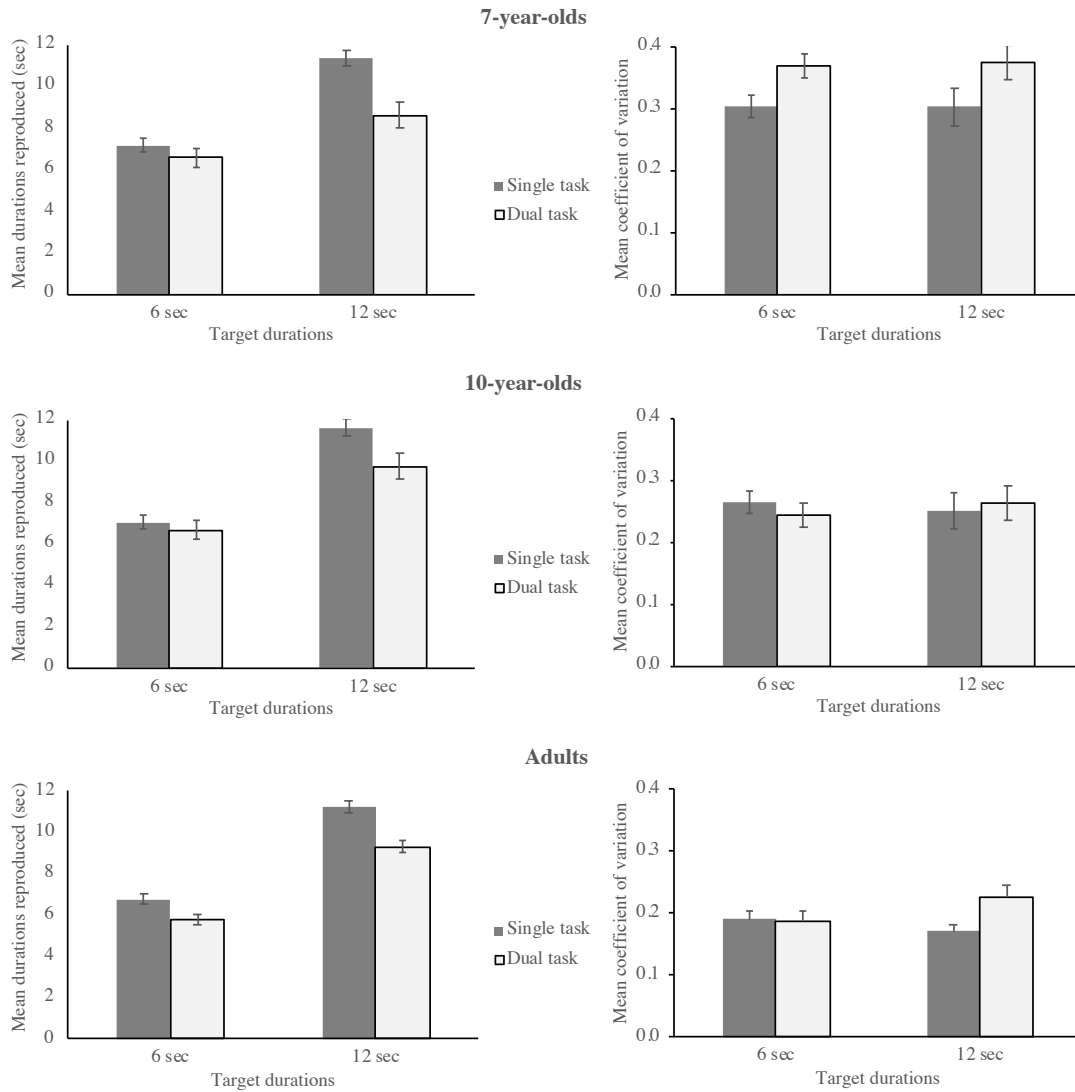
Figure 4. Mean durations reproduced (left panels) and mean coefficients of variation (right panels) for the adults and the children aged 7 and 10 years old in the single and dual-task conditions as a function of the target duration (6 sec vs. 12 sec). Bars represent standard error. In the three age groups, the difference in duration reproduced between the single and dual task conditions was greater for longer than shorter durations. In the dual task condition, the difference in duration reproduced between the 6 and 12 sec target duration was lower in the younger children. The variability was higher in the dual-task than single-task condition and it decreased with age.
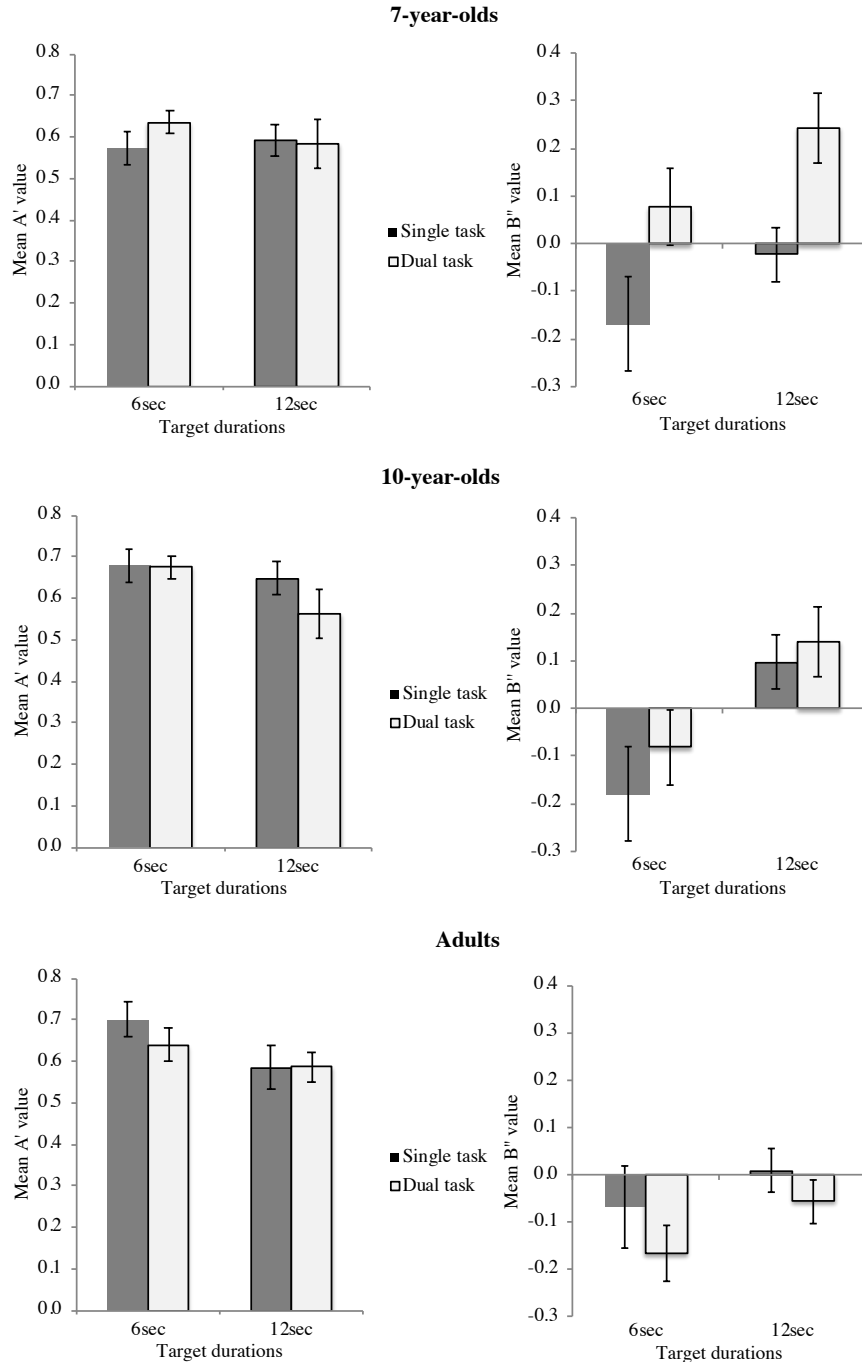
Figure 5. Mean discriminability *A'* (left panels) and mean decision criterion *B"* (right panels) for the adults and the children aged 7 and 10 years old in the single and dual-task conditions as a function of the target duration (6 sec vs. 12 sec). Bars represent standard error. Overall, *A'* was higher for 6 sec than 12 sec target durations. Overall, *B"* was more negative for short than long stimulus duration. Exclusively in younger children, it shifted from negative in the single-task condition to positive in the dual-task condition.
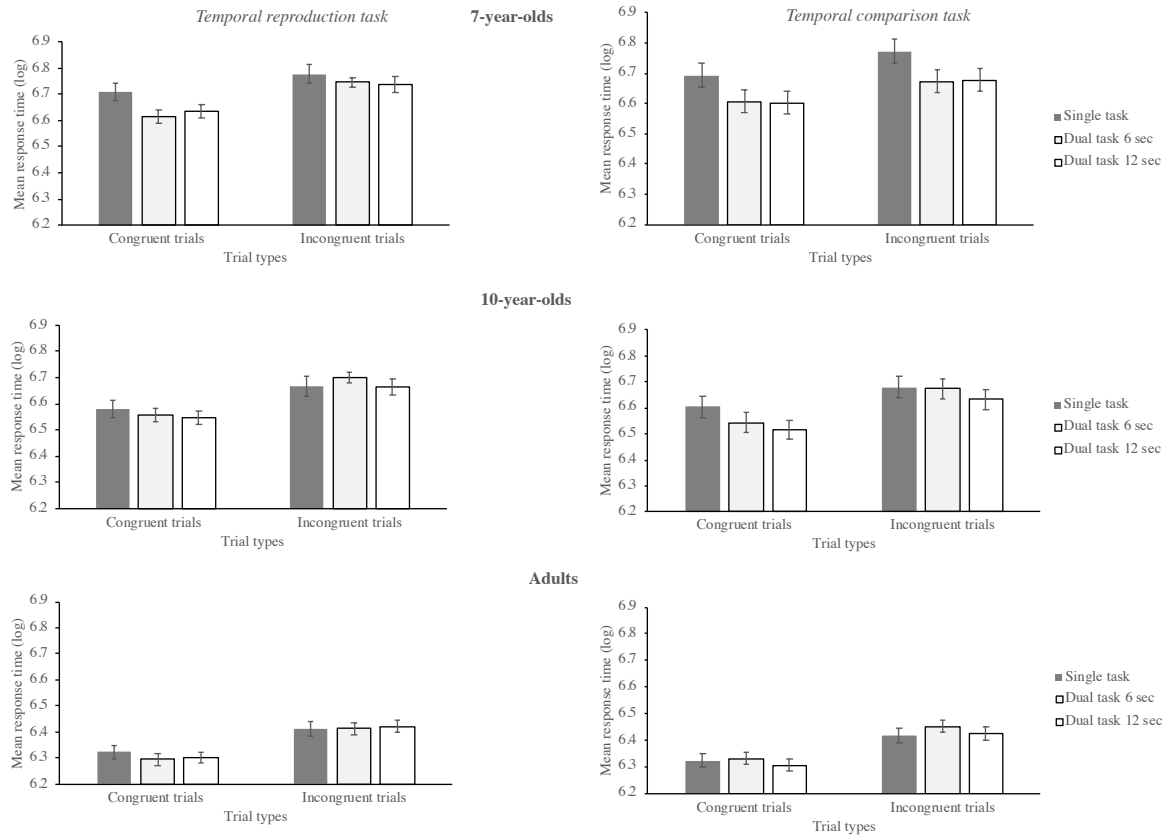
Figure 6. Mean response time (standard error) for the adults and the children aged 7 and 10 years old as a function of the trial types and conditions when the concurrent temporal task performed in the dual-task conditions was the reproduction task (left panels) and the comparison task (right panels). Only RTs of younger children varied as a function of the task condition. Task condition affected RTs in congruent but not incongruent trials. There was no effect of the temporal task.
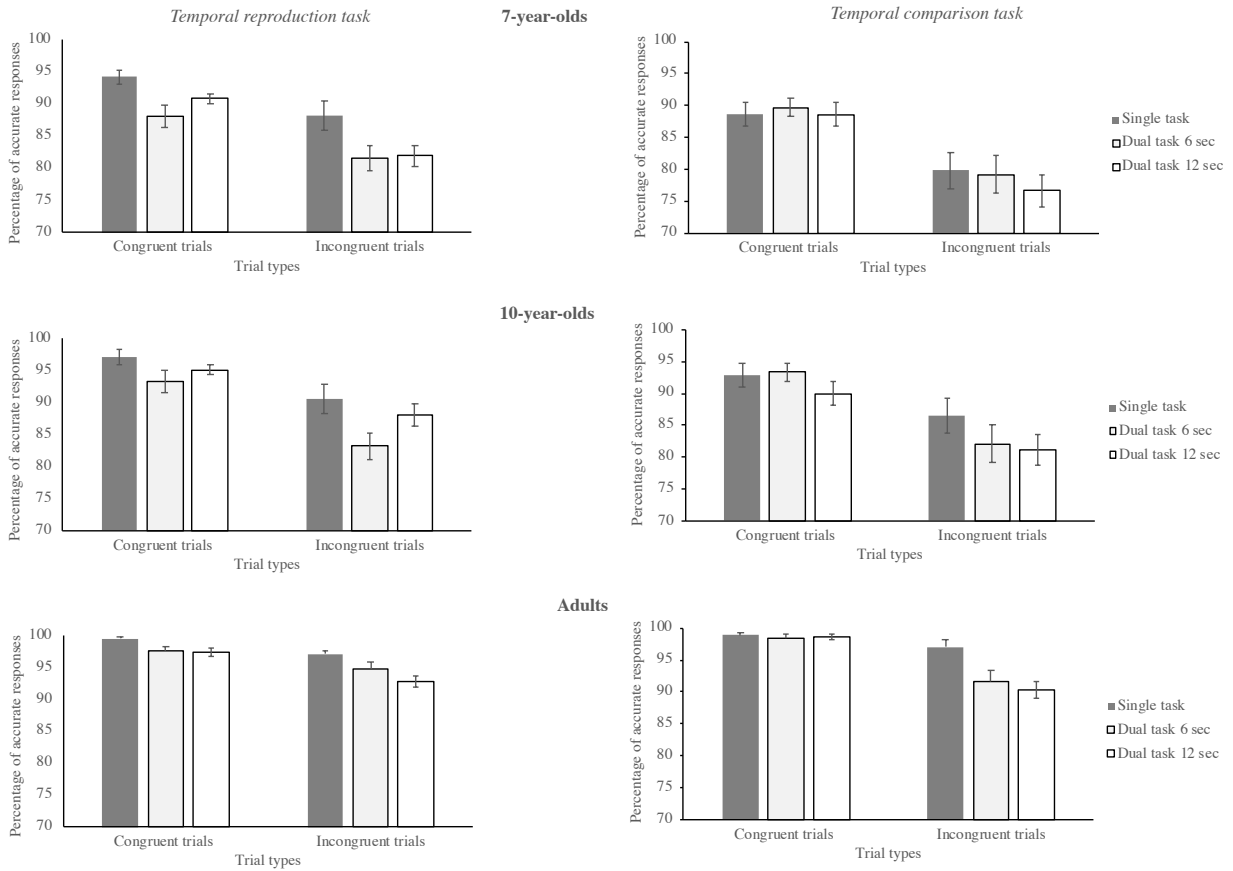
Figure 7. Mean percentage of accurate responses (standard error) for the adults and the children aged 7 and 10 years old as a function of the type of trials and the condition when the concurrent temporal task performed in the dual-task conditions was the reproduction task (left panels) and the comparison task (right panels). Whatever the age group, accuracy dropped from the single-task to the dual-task condition for both temporal tasks.