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**Simultaneous Processing of Durations in Children and Adults:
when Attention predicts the Overestimation of Time.**

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The development of abilities to process time depends on the nature of time processing, whether it is automatic as when subjects do not consciously process time, or controlled, when they are aware that the aim of their task is to estimate time (Droit-Volet & Coull, 2016). For example, from the youngest age, children can automatically learn short durations associated with regularly presented events or actions (e.g., Brannon *et al.*, 2008). However, before the age of 4, they cannot abstract the duration learned in a specific context and transpose it to any other action in a new situation (Droit-Volet & Rattat, 1999). It is only when the cognitive capacities are sufficiently developed that children are able to judge a wide range of durations in varied and novel contexts (Droit-Volet, 2013, 2016). Many developmental studies have indeed observed a significant correlation between improvement in time judgment skills and increased cognitive abilities (Droit-Volet, 2013, 2016; Droit-Volet & Hallez, 2019; Droit-Volet & Zélanti, 2013a,b; Hallez, 2020; Hallez & Droit-Volet, 2017, 2019; Zélanti & Droit-Volet, 2011, 2012).

The study of time perception in children thereby argues in favor of a central role of cognition in time processing (Droit-Volet, 2013; Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017, 2019; Zakay, 1992; Zélanti & Droit-Volet, 2011). Among the cognitive functions that develop progressively during childhood (Gathercole, 1998; Kail & Ferrer, 2007; Suades-González *et al.*, 2017), attention has been identified as one of the main causes of distortion in time judgment. The dual-task paradigm clearly illustrates the importance of this cognitive variable. In a dual-task paradigm, participants have to process time by performing a temporal task simultaneously with a non-temporal task in which no temporal processing is required (e.g., color discrimination, stroop task, memory task, etc.). In this paradigm, temporal performance is always found less accurate (with shortening of perceived duration usually found) in a dual- rather than in a single task, independently of the tasks used (Block, Hancock & Zakay, 2010; Koch, Poljac, Müller & Kiesel, 2018). These results have been replicated with children (Gauthier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017, 2019). However, time distortion in dual-task situation was higher in children than in adults due to their lower attention capacities, as assessed by validated neuropsychological tests (Hallez & Droit-Volet, 2017, 2019). This confirms the importance of the development of attention skills in the accurate judgment of time.

According to attentional models of time perception, duration processing is an effortful process that draws on a pool of limited attentional resources shared by the processing of other information (Thomas & Cantor, 1975; Thomas & Weaver, 1975). The most popular timing theories presume that time is processed by means of a single clock-like system (“clock”) composed of a pacemaker and an accumulator (Church & Gibbon, 1982; Gibbon, 1977; Gibbon, Church & Meck, 1984; Treisman, 1963). The perceived duration results from the number of pulses generated by this pacemaker and transferred to the accumulator (counter). A switch controlled by attention guarantees that the pulses are transmitted by closing the circuit when a signal indicates the start of the temporal interval. To account for time distortion in a dual-task procedure, Zakay and Block (1996) extended this simple attention-switch mechanism by adding an attentional gate whose opening varies as a function of the allocated attentional

resources (attentional gate). When attentional resources are allocated to time, the gate opens wider. As a result, more pulses pass through and time is judged to be longer. Conversely, when the attention allocation to time is limited, fewer pulses pass through and time is judged to be shorter. This model has since been widely validated empirically (Block *et al.*, 2010). The usefulness of adding a gate to the clock system has nevertheless been debated. Indeed, the idea of a single attention switch that flickers throughout the processing of the entire duration, closing and opening according to the attention phases, leads to the same predictions about timing performance (Lejeune, 1998, 2000; Zakay, 2000). Regardless of the putative mechanisms proposed, the lower efficiency of this attention-switch system would explain the greater time distortion of young children in the dual-task situation (Hallez & Droit-Volet, 2017).

Attentional models of time perception have been constructed by taking into account the processing of only one interval, or the sequential treatment of two different intervals, but not the timing of several events simultaneously. Although this is a daily activity, very little is known about our abilities to time multiple durations, and no study have been conducted in children. The question is therefore: Are children capable of estimating several durations presented simultaneously, like adults, despite their lower attention capacities, and what difference might be observed between their performance and that of adults, if there is any difference?

A small number of studies have shown that humans adults are able to time different stimuli presented simultaneously (Ayhan, Revina, Bruno & Johnston, 2012; Burr, Tozzi & Morrone, 2007; Cheng, Yang, Han, Ding & Fan, 2014; Johnston, Arnold & Nishida, 2006; Klapproth, 2011; Rousseau & Rousseau, 1996; van Rijn & Taagten, 2008), as has also been found in other animals (rats or pigeons) (Church, Guilhardi, Keen, Macinnis & Kirkpatrick, 2003; Meck & Church, 1984; Meck & Williams, 1997; Roberts, 1995). However, temporal interference effects on time estimates in the multi-timing tasks are inconsistent between studies, such that researchers were led to formulate different hypotheses about the mechanisms underlying the processing of concurrent durations. In the framework of clock models, some authors have suggested several pacemaker-accumulator systems, one for each stimulus duration, i.e., multiple independent clocks (Buhusi & Meck, 2005, 2009; Matell *et al.*, 2004, 2006). Others have suggested a single timing source (pacemaker) but multiple accumulators, one per duration (Meck & Church, 1984; van Rijn & Taatgen, 2008). According to the latter approach, the time stream would thus be broken down into a series of segments identified with the changes in temporal stimuli (onsets and offsets of stimuli). Some segments would therefore be common (i.e., overlap between durations) and others not, depending on the durations used. The pulses associated with each time segment would then accumulate in a specific counter, and add up to reach the target duration. Based on the attentional gate model, Brown and West (1990) only considered a competition for the same attentional resources between the parallel processing of two different streams of temporal information. The predictions change depending on whether single or multiple clocks are proposed. An accurate estimate of simultaneous durations is predicted for multiple clocks. The same temporal accuracy is predicted for a single clock and multiple accumulators. However, following this logic, during a multiple temporal processing, if time distortion occurs for one duration, it directly affects the second duration, as durations are based on the sum of time segments. Conversely, a shortening of perceived duration is expected as a result of competition for attentional resources, as fewer pulses are accumulated when attention is distracted away from a temporal task.

Until now, no multiple timing task has never been used with children. However, recent studies have shown that the effect of temporal context on temporal performance is stronger in participants with limited attention and working capacities, as in young children (Karaminis, Cicchini, Neil, Cappagli, Aagten-Murphy, Burr & Pellicano, 2016; Hallez, Damsma, Rhodes, Van Rijn & Droit-Volet, 2019, also see Jazayeri & Shadlen, 2010). By using a signal to warn of the arrival of a stimulus to be timed, Droit-Volet (2003) also showed that the attentional-

switch system would be more variable and slower in younger children, an idea which seems to be supported by recent modelling of temporal estimates in childhood (Hallez & Droit-Volet, 2020). Since switching needs more time in children than in adults, we can assume that any switching-related effect would be greater in children than in adults in a multi-timing task with a series of onset and offset signals. Based on the hypothesis of a single clock but multiple accumulators, a difference in time estimates between children and adults would therefore be observed. A delay in switching latency would result in a greater number of pulses accumulated for the segment interval under consideration, i.e. a lengthening of perceived duration. However, a first alternative possibility is that time estimates in children and adults would be similar as predicted by the multiple independent clocks hypothesis. A second alternative possibility is a greater shortening effect in children than in adults related to competition for attention resources in the case of multiple non-independent clocks. This hypothesis is directly linked with developmental studies in dual-task procedures (involving both a temporal and non-temporal task) showing greater time distortion from single- to dual-task procedures as reported above (Gautier & Droit-Volet, 2002; Hallez & Droit-Volet, 2017, 2019). In summary, depending on the type of internal clock structures, we assumed: (1) longer time reproduction in the multi-timing condition compared to the solo timing condition (a single clock but multiple accumulators hypothesis), (2) no significant differences in time reproduction between the single and the multiple timing (multiple independent clocks hypothesis) and (3) shorter time reproduction in the multi-timing condition compared to the solo timing condition (multiple non-independent clocks).

Therefore, we ran two experiments with children aged from 5 to 8 years, and adults, to examine their temporal judgment in a multi-timing task and also to assess the role of the development of selective attention capacities compared to other cognitive capacities. Individual cognitive capacities were assessed with neuropsychological tests validated both in children and adults.

Experiment 1

Method

Participants

The sample consisted of 65 participants: 22 children from 5 to 6 years of age (9 females and 13 males, mean age = 5.54 years, $S.D = 0.25$), 24 children from 7 to 8 years of age (8 females and 16 males, mean age = 7.8 years, $S.D = 0.17$) and 19 adults (18 females and 1 male, mean age = 21.75, $S.D = 2.22$). The *a priori* compute of required sample size run on G*power based on repeated measures within-between interaction statistical test showed that the sample size is sufficient, this one being higher than 36 (effect size $f = 0.25$; $1-\beta = 0.95$; $N_{groups} = 3$, $N_{measurements} = 6$, $r = 0.5$). The children were enrolled from various nursery and primary schools in the Auvergne region of France. The adults were undergraduate Psychology students at Clermont Auvergne University. All participants were rewarded for their participation. Rewards were “panini” pictures for the children and course credits for the students. The children’s parents and the adult subjects signed written informed consent forms for their participation in this experiment, which was carried out according to the principles of the Declaration of Helsinki and approved by the audit committee of the Academy of the Education French Ministry.

Material

Participants were seated in front of a 17-inch computer screen, in a neutral, quiet room at their school or university. Using a program written in Python and compiled in C, the computer delivered and recorded all the experimental events. The participants gave their responses with their preferred hand using a computer mouse. The temporal stimuli were 3 squares (5 cm) of different colours: blue, green and orange. They were displayed on a black background in a circular area of 18 cm centred on the screen and were closely packed together to avoid spatial

effects (Cicchini & Morrone, 2009). The presentation location of the squares in this area was randomly chosen but the squares could not be superimposed.

Procedure

Temporal Reproduction Task

The participants performed an initial training phase consisting of 6 trials with the stimulus durations of 3 and 6 s: 3 demonstration and 3 training trials. The demonstration trials were made by the experimenter in front of the participant whereas the training trials were made by the participant himself. Before the training phase, the experimenter asked the child to name the colours to verify that he/she was able to discriminate the different colours. In the training phase, only one temporal stimulus (square) was presented, with the result that the participant already knew the stimulus to be judged. Then, in the testing phase, they were instructed that 1, 2 or 3 squares were likely to appear simultaneously. They therefore had to pay attention to the durations of the different squares, because they would find out which square was to be estimated only after their presentation. Each trial began with the words “Ready?” after a randomly selected inter-trial interval of between 500 and 1000 ms. The investigator pressed the spacebar when the participant was ready. After a 250-ms delay following the spacebar pressing, the temporal stimuli (squares) appeared. There were either 1 square (solo timing), 2 squares (dual timing), or 3 squares (triple timing). Then, a reproduction signal (1 s) appeared (i.e., picture of a finger pressing a button). Its colour indicated the target temporal stimulus to be reproduced. In addition, after a short 300-ms interval, a square in the same colour was presented in the centre of the screen, and the participant had to click on the computer mouse when he/she judged that the duration was the same as the target temporal stimulus. The testing phase was composed of 36 trials (random presentation), i.e. 6 trials for each duration (3 and 6 s) presented in 3 different conditions: solo timing, dual timing, triple timing.

The location and colour of the target temporal stimulus were randomly chosen. The location and colour of the additional temporal stimuli were also random, with a duration randomly selected within a temporal window of between 1 and 12 s, the only constraint being that there had to be the same number of shorter and longer stimulus durations than the target-stimulus duration. In other words, for each of the two target durations (3 and 6 s), there were three trials with a longer concurrent duration and three trials with a shorter concurrent duration in the dual-timing condition, and two trials with two longer concurrent durations, two trials with two shorter concurrent durations, and another two trials with a longer and a shorter concurrent duration in the triple-timing condition. To limit the amount of changing information for children, we fixed the same presentation onset for the different squares in Experiment 1.

Neuropsychological tests

Following the temporal reproduction task, the participants received 4 neuropsychological tests, the order of presentation of which was randomized between participants. The neuropsychological tests assessing short-term and working memory comprised the Corsi Block-Tapping Test (Corsi, 1972), in which the participants had to reproduce a block tapping sequence produced by the investigator in a forward (short-term memory) and backward sequence (working memory). There were 8 block-tapping sequences with 2 trials for each sequence. When the participants succeeded in one of the two trials in the sequence, the test continued with a longer block-tapping sequence (minimum 2, maximum 9). The third test was the “Sky Search” test from the TEACH (Test of Everyday Attention of Children; Manly, Robertson, Anderson & Nimmo-Smith, 2006). This test was used to assess selective attention (attention). The participants had to circle all pairs of identical spaceships out of 130 possible pairs. In this test, the lower the scores, the higher the attention capacity, since the score is allocated on the basis of the number of detected pairs of spaceships divided by the time in seconds taken to complete the test. The last neuropsychological test measured the information processing speed. It consisted of the “Code B” and the “Symbol B” sub-tests of the

Wechsler Intelligent Scale for Children (Wechsler, 2005). In the first sub-test, the participants saw 9 digits paired with a specific figure. They then had to draw the corresponding figure for each of the 119 presented digits and with a constrained time of 120 s. In the second sub-test, they had to indicate in each of the 60 trials if a proposed symbol matched one of the 2 target symbols taken from a series of 5 symbols. The interest of these last two neuropsychological tests is that the completion time is an integral part of the score. This highlights inter-individual differences between the adults and counters a potential ceiling effect found in other tests.

Results

Temporal accuracy

Figure 1 presents mean durations reproduced by the children and the adults for the solo, dual and triple conditions. 0.73% of the trials were rejected from our sample because they were superior or inferior to 3 standard deviations (17 trials out of 2340). We then calculated a time error (TE) for each participant: $(R-T)/T$, where T is the target duration and R the participants' temporal reproduction. A TE value shorter or longer than zero indicates that the temporal reproduction is shorter (underestimation) or longer (overestimation), respectively, than the target duration. A TE close to zero indicates an accurate time judgement.

Insert Figure 1 here

The ANOVA on the TE, with one between-subject factor (age group) and two within-subject factors [target duration (3, 6 s), timing condition (solo, multiple timing)], showed a significant linear effect of the timing condition, $F(1, 45) = 5.67, p = .02, \eta^2_p = .11$, revealing an increase of the time error (toward a temporal lengthening) from solo ($M_{solo} = .08, SD = .46$) to multiple timing ($M_{multiple} = .19, SD = .51$) (Figure 2). The ANOVA did not show a significant age \times timing condition interaction, $F(2, 90) = 1.22, p = .30$, showing that the multiple timing effect was not significantly moderated by the age.

The ANOVA also showed a significant duration \times timing condition interaction, $F(2, 90) = 3.39, p = .04, \eta^2_p = 0.10$, whereas the target duration \times timing condition \times age was not significant, $F(2, 90) = 0.50, p = .61$, such as for the main effect of age, $F(2, 62) = 1.22, p = .30$. As illustrated Figure 2, the significant duration \times timing condition interaction indicates that the effect of multi-timing on temporal performance was higher for the 3-s than for the 6-s target duration. Indeed, the difference in TE between the single and the dual or the triple timing was higher for 3 s than for 6 s ($t(64) = 3.43, t(64) = 3.08$, respectively, $p < .01$).

Apart from the multi-timing effect, the ANOVA showed a significant main effect of the target duration, $F(1, 45) = 55.42, p < .0001, \eta^2_p = 0.47$, indicating that the short duration (3 s) were overestimated and the longer one (6 s) underestimated (Figure 2), which is consistent with Vierordt's law. The target duration \times age also reached significance, $F(1, 45) = 3.39, p < .04, \eta^2_p = 0.10$, such as the Vierordt's law tended to decrease with age. Additional paired t -test launched on the difference from 3 to 6 seconds productions showed no difference between child groups of 5-6 years old ($M = .46, SD = .42$) and 7-8 years old ($M = .43, SD = .46$), $t(46) = 0.21, p = .80$, Cohen's $d = 0.06$), while both groups significantly differed from adults ($M = .18, SD = .20$) (5-6 years olds vs adults: $t(41) = 2.87, p = .007$ Cohen's $d = 0.86$; 7-8 year olds vs adults: $t(46) = 2.50, p = .018$, Cohen's $d = 0.71$).

Insert Figure 2 here

Correlations between the single-/multiple timing difference in time error and cognitive abilities

Table 1 shows the raw scores obtained in the different neuropsychological tests in each age group. The ANOVAs showed a significant main effect of age for all neuropsychological scores: short-term memory, $F(2, 55) = 44.62, p < .001, \eta^2_p = 0.62$; working memory, $F(2, 53) = 57.17, p < .001, \eta^2_p = 0.68$; information processing speed, $F(2, 56) = 358.25, p < .001, \eta^2_p = 0.89$; and attention, $F(1, 53) = 28.84, p < .001, \eta^2_p = 0.52$. In summary, the younger the participants were, the lower their cognitive capacities.

Insert Table 1 here

In order to identify the cognitive component correlating with the temporal lengthening from solo to multi-timing conditions, we calculated the difference in TE from solo to multiple timing. A correlation analysis was then run between this difference index (for 3 and 6 s), age, and neuropsychological z-scores. As presented Table 2, for all the target durations, and for both the 3s and 6s durations, the temporal distortion induced by the multiple timing was significantly related to selective attention (3s: $r = -0.39$, $p = .003$; 6s: $r = -0.37$, $p = .005$). It was also related to working memory, although in a lesser extent, for the 3-s target duration ($r = 0.29$, $p = .03$), and not for the 6-s target duration ($r = 0.16$, $p = .24$). The correlations with the other variables failed to reach significance: processing speed, short term memory and age in months (all $p > .05$).

Insert Table 2 here

For the 3s-target duration, we then ran a hierarchical regression on the single-/multiple-timing TE difference, including the scores of working memory and selective attention, to identify which component was the best predictor of time overestimation in the multiple timing condition. Only attention reached significance ($B = -.03$, $SE = 0.01$, $b = -.39$, $t = -2.12$, $p = .04$). Working memory was no longer a reliable predictor of time distortion from solo to multiple timing ($B = .002$, $SE = 0.013$, $b = -.013$, $t = 0.57$, $p = .95$). In summary, these results validate the key role of attention in difference in time estimated between children and adults in the multi-timing task.

Effect of the length of the concurrent duration

In order to examine the difference in temporal accuracy (TE) as a function of the length of the concurrent duration, the concurrent duration was split into two categories: shorter or longer than the target duration. The triple-timing trials with both a shorter and a longer concurrent duration were not considered. An ANOVA was thus performed on the TE with the concurrent duration as a factor (shorter *vs* longer concurrent duration), but also the target duration and the age group. This ANOVA did not show any significant effect related to the length of the concurrent duration: i.e. main effect, $F(1, 62) = 0.02$, $p = .89$, nor interactions (concurrent duration \times age, $F(2, 62) = 2.93$, $p = .06$; concurrent duration \times durations, $F(1, 62) = 3.06$, $p = .08$; concurrent duration \times durations \times age, $F(2, 62) = 0.06$, $p = .93$). Consistently with the previous results, there was only a significant target duration effect, $F(1, 48) = 82.85$, $p < .0001$, $\eta^2_p = .57$, and a target duration \times age interaction, $F(2, 48) = 3.30$, $p = .04$, $\eta^2_p = .10$. As a result, the time distortion in the multi-timing condition was the same whatever the length of the concurrent duration, and this was true in the children as in the adults.

Discussion

The results of Experiment 1 showed that the children as well as the adults were able to process different durations simultaneously. However, timing several durations simultaneously produced temporal distortion, and the magnitude of this distortion was related to individual selective attention capacities. Indeed, the temporal distortion increased with the decrease in attention capacities. In other words, the less participants are able to pay attention to durations, the greater the time distortion in a multi-timing task. Rather than age *per se*, it is therefore selective attention capacities that influence the accuracy of judgment of a duration presented concurrently with other durations. Therefore, our results suggest that time distortions in multi-timing are not linked with an internal clock-like system that is functional as an early age (Coull & Droit-Volet, 2018; Droit-Volet, 2016), but rather to attention devoted to different durations when these are presented together.

In our study, the time distortion in presence of different concurrent durations consisted in lengthening time estimates, and not in shortening them, as it is the case in non-temporal dual tasks. The mechanisms underlying the processing of multiple temporal signals are therefore different from those underlying the processing of multiple signals of different types (such as

temporal vs non-temporal). The lengthening of time estimates observed in our multi-timing task is consistent with the predictions associated with the assumption of a single pacemaker but different counters (Church, 1984; Van Rijn & Taatgen, 2008). According to this account, the time flow would be divided into different segments (accumulated time units) indicated by signals, i.e. the onset and offset of stimuli. Time distortion would therefore occur because the participants have difficulties paying attention selectively at the beginnings and ends of a series of temporal stimuli. An attention detection bias at the precise moment when the stimulus ends in a multi-timing task would have induced a delay in the opening of the attentional switch, such that an additional amount of pulses would be counted for the first duration. The encoding of the duration of the first interval presented would then affect the judgment of the other intervals, and of the target duration as a whole. As found, the additional amount of time would therefore be larger for the short target duration (3s) than for the long target duration (6s), probably because the short duration requires further selective attention due to the more rapid change in stimuli. Therefore, our developmental results from the first experiment highlighted the key role of selective attention in the case of a clock system with different accumulators that divides time into several segments according to the offsets and onsets of temporal stimuli (Meck & Church, 1984; van Rijn & Taatgen, 2008).

To confirm the role of attention in timing of multiple durations using participants with different attentional capacities, we decided to run a second experiment in children and adults with the aim to replicate the results found in Experiment 1. However, we also wanted to further examine the role of attention in time stream segmentation by using stimulus onset asynchrony (SOA) and not only offset asynchrony as in Experiment 1. Using both stimulus onset and offset asynchronies would allow us to better test the effect on timing of the length of the overlap between the target and the concurrent duration, as well as the presentation order of durations, and their length. Our hypotheses were as follows: (1) Time reproduction should be longer in the multi-timing condition than in the solo timing condition, thus replicating findings of Experiment 1. We also expected that (2) the lengthening effect in the multi-timing condition should be higher in participants with lower attention capacities (i.e., in children). In addition, in the theoretical framework of one pacemaker and multiple counters and of critical role of selective attention, we hypothesized that (3) a longer overlap between two concurrent durations should reduce temporal distortion in multi-timing, and that (4) the target duration presented first should be judged longer than that presented second (see discussion). (5) The magnitude of this effect related to characteristics of the concurrent durations would be also related to individual attention capacities.

Experiment 2

Method

Participants

Sixty-nine subjects participated in this experiment: 18 children from 5 to 6 years of age (14 females and 4 males, mean age = 5.67 years, $S.D = 0.33$), 25 children from 7 to 8 years of age (14 females and 11 males, mean age = 7.50 years, $S.D = 0.75$) and 26 adults (22 females and 4 males, mean age = 19.83, $S.D = 1.33$). The children and adults were enrolled from the same schools and the same university as those involved in Experiment 1. The participants were also rewarded in the same way and gave their written informed consent to participate in this experiment. The parents signed the consent forms on behalf of the children. This experiment was conducted according to the principles of the Declaration of Helsinki and was approved by the review committee of the Academy of the French Ministry for Education.

Material and procedure

The material was similar to that used in Experiment 1. The neuropsychological tests employed to assess individual cognitive capacities were also the same, except that the short-

term and information processing speed tests that generated no significant results in Experiment 1 were no longer used. We therefore assessed the capacities of all participants in terms of working memory and attention.

The same procedure was adopted except that the onset of the different squares to be estimated was not synchronised. The shortest target duration was also longer, i.e., 4 seconds (4 and 6 seconds) instead of 3 seconds, to better control the difference in overlap between durations in the case of the shortest target duration. There was also only one concurrent duration. The participants were thus informed that 1 or 2 squares were likely to appear but that they must pay attention to the duration of the different squares because they will only know which square has to be judged following the presentations. In Experiment 2, when two squares were presented simultaneously, the target square appeared before or after the onset of the second square (Figure 3). Regardless of the order of appearance (before or after), the duration of the temporal overlap between the two squares was either 16 or 33% of the total target duration. In Experiment 2, the duration of the second square (concurrent duration) was also controlled, and was 2 seconds longer or shorter than that of the target square: i.e., 2 s and 6 s for the 4-s target duration, and 4 s and 8 s for the 6-s target duration. Therefore, as illustrated in Figure 3, there were 16 experimental conditions (2 target durations \times 2 temporal overlaps \times 2 target duration sequences \times 2 concurrent durations) and 2 control conditions where only one square was presented (one for each target duration). There were 5 trials for each condition, thus totalling 100 trials. The participants were given 48 additional distracting trials, where the duration of the target square differed from 4 and 6 s: i.e., 1, 2, 3, 5, 7 or 8 seconds. The purpose of the distracting trials was simply to ensure that the participant could not identify the target durations of 4 and 6 seconds. These distracting durations were thus presented in the different conditions: 6 distracting durations \times 2 temporal overlaps \times 2 target duration sequences \times 2 concurrent durations. All the trials were randomly presented.

Insert Figure 3 here

Results

Temporal accuracy.

Figure 4 shows the mean duration reproduced by children and adults in the solo and the dual-timing condition.

Insert Figure 4 here

As for Experiment 1, we initially performed an ANOVA on the TE $[(R - T)/T]$, with the age as a between-subject factor and two within-subjects factors: timing condition (solo vs dual timing) and target duration (4 vs 6 s). 1.17% of the trials were rejected from our sample because they were superior or inferior to 3 standard deviations. The ANOVA showed a significant main effect of the timing condition, $F(1, 63) = 8.76, p = .004, \eta^2_p = 0.12$ (Figure 5). This confirmed that the target duration was judged longer in the multi-timing condition ($M = .27, SD = .79$) than in the single timing condition ($M = -.03, SD = .36$).

Interestingly in Experiment 2, when there was both offset and onset asynchronies in stimulus durations, the ANOVA also found a main effect of age, $F(1, 63) = 20.82, p = .001, \eta^2_p = 0.18$, as well as a significant timing condition \times age interaction, $F(1, 63) = 5.95, p = .004, \eta^2_p = 0.15$. As indicated the comparison between age groups for the differences in TE between the solo and the dual timing ($M_{5-6\text{years}} = -.94, SD = 1.66; M_{7-8\text{years}} = -.33, SD = .91; M_{\text{adults}} = 0.15, SD = .40$), the time distortion induced by the multi-timing was higher in the children than in the adults, no difference being found between the two child groups (5-6 years vs 7-8 years: $t(43) = -1.54, p = 0.13$, Cohen's $d = -0.48$; 7-8 years vs adults: $t(51) = -2.49, p = 0.02$, Cohen's $d = -.70$; 5-6 years old vs adults: $t(44) = -3.24, p = 0.002$, Cohen's $d = -.99$).

The timing \times duration \times age interaction was also significant, $F(2, 63) = 8.86, p < .001, \eta^2_p = 0.21$. This 3-way interaction suggests that the temporal distortion with the multi-timing was greater in the children than in the adults and was more marked for the short duration of 4s than for

the long duration of 6s. The ANOVA also subsumed a series of other significant effects involving the target duration. Such as in the previous study, the significant main effect of target duration, $F(1, 63) = 22.68, p < .0001, \eta^2_p = 0.26$, indicated a Vierordt Effect with the short duration (4 s) overestimated and the longer one (6 s) underestimated (Figure 5). This effect was more pronounced in the children as suggested by the significant target duration x age interaction, $F(2, 63) = 10.35, p < .0001, \eta^2_p = 0.24$. Finally, the target duration x timing condition, $F(1, 63) = 78.67, p < .0001, \eta^2_p = 0.54$, once again revealed that the effect of overestimation was greater for the short duration (4 s) in comparison to the longer duration (6 s).

Insert Figure 5 here

Correlations between the single-/multiple timing difference in time error and cognitive abilities

Table 1 shows the raw scores obtained in the different neuropsychological tests for each age group. The ANOVAs showed a significant main effect of age for both working memory, $F(2, 68) = 53.44, p < .001, \eta^2_p = 0.62$, and attention, $F(2, 68) = 29.49, p < .001, \eta^2_p = 0.47$, indicating an increase in these cognitive capacities with age.

Table 3 shows the correlations between the solo-dual timing difference in TE (4- and 6-s target duration), age, and neuropsychological scores. As for Experiment 1, the TE was significantly correlated with selective attention for both durations (4s: $r = -.45, p < .001$; 6s: $r = -.42, p < .001$). Although in a lesser extent, working memory was significantly correlated with the 4-s target duration ($r = .36, p = .002$), but not the 6-s target duration ($r = .24, p > .05$). Conversely to Experiment 1, there was also a significant correlation between TE and age for the two target durations (4s: $r = .37, p = .002$; 6s: $r = .27, p = .03$). This is consistent with the results of the ANOVA suggesting that the changes in SOA between Experiment 1 and 2 increased the influence of age.

Insert Table 3 here

Faced with these results, we launched two hierarchical regressions, one for the duration of 4s and the other for that of 6s, with 3 factors for the former (age, working memory, selective attention) and 2 factors for the latter (age, selective attention). These 2 regressions found that only the selective attention capacities were significant predictors of the inter-individual differences in the magnitude of time distortion for the multi-timing, both 4 s ($B = -0.43, SE = 0.19, b = -.34, t = -2.34, p = .02$), and 6 s ($B = -0.37, SE = 0.13, b = .39, t = -2.79, p = .007$). Working memory and age lost their predictive power (4s - working memory: $B = 0.08, SE = 0.23, b = .06, t = .34, p = .73$; age: $B = 0.002, SE = 0.003, b = .13, t = 0.74, p = .46$; 6 s - age: $B = .001, SE = 0.002, b = .05, t = 0.33, p = .74$).

Impact of the concurrent duration characteristics on timing

We analysed the effect on timing of different characteristics of the concurrent duration for both target durations (4 and 6 s): overlap (16 vs. 33%), presentation sequence of the target duration (first vs. second), and short or longer concurrent duration [short (-2 s) or longer (+2 s) than the target duration].

In the adult group, the ANOVA highlighted a significant 4-way interaction, $F(1, 25) = 4.41, p = .046, \eta^2_p = 0.15$, with a significant effect of all characteristics of the multi-timing task (target duration: $M_{4s} = 0.44, SD_{4s} = 0.93, M_{6s} = 0.04, SD = 0.59, F(1, 25) = 18.36, \eta^2_p = 0.42$; overlap: $M_{16\%} = 0.25, SD_{16\%} = 0.79, M_{33\%} = 0.20, SD_{33\%} = 0.73, F(1, 25) = 8.15, \eta^2_p = 0.25$; target order: $M_{\text{target first}} = 0.20, SD_{\text{target first}} = 0.76, M_{\text{target second}} = 0.26, SD_{\text{target second}} = 0.75, F(1, 25) = 22.99, \eta^2_p = 0.479$; shorter/longer concurrent duration: $M_{\text{shorter}} = 0.22, SD_{\text{shorter}} = 0.80, M_{\text{longer}} = 0.23, SD_{\text{longer}} = 0.71, F(1, 25) = 30.16, \eta^2_p = 0.55$, all $p < .01$). Therefore, in the dual-timing condition, the target duration was judged longer with a small (16%) as opposed to large (33%) overlap between the concurrent durations. It was also judged longer when the concurrent duration was presented second, i.e., after rather than before the concurrent duration. And lastly,

it was judged longer when the concurrent duration was longer as opposed to shorter than the target duration. There was nevertheless a significant interaction between the target duration and the shorter/longer concurrent duration, $F(1, 25) = 10.65$, $p = .003$, $\eta^2_p = 0.42$, indicating that this effect was more important for the short target duration (4 s) than for the longer one (6 s). In conclusion, an additional amount of time was added to time estimates when a second duration was simultaneously presented, and the proportion of the temporal extension depends on each characteristic in a temporal context.

In the children's groups, we only observed a significant and major effect of the target duration [5-6 years, $F(1, 17) = 28.08$, $\eta^2_p = 0.62$; 7-8 years, $F(1, 24) = 36.91$, $\eta^2_p = 0.61$] and a significant target duration \times target duration order interaction [5-6 years, $F(1, 17) = 6.73$, $\eta^2_p = 0.28$; 7-8 years, $F(1, 24) = 5.51$, $\eta^2_p = 0.19$, $p < .05$]. The other characteristics of the concurrent duration were not critical factors for the time estimates: overlap, shorter/longer concurrent duration, target order ($p > .05$). In fact, in the dual-timing condition, the 6-s duration was judged longer than the 4-s duration, and more importantly when it was presented first rather than second. However, irrespective of the target order presentation in the multi-timing condition, the lengthening effect always occurred compared to the single-timing condition, with the target duration presented first (averaged over duration) [7-8 years, 0.27 vs. -0.23, $t(24) = 2.17$, $p = .04$, 5-6 years, 0.77 vs. -0.88, $t(17) = 2.79$, $p = .01$], and the target duration presented second [7-8 years, 0.30 vs. -0.23, $t(24) = 2.26$, $p = .03$, 5-6 years, 0.76 vs. -0.88, $t(17) = 2.78$, $p = .01$]. In conclusion, in adults and children alike, there was a time distortion in the multi-timing conditions, but this time distortion was insensitive to all the different aspects of the temporal context, except if the long target duration was presented initially.

Correlations between time error for the different concurrent duration characteristics and cognitive abilities

Table 4 shows the correlation between age (in months), attention and working memory, and differences in TE between each characteristic of the different concurrent duration presentations: overlap [dif(16%, 33% overlap)], presentation order of the target duration [dif(First, Second)], shorter or longer concurrent duration [dif(Shorter, Longer)]. It appears that the additional lengthening effect as a function of the concurrent duration presentation was systematically linked to individual attention capacities. Indeed, the lengthening effect that was greater for the small overlap (16%) (greater SOA) compared to the greater overlap (33%) between durations increased for the participants with poorer attention capacities, at least for the longer target duration of 6 s ($R_{6s} = 0.27$, $p < .05$). The lengthening of time estimates induced by the target duration presented second ($R_{4s} = -0.27$, $R_{6s} = 0.47$) or by the longer concurrent duration also correlated significantly with attention capacities ($R_{4s} = -0.25$). However, the direction of the correlation differed depending on the target duration, with a positive correlation being documented for 6 s ($r = 0.47$) and a negative correlation for 4 s ($r = -0.27$, $r = -0.25$). In the case of the attention test used in our study, a positive correlation indicated an increased lengthening effect with reduced attention capacities and a negative correlation a decreased lengthening effect with reduced attention capacities. Consequently, the increase in magnitude of the time distortion with reduced attention capacities depended on the length of the duration to be reproduced, and was larger for the long 6-s duration than for the short 4-s duration. A link between temporal performance and age and working memory was observed only for the short target duration of 4 s in addition to attention. The lower the working memory capacities, the shorter the 4-s duration was reproduced when it was presented first ($R = 0.31$, $p < .05$), and when it was presented with a longer concurrent duration ($R = 0.28$, $p < .05$). As discussed later, this suggests that memory-related processes also contributed to explain the value of temporal reproductions in the specific case of the short target duration.

Discussion

The results of Experiment 2 with both stimulus onset and offset asynchronies replicated those of Experiment 1. They confirmed children's and adults' ability to judge simultaneously different durations. They also confirmed an interfering effect of concurrent durations which resulted in a lengthening of time estimates. Moreover, the lower the participant's attention capacities, the higher this interference effect.

However, the more complex task used in Experiment 2 highlighted developmental differences. Indeed, the temporal distortion in the dual timing task compared to the solo timing one was higher in the children than in the adults. In addition, there was only a main source of temporal distortion in the multi-timing task for the children while there were several sources for the adults. In children, this was the order of presentation of durations. Indeed, when two concurrent durations were presented with different onsets, the interference lengthening effect was larger on the judgment of the duration presented first. This finding is consistent with the hypothesis of an attention deficit leading to a delay in the detection of the offset of the first stimulus duration when the second duration was still presented on the screen. As a result, the clock-switch would open later and more pulses would be accumulated, thus resulting in a lengthening effect.

Unlike the children, the adults' time estimates were influenced not only the presentation order of durations, but also by their overlap and their length. Indeed, adults produced greater temporal distortion (lengthening effect) with a short overlap (16%) than a long overlap (33%), and when the concurrent duration was longer than shorter than the target duration. In addition, our results revealed that the magnitude of these different interfering effects were linked to scores of selective attention. It is now well established in the literature that the adults have greater attentional flexibility and selective attention capacities than children (Cowan *et al.*, 2006; Plude, Enns & Brodeur, 1994). The interference effects in a multi-timing task were therefore lower in the adults than in the children as shown our results. However, the interference effects were more varied, probably due to adults who paid more attention to all the stimulus changes on the screen.

General discussion

In our study, the children and adults had to simultaneously process several stimulus durations. Which stimulus had to be judged was unpredictable – hence the participants had to pay attention to all temporal stimuli. The number, colour and spatial localisation of the target stimulus were also unpredictable to avoid attention effects (see Kim, Tsai, Ojemann & Verghese, 2017). In addition, the children only responded to one duration (target) to avoid competition between outputs for decision and motor programmes during temporal reproduction. In the first experiment, we used stimulus durations with the same onset but different offsets to limit the amount of varying information to be processed by young children. In the second experiment, we used a more controlling methodology with both different onsets and offsets, allowing us to control both the overlap between the durations (SOA), the presentation order of the target duration and the length of the concurrent duration.

Our study was the first to experimentally test multi-timing in children. It showed for the first time that young children, from 5 years of age, were able to process several (at least two or three) durations simultaneously. Indeed, their judgments of durations in a multi-timing task remained orderly as in adults (e.g., increase in durations produced in relation to increasing durations of stimuli). In addition, like the adults, the children's temporal judgement was subject to temporal interference effects when they timed several stimulus durations simultaneously. Consistent with earlier multi-timing studies (Brown & West, 1990; Cheng *et al.*, 2014; Klapproth, 2011; Morgan, Giora & Solomon, 2008), this temporal interference effect resulted in a lengthening of time estimates. However, the interference effect in multi-timing was greater in the children than in the adults, at least when there was both an asynchrony in the beginning and end of the stimulation durations. With only stimulus offset asynchrony, no significant effect

of age was observed. However, regardless of the multi-timing context, the magnitude of temporal interference increased as selective attention capacities decreased.

Temporal interference in the multi-timing condition therefore produced a lengthening of time estimates rather than shortening, as observed in a dual-task with concurrent non-temporal information. A shortening effect has been explained by the processing of non-temporal information that competes for attentional resources with the processing of temporal information (Zakay & Block, 1996). The direction of time distortions towards lengthening in the multi-timing context therefore suggests that simultaneous processing of different durations does not compete for attentional resources, like the processing of non-temporal information.

As reported in the introduction, several hypotheses have been suggested to account for the specific mechanisms underlying the multi-timing. Some researchers (Cheng, Yang, Ding & Fan, 2014; Johnston, Bruno & Ayhan, 2011; Johnston, Arnold & Nishida, 2006) assume that individuals use different internal clocks (pacemaker-accumulator systems) to process durations presented in parallel, one for each stimulus duration (Eisler, 1981; Meck & Church, 1984, p. 2). Therefore, each pacemaker generates pulses that increment their own accumulator. In this case, the pacemaker-accumulator systems are independent and no temporal interference is expected, apart from perhaps at the memory or decision level. This model is therefore inconsistent with our results showing temporal interference effects in the multi-timing task. In addition, our results showed a decrease in time estimates in adults (but not in children) with an increased overlap (30% overlap) between the durations, which refutes this multiple independent clocks model. Indeed, this shortening with a larger overlap between the durations can only be explained by a single pacemaker that generates pulses shared between multiple accumulators (Van Rijn & Taagten, 2008). With a single pacemaker, there are indeed fewer pulses to increment each accumulator when two durations are presented concomitantly.

Other researchers claim that a single pacemaker and a single accumulator (e.g., a master clock) are used to process multiple durations. This master clock continuously operates during timing, and a series of temporal segments are stored in the memory as sequential timing (Bryce & Bratzke, 2016; Church, 1984). In this context, initial time estimates in the dual-timing condition must be close to those in the solo-timing condition, because the timing is similar. If the first estimate is too long, the second estimate must also be too long, because, in this case, the estimated second duration depends on the first duration. However, our results showed a lower accuracy of the first presented target duration in the dual-timing condition compared to the single-timing condition in both adults and children. Furthermore, there was no significant effect in terms of the length of the concurrent duration, at least in children. In addition, as stated by van Rijn and Taatgen (2008, p 368), with “only a single pacemaker and a single accumulator, there is no reason to assume any attention or dual tasking cost apart from possible dual-tasking penalties in the memory and decision process”. Notably, our results showed the critical role of attention in the temporal interference effects in a multi-timing task.

Van Rijn and Taagten (2008) therefore concluded that the best mechanism to account for temporal performance in the multi-timing task is a single pacemaker with multiple accumulators. They mainly based their conclusion on their findings about the SOA effect on time estimates, i.e., shorter time estimates (or no difference in time estimates) with the decrease of SOA (longer overlap in our study: 33% overlap). Our data replicated this finding in adults by showing shorter time estimates with the longer overlap (33%) between the concurrent durations in the adults. However, as discussed below, the effect was not significant in the children. To sum up, the temporal interference effects obtained in our study provide evidence against multiple independent clocks, and support a single mechanism that “strategically uses the output of a single time source for parallel timing” (van Rijn & Taatgen, 2008, p. 373). However, some differences in “this strategically use” occurred as a function of attentional capacities and executive functions, known to be limited in children.

Our data using participants with different attentional capacities indeed demonstrates the major role of selective attention in multi-timing. Indeed, our results indicated that the lower attentional capacities are, the higher the temporal interference effect in the multi-timing tasks used in our studies, i.e. the longer the time estimates. Furthermore, the SOA effect on time estimates (i.e., shorter time estimates with reduced SOA) was directly linked to individual attention capacities. In the same way, the difference in time estimates when the target duration was presented first or second was related to attention capacities. In contrast, the temporal interference effects observed were not significantly linked to capacities of short-term memory, working memory and information-processing speed. However, when the shortest target durations (4 s) were presented first with a longer concurrent duration in the multi-timing condition with both stimulus onset and offset asynchrony, working memory capacities explained a proportion of the variance in temporal interference effects. This finding can be explained by the maintenance and updating of temporal information in memory that was longer and larger for the shortest target duration, because the participants did not know in advance which stimulus duration had to be reproduced until the end of the longest stimulus duration. Consequently, the participants with lower memory capacities would lose more pulses when the shortest target duration (4 s) had to be retained in the memory whilst processing other durations. This lends additional support to the existence of different accumulators working in parallel for the processing of different durations presented simultaneously.

An important question is why selective attention is the main factor associated with the lengthening of time estimates in the multi-temporal tasks used in our experiments. A future study should focus on the respective role of selective and divided attention capacities, even though it is difficult to distinguish these two operations of attention with validated neuropsychological tests. Developing specific cognitive tasks would be interesting, but it is difficult to validate these tasks for children of different ages. Within the framework of the internal clock model, we can nevertheless assume that the additional part of pulses in the accumulation process in a multi-timing task was due to the attention-controlled switch system. This switch system would thus be less efficient in the participants with lower selective attention capacities as indicated the children's temporal performance. In her study, Droit-Volet (2003) demonstrated a slower attention-controlled switch system in younger children's timing. The developmental scalar timing models used to account for differences in temporal judgment between the visual and auditory modality also support this attentional-switch-related hypothesis (Droit-Volet, Meck & Penney, 2007; Droit-Volet, Tourret, & Wearden, 2004). This is also consistent with all developmental studies showing that young children with lower attention abilities are more subject to time distortion (for a review see Droit-Volet, 2013, 2018; Coull & Droit-Volet, 2018). In addition, our results showed that the most salient information in the multi-timing task for children was the appearance and the disappearance of one duration during the processing of another duration, and the length of the first duration to be processed. The other temporal context dimensions tested (duration of SOA, shorter or longer concurrent durations) had, in comparison, little impact on temporal judgment. The development of accuracy in timing of multiple durations would thus also require increasing attention devoted to different aspects of the context. In other words, temporal interference effects would be higher in children in multi-timing, but less sensitive to small changes in the temporal context.

In conclusion, our results showed that the temporal interference effects in the multi-timing context were higher in young children than in adults and were mainly related to their limited attention capacities. Indeed, the poorer the attention capacities, the higher the interference effects in a multi-timing task. We have explained these findings by the temporal interference that could act upon the attention-switch system described in the internal clock model - a system that would be less efficient in young children with lower attention capacities. To verify this explanation, other experiments must now be conducted. For instance, it would be

interesting to test multi-timing in tasks other than temporal reproduction used in our experiments. In this task, other mechanisms related to motor abilities and motor inhibition could affect young children's temporal performance (Droit-Volet, 2010; Hallez, 2020). It would also be important to construct a series of specific cognitive tasks to facilitate identification of the role of different attention components in the multi-timing task, thus opening up an extensive field of experimental research.

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Figure captions

Figure 1. Mean reproduced duration for the 3 and the 6s target duration, associated with solo and multiple timing condition for each age group (5-6 years; 7-8 years; adults).

Figure 2. Mean time error plotted against (A) the different timing conditions (solo, dual and triple timing) and (B) the stimulus durations (3, 6 seconds).

Figure 3. Illustration of temporal stimuli used in the multi-timing conditions of Experiment 2.

Figure 4. Mean reproduced duration for the 4 and the 6s target duration for the solo and the dual timing condition for each age group (5-6 years, 7-8 years, adults).

Figure 5. Mean time error for the two timing conditions (solo, dual) for both the 4 and 6s durations.

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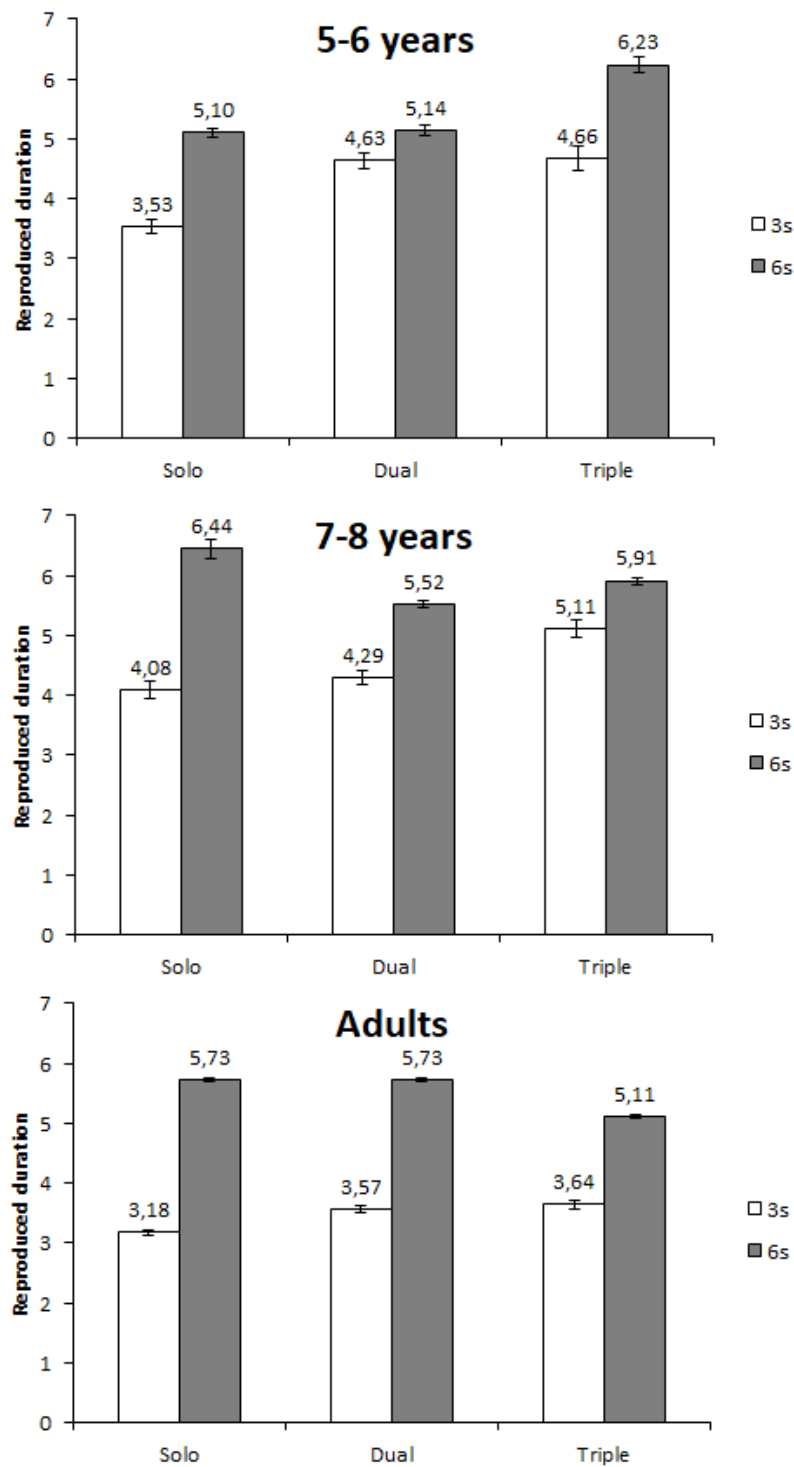
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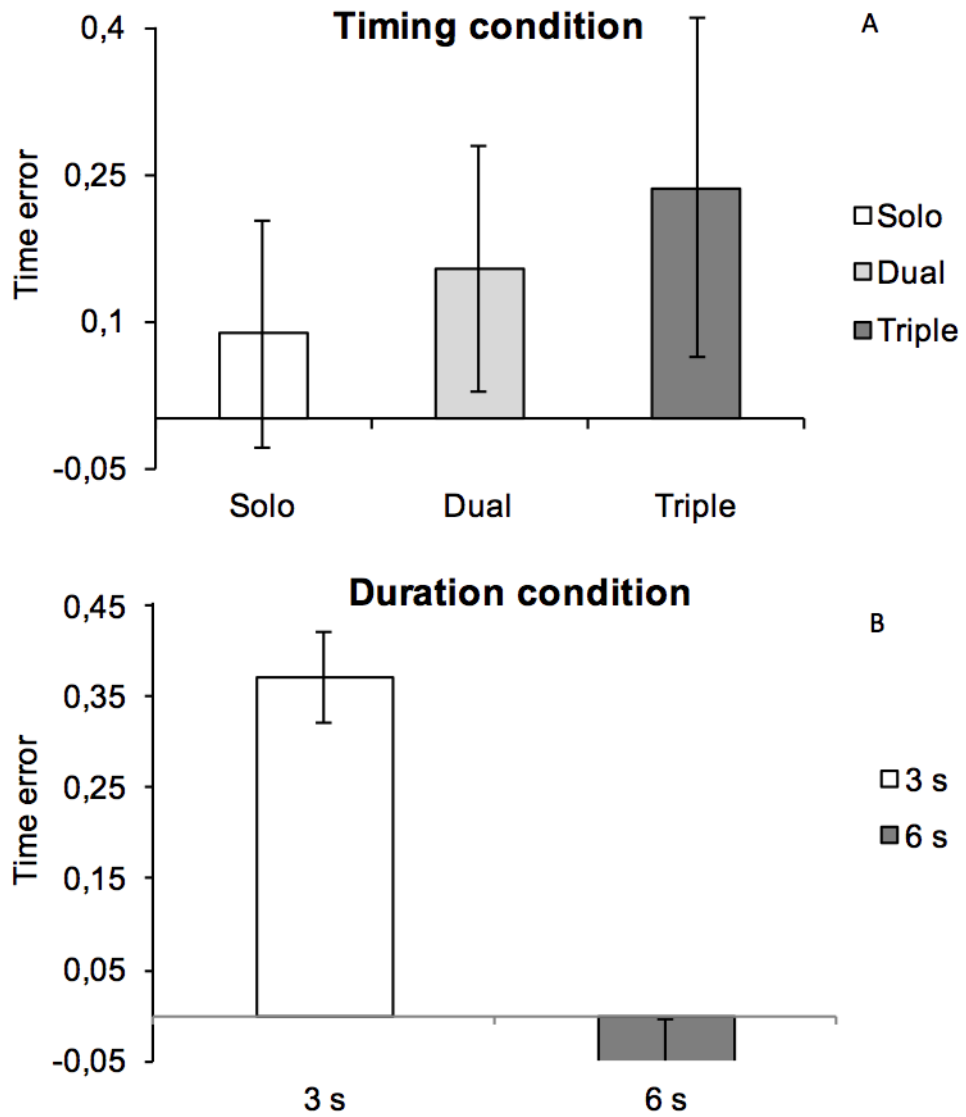
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Figure 1



Mean reproduced duration for the 3- and 6-s target durations associated with solo- and multi-timing conditions for each age group (5- and 6-year-olds, 7- and 8-year-olds, and adults).

Figure 2



Mean time errors plotted against the different timing conditions (solo, dual, and triple timing) (A) and the stimulus durations (3 and 6 s) (B).

Figure 3

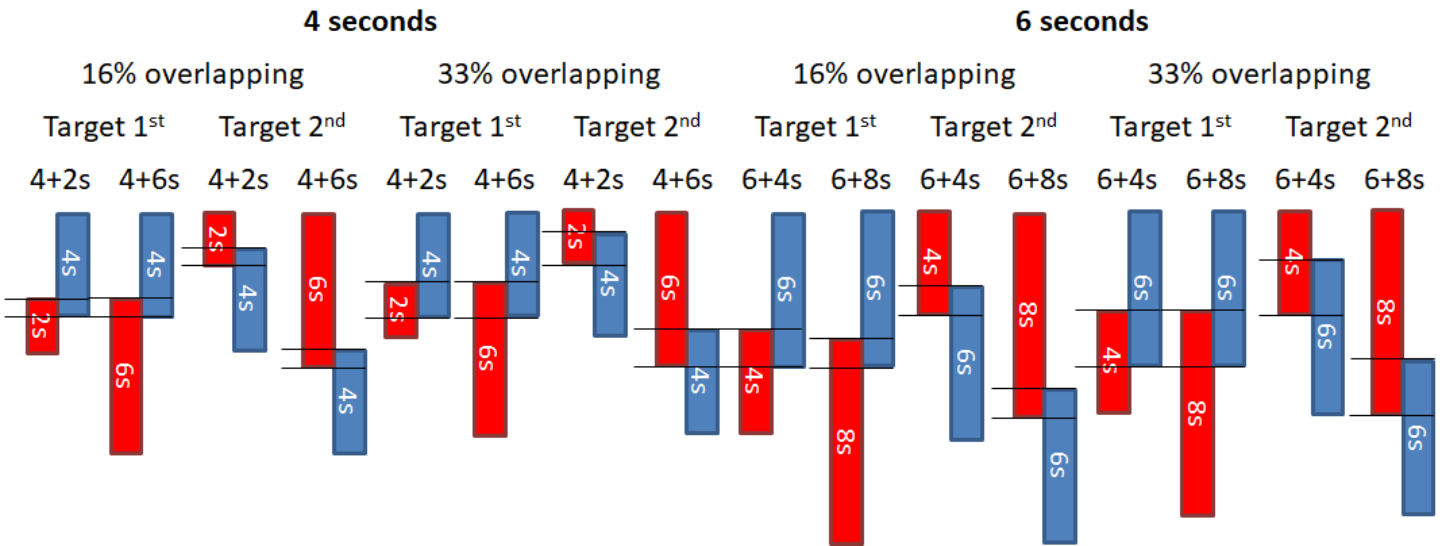
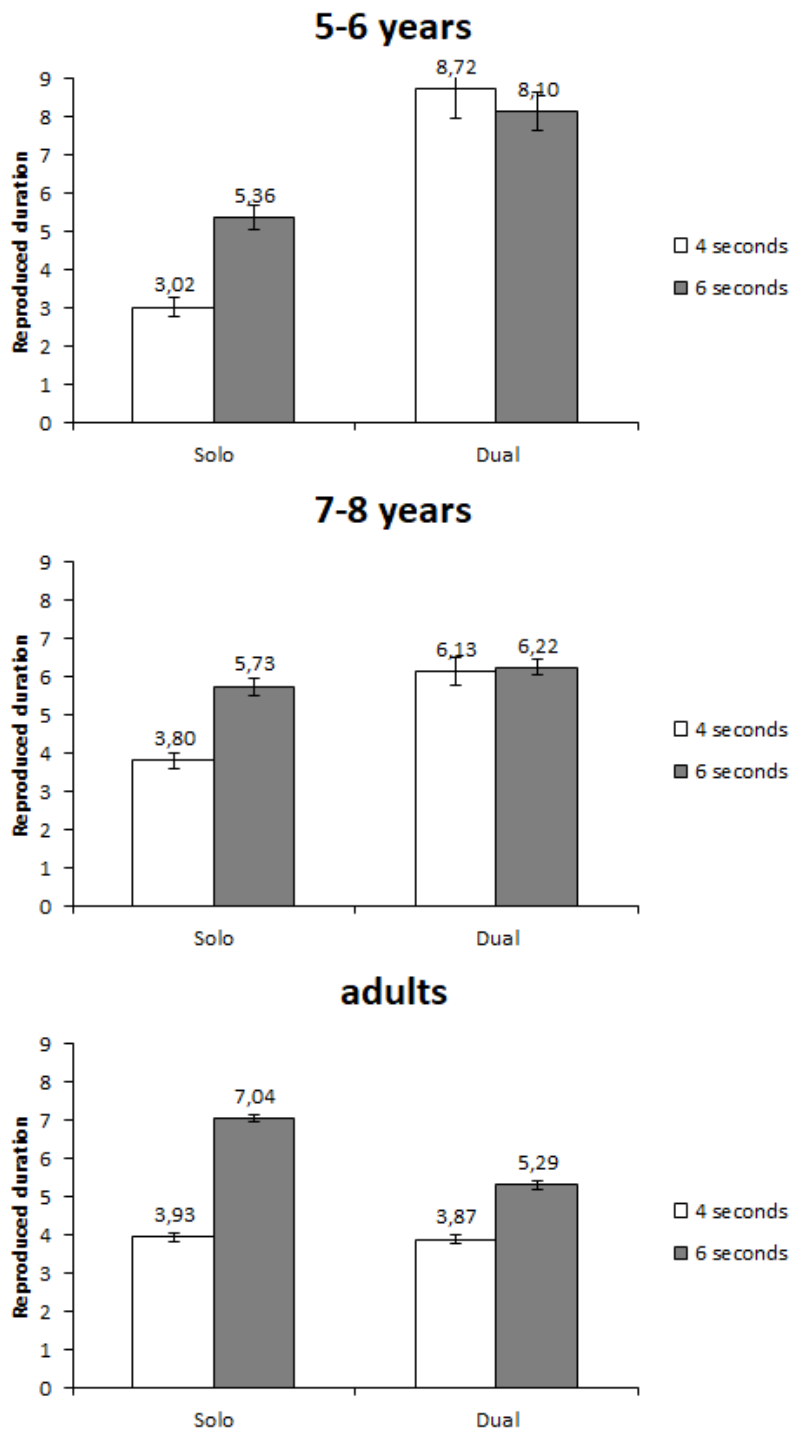


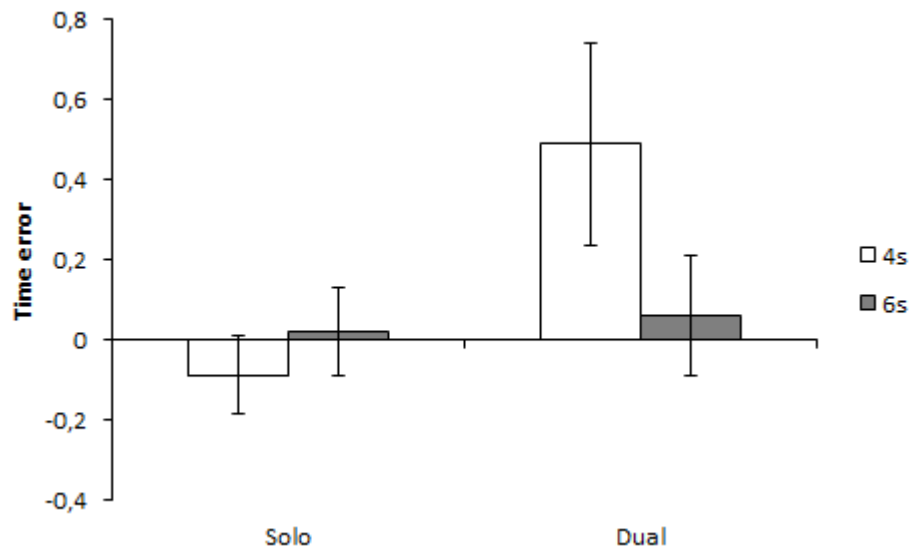
Illustration of temporal stimuli used in the multi-timing conditions of Experiment 2.

Figure 4



Mean reproduced durations for the 4- and 6-s target durations for the solo- and dual-timing conditions for each age group (5- and 6-year-olds, 7- and 8-year-olds, and adults).

Figure 5



Mean time errors for the two timing conditions (solo and dual) for the 4- and 6-s durations.

Table 1. Mean, Standard Deviation, minimum and maximum of raw scores of different neuropsychological tests in the different age groups for Experiment 1 and 2.

	5-6 years			7-8 years			Adults		
	M	SD	[Min;Max]	M	SD	[Min;Max]	M	SD	[Min;Max]
<i>Experiment 1</i>									
Short-Term Memory	4.47	1.37	[2; 6]	6.74	1.45	[4; 9]	9.50	1.88	[6; 13]
Working Memory	2.94	1.43	[0; 5]	5.62	1.66	[3; 9]	9.06	1.95	[4; 12]
Processing speed	13.35	4.63	[4; 23]	26.46	4.54	[16; 32]	58.75	6.45	[48; 69]
Selective Attention	16.46	6.89	[7; 32]	8.95	5.14	[4; 23]	3.31	1.22	[2; 8]
<i>Experiment 2</i>									
Working Memory	2.5	1.58	[0; 6]	4.58	1.66	[2; 9]	7.58	1.53	[5; 11]
Selective Attention	19.96	13.74	[7; 59]	9.00	5.14	[4; 15]	3.00	0.86	[2; 6]

Table 2

Correlations between the solo/multiple-timing differences in reproduced durations associated with the 3-s, 6-s, and overall target durations, age, and the different neuropsychological scores: Experiment 1.

	3 seconds	6 seconds
Age in months	.11	.01
Short-term memory	.16	.19
Working memory	.29*	.16
Processing speed	.21	.10
Selective attention	-.39**	-.37**

* $p < .05$.

** $p < .01$.

Table 3

Correlation between the solo/dual timing difference in reproduced duration associated with the 4s, 6s and overall target durations, age in months and the different neuropsychological scores.

	4 s	6 s
Age in months	0.37**	0.27*
Short-term memory	0.36**	0.24
Selective attention	-0.45**	-0.42**

Table 4. Correlations between the age, the attention and working memory scores and the differences in time error between different characteristics of multi-timing in the dual timing.

	Age	Attention	Working memory
4 s - Dif(16%, 33% overlap)	.01	-.15	-.01
6 s - Dif(16%, 33% overlap)	-.10	.27*	-.18
4 s - Dif(target 1 st , 2 nd)	.37**	-.27*	.31*
6 s - Dif(target 1 st , 2 nd)	-.07	.47**	-.18
4 s - Dif(Shorter, Longer Con.)	.30*	-.25*	.28*
6 s - Dif(Shorter, Longer Con.)	.16	-.08	.13

* $p < .05$, ** $p < .01$