How Is Temporal Processing Affected in Children with Attention-deficit/hyperactivity Disorder?

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ABSTRACT
We compared the performance of children with ADHD and typically developing children on two temporal tasks, a bisection task and a reproduction task, in auditory and visual modalities. Children with ADHD presented a larger variability when performing auditory and visual temporal tasks. Moreover, they overestimated the durations in bisection tasks and underproduced duration intervals in the visual reproduction task. In the context of the pacemaker-accumulator model, these results suggest that temporal deficits might result from a dysfunction in the switch and/or memory impairment.

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Introduction
Imagine yourself at the train station. The most recent announcement indicated that your train would arrive in five minutes, so you are expecting it. As time passes, you acquire the subjective perception that the five minutes have elapsed, so you go to the appropriate gate, and you reach it just before the train arrives. How were you able to correctly measure the lapse of a specific amount of time without looking at your watch? The study of the psychology of time has indicated that this capacity to measure time relies upon an internal clock that enables a person to estimate time intervals. The scalar expectancy theory (SET) (Gibbon, Church, & Meck, 1984) proposes a functional model of this internal clock that remains the most useful functional system to interpret data and dissect the neural mechanisms underlying the timing system (Wearden, 2013).

This functional model proposes that time judgments come from a pacemaker-accumulator internal clock and involve memory and comparison stages. In this model, subjects estimate time intervals using an internal clock consisting of three components: a clock stage with a pacemaker and an accumulator, a memory stage, and a decision-comparison stage. Intervals are determined by the amount of pulses that are emitted at a regular rate by the pacemaker and stored in the accumulator. A switch controls the transfer of pulses from the pacemaker to the accumulator, such that when the switch closes, pulses pass into the accumulator. Thus, the more pulses accumulate, the longer the subjective estimation of the given duration is. Next, depending on the context or the requirements of the task, the pulses stored in the accumulator can be transferred to the working memory and then to the long-term memory, called the reference memory. Finally, in the decision-making stage, the amount of pulses stored in the working-memory is compared to the amount stored in the reference memory to produce a temporal judgment.

The capacity to measure time seems deteriorated in some clinical populations, such as in children with attention-deficit hyperactivity disorder (ADHD; Barkley, Murphy, & Bush, 2001; Bauermeister et al.,...
on these observations, temporal deficits in children with ADHD could also have their origin in a dysfunction of the brain regions that support the internal clock per se.

Moreover, ADHD is characterized by symptoms of inattention, impulsivity and hyperactivity (APA, 2000). Concerning temporal processing, the symptom of inattention is particularly relevant because of the importance of selective attention and alertness level on time perception are very well documented and explained in the framework of the SET. Several studies have shown that subjective duration depends on the amount of selective attention allocated to time (for a review, see Brown, 1997, but also Block, 1992; Burle & Casini, 2001; Casini & Macar, 1997; Macar, Grondin, & Casini, 1994; McClain, 1983; Thomas & Weaver, 1975; Zakay, 1989, 1993). More precisely, they have shown that when selective attentional resources are diverted from temporal parameters, temporal judgments are degraded and come to reflect a systematic shortening of subjective duration. Thus, the less attention allocated to an interval, the shorter its estimated duration will be of the interval. In the context of the pacemaker-accumulator clock, it has been proposed that each time attention is diverted from the temporal parameters, the switch opens, and pulses are lost because they are not stored in the accumulator. As a result, fewer pulses accumulate, and the subject’s estimate of duration is shortened (Burle & Casini, 2001).

Variation in alertness levels can also affect temporal judgments (Allan, 1992; Burle & Casini, 2001; Droit-Volet, 2003; Penton-Voak, Edwards, Percival, & Wearden, 1996; Treisman, Cook, Naish, & MacCrone, 1994; Treisman & David Brogan, 1992; Wearden, 2008; Wearden, Philpott, & Win, 1999; Witherspoon & Allan, 1985). For example, Droit-Volet and collaborators (2003) investigated the effects of an increased level of alertness on temporal judgments in children in an experiment where a warning signal (a click) was delivered just before a stimulus was presented for being timed. Their results indicated that the warning signal delivery reduced temporal variability in a typically developing population. It has been proposed that variations in alertness level could produce variability in the latency of the switch closing. This variability would then increase the variability in the amount of accumulated pulses corresponding to the temporal representation of a given time interval, so variability would also increase in temporal judgments.

Based on these observations, temporal deficits in children with ADHD could also have their origin in their symptomatic inattention, which could affect the functioning of their internal clock. Interpreting the temporal deficits of children with ADHD in the theoretical framework of the SET model could better explain the temporal deficits in this population. Moreover, it could also allow for a more precise understanding of attentional deficits associated with ADHD. It is known that inattention is one of the core symptoms of ADHD (APA 2000) but it is not clear whether these children have difficulties in focusing their attention on specific information or in maintaining stable alertness level (Friedman-Hill et al., 2010; Heaton et al., 2001; Huang-Pollock, Nigg, & Halperrin, 2006; Sergeant et al., 2003). According to the SET model framework, if children with ADHD exhibit selective attention difficulties, they should have difficulties in focusing their attention on the temporal interval, leading to fewer accumulated pulses, and we should observe a temporal bias toward temporal underestimation relative to typically developing (TD) children. On the other hand, if these children have difficulties in maintaining a stable level of alertness, this could produce a variability in the latency of the switch closing and we should observe an increase in temporal
variability, as has been suggested by studies investigating alertness level effects on temporal performance in TD children.

In this study, we compared temporal performance between children with ADHD and TD children in a temporal bisection task and a temporal reproduction task. In the bisection temporal task, children were first shown repeated presentations of two standard stimulus durations (identified as short and long standards), and then they classified a range of durations (short and long, as well as intermediate stimuli) in terms of their similarity to the short or the long stimuli. In the temporal reproduction task, at each trial, children had to evaluate the duration of a first stimulus. After a brief delay, a second stimulus was presented, and children had to wait until they estimated that the same duration had elapsed, before stopping the presentation of the stimulus by pressing the response key. Both tasks provide measures for both temporal precision (that is, temporal variability) and temporal accuracy (that is, the direction of the temporal error, also called temporal bias).

One previous study carried out in adults with ADHD with a temporal bisection task demonstrated that temporal difficulties encountered by the participants when they were performing a temporal bisection task might be explained both by an alertness effect at the level of the switch that directs pulses into the accumulator and also by a distortion of the durations stored in reference memory (Suarez, Lopera, Pineda, & Casini, 2013). In the present study, we expect to generalize these results to children with ADHD, that is, before strategic compensation has developed. Moreover, we added a temporal reproduction task to the adult paradigm because, according to the pacemaker-accumulator model, the two tasks differ at the memory stage. The time reproduction task is interpreted as relying on a comparison between temporal representations stored in the short-term memory and in the accumulator, while the temporal bisection tasks relies instead on a comparison between the temporal representation stored in the short-term and the one in the reference memory. Finally, differences in performance have been reported to depend on input modality (Toplak & Tannock, 2005), so the children were tested in both the visual and auditory modalities for each task.

Subjects and methods

In all the present study, 40 children diagnosed with ADHD (aged 8–14 years; mean age = 10.6 years; sd = 2; male = 76.9%) and 42 TD children (aged 8–14 years; mean age = 10.5; sd = 2.1; male = 71.4%) participated in the experiment. All participants and their parents gave informed consent prior to the beginning of the experiment. The study was approved by the ethical committee of the University (Approval No: 160; Date: 10.08.2017).

Selection procedure for the ADHD group

Children with ADHD were recruited from a clinical sample who had been referred to the Instituto Colombiano de Neuropedagogia diagnosed by qualified neurologists as meeting the DSM IV diagnostic criteria for ADHD. The assessment was performed using a semi-structured clinical diagnostic interview (DSM IV checklist) that was administered by neurologists specialized in ADHD to the children’s parents and teachers separately. Further, one parent for each child completed a behavior rating scale (EDAH, Evaluacion del Deficit de Atencion e Hiperactividad, Farré & Narbona, 1998). For this study, in order for the ADHD group to be as homogeneous as possible but also not reduced to only one symptom (impulsivity or attention), only children who had been diagnosed with the combined ADHD type were contacted and solicited for their participation.

Selection procedure for the TD children group

Children from the TD group were recruited via local schools. TD children were matched on age and gender to the children with ADHD. All children met the following inclusion criteria: absence of current diagnosis or any history of ADHD, as certified by the parent’s completion of the EDAH;
absence of any learning disability, indicated by teachers’ or school psychologists’ reports; and no concurrent treatment with any psychotropic medication.

**Exclusion criteria for both groups**

Exclusion criteria included the absence of the child’s assent or parental consent; a diagnosis of any psychiatric disorder besides ADHD or any significant indicator of a psychiatry disorder (such as major depression, panic disorders, suicide risk, anxiety, substance abuse, psychoactive substance use, or psychotic disorder), as assessed with a Spanish version of the structured psychiatric interview Children’s Interview for Psychiatric Syndromes (CHIPS); or an intelligence quotient (IQ) of < 70, as assessed by the vocabulary-block design, short-form of the Spanish Wechsler Children Intelligence Scale (WISC III). The use of the vocabulary-block design to assess IQ was based on the instructions for WISC III clinical administrators (Sattler & Saklofske, 2003).

**Complementary neuropsychological assessments**

In addition to measures of IQ, all participants received complementary neuropsychological tests to assess their working memory and attention. Working memory was assessed using the working memory index from the WISC IV, which included arithmetic, digit span, and letter–number sequencing subtests. Attention was assessed using a modified version of the continuous performance task (CPT). In this modified version, in each trial, a letter appeared on the computer screen, and participants were required to press the spacebar as soon as any letter appeared, except for the letter X, which appeared in 30% of trials. When a participant pressed the spacebar for the letter X, an error of commission was counted. Errors of omission were counted when participants did not press the spacebar for trials where letters other than X appeared. Mean reaction times (RT) and standard deviations were also calculated for each subject. Three inter-stimulus intervals (ISI), namely, 1, 2, or 4 s, were used, each corresponding to a different experimental block of 20 trials. The CPT task took approximately 10 min per participant in total.

**Temporal tasks**

Participants were comfortably seated in a dimly lit, soundproof room, and the experiment was controlled by a computer running T-scope software (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Participants completed two experimental sessions for each task, one using the visual modality and one using the auditory modality. The order of sessions was counterbalanced between participants (in each group, half the participants carried out the visual modality session first, followed by the auditory modality, and this was done in the reverse order among the other half).

**Bisection task procedure**

In the bisection temporal task, we used a similar protocol to the one used in a previous study (Suarez et al., 2013). For each modality (auditory or visual), each participant performed a training phase before the test phase. In the training phase, participants learned to distinguish two standard stimulus durations (identified as short and long standards). In the auditory modality, the short and long standards were of 150 and 430 ms respectively, and in the visual modality, they were of 300 and 900 ms respectively. Different duration ranges were used in each modality because their respective temporal thresholds are known to be different (Goldstone & Lhamon, 1974).

The training phase consisted of two parts. First, participants were presented with the two standard durations, each presented five times in alternation. In the auditory modality, a white noise was presented, and in the visual modality, a red circle appeared in the center of the screen. Participants were instructed to concentrate their attention on the duration of the stimuli, and no response was required. The experimenter described the stimuli to the participants with the Spanish word for short
or long in tandem with the presentation. Next, the two standard durations were randomly presented 10 times, and participants had to indicate whether the stimulus presented was short or long by pressing the appropriate response key, using either the right or the left index finger. The association between the response (short or long) and the hand used (right or left) was counterbalanced between participants. Feedback was not given after each response trial but only at the end of the block of 10 trials, as in the test phase.

In the test phase, participants were required to classify a range of durations (short and long, as well as intermediate stimuli) in terms of their similarity to short or long standards. In the auditory modality, the white noise could last for five different durations (150 ms, 220 ms, 290 ms, 360 ms, or 430 ms), and in the visual modality, the red circle could appear on the screen for five different durations (300 ms, 450 ms, 600 ms, 750 ms, or 900 ms). Participants were required to indicate whether the presented stimuli were similar to the short or long standards by pressing the appropriate response key. Feedback was not given at the end of each trial but only at the end of the block. Each session contained two blocks of 50 trials, corresponding to five stimuli (that is, five durations), each delivered 10 times (intertrial interval = 2 s). In each modality, the percentage of “long” responses was computed for each interval duration.

**Reproduction task procedure**

In the reproduction tasks, participants were presented with a stimulus, called the sample stimulus for an interval of time, and then they were required to reproduce the same interval of time of that sample stimulus.

In the visual modality, the sample stimulus (a drawing of an elephant) appeared at the center of the screen and remained there for 1500 ms. After an empty interval of 1 s, the test stimulus (a drawing of a lion) appeared on the screen, and the children were required to press the spacebar to erase the lion when they judged that the lion had remained on the screen as long as the elephant had. The following trial began 2 s after the spacebar press or 4 s after the onset of the test stimulus if the child had not yet pressed the spacebar.

In the auditory modality, the sample stimulus, a 700 Hz tone, was delivered through headphones for 1500 ms. Then, after an empty interval of 1 s, the test stimulus, a 300 Hz tone, was delivered in the same way, and the children were required to press the spacebar to stop the tone when they considered that the test tone had lasted as long as the sample tone. The subsequent trial began 2 s after the spacebar press or 4 s after the onset of the test stimulus if the child had not yet pressed the spacebar.

For each modality, before two blocks of 10 trials each were completed, children completed 4 trials of training to familiarize them with the task. We recorded the duration reproduced by children at the nearest ms.

**Data analysis**

**Bisection tasks**

The classification data obtained in the duration bisection tasks may be quantified as the proportion of long responses the participant made for each signal duration, and these data can be well described by a sigmoidal function. From the psychophysical function, two dependent variables can be estimated for each participant and for each modality: the point of subjective equality (PSE) and the difference limen (DL). There are different ways of calculating the PSE (Wearden & Ferrara, 1995) but they generally yield similar results. Here, we used the linear regression method which is often employed to derive slope and intercept parameters used to calculate the PSE (Casini, Pech-Georgel, & Ziegler, 2018; Droit-Volet, Meck, & Penney, 2007; Droit-Volet & Wearden, 2001; Millot, Laurent, & Casini, 2016; Wearden, 1991). Linear regression was calculated on all points of each individual’s psychometric function. All regressions produced r2 values of at least 0.9.
The PSE is the signal duration at which a participant is equally likely to classify a given signal as short or long. It represents the subjective midpoint between the short and long anchor values that the participant had been presented with during training. A PSE decrease (that is, a leftward shift of the curve) means that participants chose more often to classify a stimulus as long. Conversely, a PSE increase (that is, a rightward shift of the curve) means that participants were biased toward classifying a stimulus as short. Thus, observing each participant’s PSE allows us to observe whether the participant exhibited a bias in temporal judgment toward either a shortening (underestimation) or a lengthening (overestimation) of durations. The DL is a measure of the slope of the participants’ response function when plotted. It is calculated from the regression line and corresponds to half the difference between the duration the participant classifies as long 25% of the time and the duration the participant classifies as long 75% of the time. This can be interpreted as a measure of temporal precision, where steep slopes indicate precise temporal processing, while shallow slopes indicate greater variability in the interval-timing system.

The most interesting feature of these measures is that they allow for subtle differences between groups to be detected, differences that are often missed by other measures. Indeed, DL and PSE may differ between groups, indexing the differences in judgments for very close intermediate durations, whereas no differences are observed for the anchor durations.

Reproduction tasks
The data (duration intervals in ms) obtained in the time reproduction tasks were analyzed using two measures: the relative temporal reproduction (RTR) score and the coefficient of variation (CV). The RTR score corresponds to the difference between temporal reproduction and the target duration divided by the target duration. This score indicates the extent to which the participants reproduced longer intervals than the target interval (overproduction is indicated by positive values) or smaller intervals than the target (underproduction is indicated by negative values). It allows for comparing the temporal reproductions between different duration ranges. The CV corresponds to the ratio of the standard deviation of any trial-produced duration to the mean produced duration for each subject. It is a measure of timing variability that takes into account the duration being timed.

Normality was tested for each variable using the Kolmogorov-Smirnov test. To compare the performance of control and ADHD groups, we used t tests when the distribution was normal and Mann-Whitney tests when the distribution was not normal. Cohen’s d were used to compute the effect size (standardized difference between the two means) for the two group comparisons. A commonly used interpretation is to refer to effect sizes as small ($d = 0.2$), medium ($d = 0.5$), or large ($d = 0.8$) (Cohen, 1988). In the bisection task, analyses were carried out for 41 TD children and 35 children with ADHD in the visual modality, and for 40 TD children and 35 children with ADHD in the auditory modality. Some data were excluded from the analyses because the children obtained percentages close to 50% for long responses whatever the duration presented, preventing the computation of DL and PSE. In the reproduction task, analyses were carried out for the results from 42 TD children and 39 children with ADHD for both the auditory and visual modalities. One child with ADHD was excluded because they did not complete the temporal reproduction tasks.

Results
Demographic and neuropsychological variables
The differences between the demographic characteristics of the TD and ADHD groups were tested using independent-sample t tests. As shown in Table 1, significant differences existed in IQ scores, working-memory, and CPT indices. Children with ADHD exhibited lower IQ scores and working-memory indices when compared to TD children. Concerning the CPT task, they were faster only in the CPT 4 s. Nonetheless, they were more variable and committed more errors than TD children whatever the ISI, which suggests that they had more difficulties in performing the task.
**Bisection tasks**

**Visual modality**

In the visual bisection task, the DL and the PSE differed between groups. As shown in Figure 1, the mean DL was larger for children with ADHD (292 ms) than for TD children (133 ms) ($U = 352; p < .0001; \text{effect size: Cohen’s } d = 0.69$), suggesting that children with ADHD exhibited greater variability in their judgments and had greater difficulty in discriminating between the short and long stimuli compared with TD children. Mean PSE was lower for children with ADHD (589.2 ms) than for TD children (639.6 ms) ($t_{74} = 2.02; p < .04; \text{effect size: Cohen’s } d = 0.46$), indicating that for the

**Table 1.** Demographic and neuropsychological characteristics of TD children and children with ADHD from a Caribbean community.

| Variable                        | TD group (n = 42) | ADHD group (n = 40) | Statistical index | p     |
|---------------------------------|-------------------|---------------------|-------------------|-------|
| **Demographics**                |                   |                     |                   |       |
| Age                             | 10.6 (2)          | 10.5 (2.1)          | 2.21              | 0.896 |
| **Neuropsychological measures** |                   |                     |                   |       |
| Estimated IQ index              | 113.6 (17.3)      | 94.1 (14.3)         | 5.57              | <0.001|
| Working memory index            | 129.8 (16.7)      | 105.6 (14.3)        | 7.02              | <0.001|
| EDAH (centile)                  |                   |                     |                   |       |
| Hyperactivity (H)               | 24.82 (23.1)      | 86.3 (18.6)         | 13.28             | <0.001|
| Attention (A)                   | 21.3 (17.2)       | 84.9 (15.2)         | 17.185            | <0.001|
| Conduct disorder                | 34.35 (25.3)      | 85.30 (23.3)        | 9.5               | <0.001|
| Combined type (H + A)           | 17.50 (18.7)      | 88.17 (17.8)        | 17.65             | <0.001|
| CPT                             |                   |                     |                   |       |
| Hit RT, ISI 1 s                 | 447               | 507                 | 1.36              | 0.17  |
| % commissions, ISI 1 s          | 0.90              | 2.75                | 6.37              | <0.001|
| CV, ISI 1 s                     | 0.18              | 0.25                | 4.85              | <0.001|
| Hit RT, ISI 2 s                 | 496               | 465                 | 1.65              | 0.10  |
| % commissions, ISI 2 s          | 0.83              | 2.6                 | 6.28              | <0.001|
| CV, ISI 2 s                     | 0.20              | 0.25                | 3.69              | <0.001|
| Hit RT, ISI 4 s                 | 506               | 459                 | 2.32              | 0.02  |
| % commissions, ISI 4 s          | 0.52              | 2.37                | 7.5               | <0.001|
| CV, ISI 4 s                     | 0.17              | 0.22                | 3.04              | 0.003 |

ADHD = Attention Deficit Hyperactivity Disorder; TD = Typically developing children; CV = Coefficient of variation; df = degrees of freedom; ISI = Inter-stimulus interval; IQ = Intellectual quotient; RT = mean reaction time in ms.

**Table 1**. Visual temporal bisection task. (A) Mean difference limen (DL in milliseconds) for both groups. (B) Mean PSE (in milliseconds) in both groups. A decrease in PSE means that patients overestimated durations.

**Figure 1.**
intermediate targets, the probability that durations were judged to be long was larger in children with ADHD than in TD children; this means that children with ADHD overestimated intermediate durations.

**Auditory modality**

In the auditory bisection task, the differences between groups were significantly different for DL and PSE as well. Figure 2 shows an increase in mean DL between children with ADHD (127 ms) and TD children (72 ms), \( t_{73} = 3.39; p = .001 \); effect size: Cohen’s \( d = 0.78 \), again suggesting that participants with ADHD were more variable in their judgment of intermediate durations. Mean PSEs were lower for children with ADHD (320 ms) than for TD children (347 ms) \( t_{73} = 2.31; p = .02 \); effect size: Cohen’s \( d = 0.55 \); this means that children with ADHD also overestimated the durations of the intermediate intervals in the auditory modality.

**Comparisons between auditory and visual modalities**

We compared modalities to address two issues. The first one was investigating whether overestimation was of a similar size in both modalities. The second one was determining whether scalarity was observed in children with ADHD. Scalarity is a property of the scalar model that means that variability grows linearly with mean time estimation. Violation of scalarity is a good index for a dysfunction in the internal clock. Indeed, due to the scalar property characteristic of temporal processing, an effect on the pacemaker rate should be multiplicative with the duration values (Burle & Casini, 2001; Penney, Gibbon, & Meck, 2000). Thus, if the pacemaker runs faster, the effect has to be greater for longer than for shorter durations (i.e., proportional to the duration values).

To address these questions, as observed in Table 2, we used two indices computed from temporal variables. First, we compared the size of the overestimation between the modalities by using the PSE-shift size index for each subject in each modality. The PSE-shift size expresses the percentage of overestimation (the size of the PSE shift) in children with ADHD compared to the mean PSE obtained for the TD group. This corresponded to the following ratio: \([(\text{mean PSE of the TD group} – \text{subject PSE})/(\text{mean PSE of the TD group})] \times 100 \). Second, to evaluate scalarity, we used the well-known Weber fraction (WF), which corresponds to the following ratio, \( \text{DL/PSE} \), calculated for each subject; this is a measure of timing variability that considers the duration timed. The durations are

![Figure 2. Auditory temporal bisection task. (A) Mean difference limen (DL in milliseconds) for both groups. (B) Mean PSE (in milliseconds) in both groups. A decrease in PSE means that patients overestimated durations.](image-url)
different in the two modalities and comparing WF between the modalities provided information about scalarity in the ADHD group. Moreover, it is important to note that the comparison of WF in the TD group revealed no difference between modalities (that is, between durations) confirming the scalar property.

The data for the ADHD group revealed no differences between the modalities for the size of the PSE shift and for the CV. The latter results suggest that scalarity also appeared in children with ADHD.

**Time reproduction task**

**Visual modality**
In the visual reproduction task, the mean RTR scores were significantly different between the groups ($t_{79} = 4.58; p < .0001$; effect size: Cohen’s $d = 0.46$). As shown in **Figure 3A**, the mean RTR score was negative for the ADHD group ($-0.045$) and positive for the TD group ($0.015$). This indicates that children with ADHD underproduced time intervals compared with TD children.

Concerning the index of variability, mean CVs were significantly different between the groups ($t_{79} = 5.17; p < .0001$; effect size: Cohen’s $d = 1.14$). As shown in **Figure 3B**, the mean CV for the ADHD group ($0.28$) was larger than for the TD group ($0.18$), indicating that children with ADHD had larger variability in their temporal reproduction.

**Auditory modality**
In the auditory reproduction task, as shown in **Figure 4A**, we found no significant difference between the groups for mean RTR scores (ADHD group: RTR score = $-0.009$; TD group: RTR

![Visual modality](image)

**Figure 3.** Visual temporal reproduction task. (A) Mean RTR score for TD and ADHD groups. (B) Mean CV for TD and ADHD groups.
score = −0.025) (t\(_{79}\) = 0.65; p = .51). However, as indicated in Figure 4B, mean CV was larger for the ADHD group (0.22) than the TD group (0.17) (t\(_{79}\) = 2.55; p < .01; effect size: Cohen’s d = 0.58), indicating that children with ADHD had larger variability in their temporal reproduction.

**Correlation analysis**

For children with ADHD, Pearson correlation coefficients were computed between 1) temporal variability indices (in the two temporal tasks) and indices recorded in the CPT tasks (mean RT, intra-subject variability and commission rate), and 2) temporal indices and WMI. There were not significant linear correlations between temporal indices and WMI. For the CPT task, a linear correlation was only found between the temporal variability in the reproduction task and the commission rate in the CPT ISI 1 s (auditory CV: r = .39, p = .02; visual CV: r = .37, p = .02). The more the children exhibited a large temporal variability, the more they made errors in the CPT task.

**Discussion**

The present study aimed to interpret the temporal deficits of children with ADHD in the cognitive framework of the SET model to better understand temporal deficits and attentional deficits in this population. Based on the literature of psychology of time, we hypothesized that if children with ADHD presented selective attention difficulties, they should have difficulties in focusing attention on temporal intervals, leading to temporal underestimation in the bisection task relative to TD children. Conversely, if children with ADHD presented difficulties in maintaining a stable level of alertness, this should produce variability in the latency of the switch closing, and we should observe an increase in temporal variability in both tasks.

Two main results were observed. First, children with ADHD presented larger variability in the performance of temporal tasks, whether they required interval estimation or interval reproduction and whether they involved the auditory or the visual modality. Second, children with ADHD overestimated durations in both temporal bisection tasks and underproduced duration intervals in the visual reproduction task.
The observed increase in variability was consistent with previous data reported in adults with ADHD using a similar protocol, suggesting that perceptual variability could be a persistent trait in patients with ADHD (Suarez et al., 2013). These results also support several other studies that have reported an increased temporal variability in children with ADHD (Barkley, 1997; Rubia, Smith, & Taylor, 2007; Sonuga-Barke & Castellanos, 2007; Toplak et al., 2006; Toplak & Tannock, 2005).

In the context of the pacemaker-accumulator model, an increase in temporal variability can be explained by an increase in the variability of switch latency. This may be due either to a dysfunction of the switch per se or to a reduction in the alertness level (Droit-Volet, 2003; Witherspoon & Allan, 1985). Indeed, to correctly detect the onset of a visual or auditory stimulus as soon as it appears, the participant must raise their alertness level and retain that higher level until the beginning of the stimulus. If they have difficulty in maintaining a high level of alertness during trials, the variability of the switch latency may increase, and temporal sensitivity may be reduced. Consequently, we could hypothesize that the larger temporal variability in children with ADHD could partly be due to the amount of noise produced by the switch closing of the internal clock resulting from variability in the alertness level. This hypothesis is supported by our correlational data showing that the children who exhibited the lowest performance in the CPT task (in terms of the rate of errors of commission) were the ones who presented the larger temporal variability. This result is also in line with the difficulty that children with ADHD have in maintaining sustained attention (Friedman-Hill et al., 2010; Heaton et al., 2001; Huang-Pollock, Nigg, & Halperrin, 2006; Sattler & Saklofske, 2003).

The second relevant result reported in this study is that children with ADHD overestimated the duration of the stimulus more often than TD children in both the auditory and visual temporal bisection tasks, and they underproduced intervals in the visual temporal reproduction task. Globally, these data suggest that children with ADHD have a biased temporal performance. Overestimations of temporal intervals have been reported in adults with ADHD in a temporal bisection task (Suarez et al., 2013). In the framework of the pacemaker-accumulator model, an overestimation of temporal intervals in the bisection procedure could be explained either by an acceleration of the pacemaker or a deficit in working memory. Indeed, pacemaker acceleration would increase the number of pulses accumulated during a given interval. Thus, subjects with this feature would be expected to overestimate temporal intervals. Nonetheless, it remains difficult to understand why the pacemaker would run faster during the test phase than in the training phase only in children with ADHD. Moreover, scalarity was maintained in children with ADHD, which speaks again of a dysfunction of the pacemaker itself.

An alternative and more plausible hypothesis would be that working memory distortion leads to the overestimation of temporal intervals. In the bisection task, participants compared a value stored in the accumulator during the current trial with values previously stored in the reference memory. Thus, if pulses are systematically lost in the transfer from working memory to the reference memory, the values stored in the reference memory would be distorted and interpreted as short. Consequently, duration in the current trial could be judged as longer than the durations previously stored in the reference memory. It has also been proposed that memory representations of anchor durations are stored as distributions (Droit-Volet & Wearden, 2001; Wearden, 1991). Therefore, memory variability in the short and long durations would also be a kind of sensitivity parameter that controls the slope of psychophysical functions. The less accurate the short and long values stored in memory are, the flatter the slope of the psychophysical function would be, as was found in this study. Therefore, it is possible that children with ADHD construct more variable representations of anchor durations in the visual and auditory modality.

Following this result, the underproduction of temporal intervals by children with ADHD that was observed in the visual reproduction task points to a deficit in memory, specifically visual working memory. Indeed, in the framework of the pacemaker-accumulator clock model, it can be assumed that in temporal reproduction tasks, the duration representation of the sample stimulus stored for each trial in the working memory is compared to the duration representation stored in the accumulator. Where there is dysfunction in the working memory, whatever the cause, it is expected
that the mnesic trace degrades as a pulse loss. Consequently, the reproduced interval would be shorter than the sample interval. This has already been observed in studies in both animals (Meck, 1983; Meck & Church, 1987a, 1987b) and humans, such as in patients suffering from hippocampus lesions (Perbal-Hatif, 2012).

An alternative explanation for temporal underproduction could be that the duration encoded during the sample stimulus presentation could be impaired. If we assume that children with ADHD had difficulty in maintaining their selective attention for the duration of the sample stimulus, then we could expect that the switch would open each time that attention is disrupted from temporal parameters. As a consequence, fewer pulses will be stored in the accumulator and a shorter estimation of the sample stimulus would be encoded, as suggested by studies investigating the effects of dual-tasks on temporal performance (for a review, see Block & Zakay, 1997; Brown, 1997; Burle & Casini, 2001). Therefore, the reproduced duration would be shorter than the sample stimulus duration.

However, this hypothesis is not consistent with data obtained in the temporal bisection task. Indeed, if deficits in temporal performance in ADHD were rooted in a selective attention deficit, each time that children with ADHD stopped attending to time in the bisection task, they should present a bias toward shorter estimates than the TD participants, which did not occur. Therefore, the data coming from these tasks are in favor of the hypothesis that the underproduction observed in the visual temporal reproduction task is due to deficits in visual working memory. Moreover, they argue against a selective attention deficit in children with ADHD as we found it for adults with ADHD (Suarez et al., 2013). This is in line with studies that have also shown preserved selective attention in children with ADHD using a variety of tasks, such as speed classification tasks (Hooks, Milich, & Lorch, 1994), visual cueing tasks (Aman, Roberts, & Pennington, 1998; DeShazo Barry, Klinger, Lyman, Bush, & Hawkins, 2001), visual search tasks (Mason, Humphreys, & Kent, 2003), and visual attention paradigms (McAvinue et al., 2015).

There are at least three limitations to the current study. First, because we chose to include only children with a diagnosis of combined type ADHD, which limits the generalizability of our results, future studies should include different subtypes of ADHD. For example, it would be relevant to compare predominantly hyperactive and predominantly inattentive subtypes. Second, we obtained a difference between groups in their IQ. We think that IQ should not be considered as a covariate in cognitive studies for at least two reasons: 1) IQ measures aptitude and potential, rather than performance and 2) IQ does not fulfill the methodological and statistical requirements of a covariate (for detailed arguments, see Dennis et al., 2009). Nonetheless, in future studies, it would be sensible to match both groups of children in age, gender and IQ. Thirdly, we did not observe underproduction in the auditory temporal reproduction task, which suggests that different and modality specific memory systems are involved in the short-term maintenance of auditory and visual durations, as has already been suggested by several authors (Rattat, 2010; Rattat & Delphine Picard, 2012). However, this hypothesis requires further investigation through the use of different paradigms.

To summarize, this study confirmed the existence of temporal deficits in children with ADHD. In the context of the pacemaker-accumulator model, our results suggest that this temporal deficit might result from an alertness impairment affecting the internal clock (and more specifically the switch component) and/or from memory impairments. Moreover, the fact that children with ADHD more often overestimated stimulus duration in the temporal bisection tasks than TD children suggests that children with ADHD could have the illusion of time stretching. The illusion of time stretching could explain several symptoms expressed in these patients, such as impulsivity, impatience, and difficulty in waiting for things that are desired, expressed as an aversion to delay and a preference for immediate rewards (Sonuga-Barke, Taylor, Sembi, & Smith, 1992). These temporal overestimations also teach us about ADHD deficits. Indeed, the temporal overestimation observed in the bisection task argues against the idea of a selective attention deficit in ADHD. The question of the type of attention affected in ADHD patients merits deeper investigation.
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