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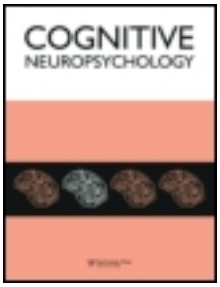

Cognitive Neuropsychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pcgn20

The cognitive structure of time estimation impairments in adults with attention deficit hyperactivity disorder

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Published online: 10 Oct 2013.

To cite this article: Isabel Suarez, Francisco Lopera, David Pineda & Laurence Casini , Cognitive Neuropsychology (2013): The cognitive structure of time estimation impairments in adults with attention deficit hyperactivity disorder, Cognitive Neuropsychology

To link to this article: http://dx.doi.org/10.1080/02643294.2013.842548

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Cognitive Neuropsychology, 2013
http://dx.doi.org/10.1080/02643294.2013.842548

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The cognitive structure of time estimation impairments in adults with attention deficit hyperactivity disorder

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We compared the performance of 15 adults with attention deficit hyperactivity disorder (ADHD) and a group of 16 control adults on a temporal bisection task in auditory and visual modalities. The point of subjective equality (PSE) and the difference limen (DL) were computed to analyse performance. The main findings were that (a) individuals with ADHD overestimated the duration of both the auditory and visual stimuli in comparison to the control group, as evidenced by a shift in their mean PSE; (b) individuals with ADHD also showed less precision in their estimates than did the control group as evidenced by flatter psychometric functions; and (c) the degrees of overestimation and imprecision in subjects with ADHD were comparable across modalities. These results, discussed in the framework of the pacemaker–counter clock model of time estimation, suggest that temporal difficulties encountered by ADHD patients might be explained both by an alertness effect at the level of the switch that directs pulses into the accumulator and also by distortions of durations stored in reference memory.

Keywords: Attention deficit hyperactivity disorder adults; Attention; Pacemaker–counter clock; Temporal bisection task.

Attention deficit hyperactivity disorder (ADHD) is the most commonly diagnosed behavioural disorder afflicting children. It corresponds to symptoms of inattention, hyperactivity, and impulsivity (APA, 2000). The persistence of the disorder into adulthood has been estimated at about 70% (Spencer, Biederman, & Mick, 2007), leading to substantial health and economic difficulties as a consequence of poor social, behavioural, and academic outcomes (Currie & Stabile, 2004).

A common characteristic of adults with ADHD is that sufferers often have difficulty with "time management" (Barkley, 1997). This trait has mainly been interpreted as the result of the inability to anticipate and predict events, both of which are considered to require an accurate perception of time intervals. Estimating time intervals

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The authors warmly thank Sarah Winlow for proofreading this text.
This work was funded by the CNRS and Aix-Marseille Université and also received the support of the programme Sostenibilidad 2009–2010 del Codi and of the Universidad de Antioquia.

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in a range from seconds to minutes is an important adaptive skill for making predictions about one's environment (Meck, 2005), such as crossing streets (Zakay & Block, 1997) and making valid decisions (Wittmann & Paulus, 2008). For individuals with ADHD, deficits in interval timing might underlie several problems. For example, impulsivity can be seen as a temporally inadequate behaviour yielding responses that are made too early, which could underlie several problems, such as deficits in waiting behaviour (Barkley, 1997), delaying responses (Sonuga-Barke, Saxton, & Hall, 1992), and delaying gratification (Douglas & Parry, 1983; Gorenstein & Newman, 1980). Individuals suffering from ADHD also have difficulty in representing past events in the correct temporal order, which could lead them to experience long frustrating time frames (Barkley, Murphy, & Bush, 2001; McInerney & Kerns, 2003).

Temporal processing has been studied mostly in children with ADHD (for review, see Toplak, Dockstader, & Tannock, 2006), and several studies report deficits in temporal reproduction and temporal production tasks, but only a few studies have investigated temporal performance in adults with ADHD. Among them, Barkley et al. (2001) extended findings on time perception in children with ADHD to adults by showing that those with ADHD made shorter reproductions and greater reproduction errors than a control group. More recently, some studies have reported difficulties in time estimation by using different tasks, such as verbal estimation (Pollak, Kroyzer, Yakir, & Friedler, 2009) and paced finger tapping (Valera et al., 2010).

Current theoretical models of ADHD provide different accounts of time perception deficits in interval timing (Toplak et al., 2006). One explanation for this finding is based on Barkley's theory (Barkley, 1997), which states that impaired working memory in ADHD results in deficient time evaluation. In time-reproduction tasks, participants must hold the target duration in memory in order to reproduce it. Therefore, the load on one's working memory is particularly critical in this task. An alternative proposed explanation of the difficulty in time-reproduction tasks is that children with ADHD cut short the task to avoid experiencing the temporal time frames that they dislike. This "delay aversion" that characterizes ADHD is expressed in underestimations that children with ADHD produce in the reproduction task (Sonuga-Barke, Taylor, Sembi, & Smith, 1992). This is congruent with the data of Smith and colleagues (Smith, Taylor, Warner-Rogers, Newman, & Rubia, 2002), who reported that children with ADHD significantly underestimated time by prematurely responding in a 12-s rather than a 5-s time-reproduction task.

Functional models of time estimation could also aid the understanding of temporal deficits observed in individuals with ADHD. The prevalent view in cognitive theories of psychological time is that we time intervals using an internal clock consisting of three components: (a) a clock stage, composed of a pacemaker–counter device, (b) a memory stage, and (c) a decision-comparison stage. An interval is specified by the accumulation of pulses emitted at a regular rate by a pacemaker. The more pulses that are accumulated, the longer the subjective estimation of duration. The influence of different factors on this internal clock has been extensively studied. One of the most documented effects is that subjective duration depends on attention allocated to time (Brown, 1997; Casini & Macar, 1997; Hicks, Miller, Gaes, & Bierman, 1977; Hicks, Miller, & Kinsbourne, 1976; Macar, Grondin, & Casini, 1994; McClain, 1983). It has been shown that, first, the more attentional resources are diverted from the temporal parameters, the worse the temporal performance, and, second, this decrease in temporal performance is due to a systematic shortening of subjective duration. This has been explained by the proposal that during periods when attention is not allocated to time, pulses are lost, reducing the number of pulses accumulated, yielding shorter estimated durations (Brown, 1997; Burle & Casini, 2001; Casini & Macar, 1997; Zakay, 1989). Therefore, symptomatic inattention in ADHD could also cause their difficulties with time estimation. If this is explained on the basis of inattention, then each

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time ADHD patients stop attending to time, some pulses would be lost; therefore ADHD patients should present a bias towards shorter estimates compared to control subjects. However, it is also possible that temporal difficulties could be due purely to temporal processing (clock stage) or to deficits at the memory or decision stages.

To better understand the cause of temporal difficulties related to ADHD, we compared the performance of adults with ADHD and of controls on a temporal bisection task. Participants were initially trained to discriminate between a short and long duration signal—the anchor durations. In the subsequent test phase, they classified probe signals as short or long, relative to the anchor durations experienced in training. Some of these probe signals were the same as the anchor durations, but most were of intermediate duration. This task has the advantage of providing two distinct measures of performance: the difference limen (DL), which can be interpreted as a measure of participants' temporal precision, and the point of subjective equality (PSE), which determines whether or not participants presented a shift in their temporal judgements with either an underestimation or an overestimation of durations. These two indices have been classically used to examine effects of attention, memory, and pacemaker changes in interval timing.

Finally, Toplak and Tannock (2005) reported greater differences between groups in the visual than in the auditory modality, suggesting a possible influence of the modality. Subjects were therefore tested using both the visual and auditory modalities.

METHOD

Participants

We tested two groups of subjects, recruited through the Science Investigation Center of the University of Antioquia (Colombia): 15 ADHD adults (age 18–29 years, mean = 22.13, 14 males) and 16 healthy adults (age 19–25 years, mean = 21.68, 11 males). All participants gave informed consent to the experimental procedure, following the Helsinki Declaration (1964). The study was approved by the Ethical Committee of the Investigation Center of the University of Antioquia (Colombia).

Selection procedure for the ADHD group

Adults in the ADHD group were recruited from the clinical database of the Neurosciences Clinic of the University of Antioquia (Colombia). All participants in the present study were selected among patients who had been diagnosed with ADHD as children, who continue to be observed by the psychiatrists of the clinic, and for whom the diagnosis was again confirmed in their young adulthood by two psychiatrists of the clinic in the last two years.

Clinical diagnoses and definitions of ADHD (i.e., affected or nonaffected, as defined by the *Diagnostic and Statistical Manual of Mental Disorders–Fourth Edition, Text Revision, DSM–IV–TR*; American Psychiatric Association, 2000) used in this clinic have been extensively described in detail elsewhere (Palacio et al., 2004) and are only briefly described here. For diagnoses in children, structured diagnostic interviews were conducted in the Neurosciences Clinic by a team of professionals supervised by an expert psychiatrist who reviewed all interviews and conducted confirmatory clinical interviews with all participants. Parents underwent a full psychiatric structured interview regarding their offspring [Diagnostic Interview for Children and Adolescents–Revised Parents Version (DICA–IV–P) Spanish version translated with permission from W. Reich (Reich, 2000)]. Parents and teachers of school-age children also provided behaviour rating scales. Final diagnoses were reached by consensus on the basis of the results of structured interviews, collateral historical information, and clinical interviews for each family lineage member through the best estimate procedure (Reich, 2000) by a committee of four bilingual clinicians, all of whom have extensive experience with ADHD. Definitely affected subjects had met full DSM–IV ADHD criteria during childhood, with onset before age 7 years, and with persistence of clearly

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impairing symptoms in more than one setting. In cases of discordance between an individual's self-report of symptoms and collateral reports, the supervising psychiatrist obtained further collateral information and probed more deeply for evidence of early impairment. For confirmation in young adulthood, patients were given a structured interview for current functioning and evaluating symptoms of ADHD described in DSM–IV by two different psychiatrists.

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 adults who had been diagnosed with the combined ADHD type in childhood and with diagnosis confirmed in young adulthood were contacted and solicited for their participation.

It is important to note that all participants selected for this study had been under medication (methylphenidate) at different periods of their life but had not taken medication in the six months prior to the experiment.

Criteria for the control group

The control group was composed of adults without ADHD recruited at the University of Antioquia. Inclusion criteria were a lack of history of diagnosis of ADHD on the basis of a retrospective assessment of ADHD by self-completion of a 61-item Spanish version of the Wender Utah Rating Scale (WURS; Rodriguez-Jimenez et al., 2001) and failure to meet the cut-off point.

Exclusion criteria for both groups

Exclusion criteria included (a) a diagnosis of additional psychiatric (major depression, panic disorder, suicide risk, anxiety, substance abuse, psychoactive substance use, psychotic disorders) or neurological disorder on the basis of a Spanish version of the structured psychiatric interview mini mental test (MINI, Sheehan et al., 1998), (b) current or recent drug abuse (less than 6 months), and (c) an intelligence quotient (IQ) of less than 80, evaluated with the short form of the Wechsler Adult Intelligence Scale–Third Edition (WAIS–III, Wechsler, 1997), including four subtests: Similarities and Vocabulary tests to estimate verbal IQ, and Picture Completion and Block Design tests to estimate performance IQ.

In addition to IQ measures, the working memory index was assessed, for both groups, using three items of the WAIS–III (Arithmetic, Digit Span, and Letter–Number sequencing).

Procedure

The experiment consisted of two different experimental sessions, each corresponding to one 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 the other half in the opposite order). Each session lasted about 15 minutes and with a break of 10 minutes between sessions.

Participants were comfortably seated in a dimly lit, soundproof room. Two response keys were available. In the auditory modality, white noise was delivered through headphones, and, in the visual modality, a red full-circle appeared on a video screen. Participants had to judge the duration of the stimulus. The experiment was controlled by a computer running T-scope (Stevens, Lammertyn, Verbruggen, & Vandierendonk, 2006).

For each modality, before the test phase, participants undertook training. In the training phase, only the anchor durations were used (auditory modality: 150 and 430 ms; visual modality: 300 and 900 ms). Different duration ranges were used in each modality, because their respective temporal thresholds are known to be different (Lhamond & Goldstone, 1974). The training phase consisted of two parts. First, participants were presented with the two standard durations, each presented four times in alternation. Participants were instructed just to observe the stimuli, with no response required. The stimuli were described for the participants by the experimenter, who indicated in Spanish whether a stimulus was "short" or "long" in tandem with its presentation. Next, the two anchor durations were randomly presented 10 times, and subjects indicated

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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 but only at the end of the block of 10 trials, as in the test phase. Feedback after each response was not necessary because the anchor durations were easily distinguished.

The mean percentages of correct responses were as follows: ADHD visual: 94.3% ± 7.6; ADHD auditory: 94.6% ± 6.6; control visual: 92.77% ± 9.6; and control auditory: 94% ± 10.5. There were no significant differences between groups in either of the concerned modalities [auditory: $t(29) = 0.49$; visual: $t(29) = 1.41$].

In the test phase, in the auditory modality, white noise could be of five different durations (150 ms, 220 ms, 290 ms, 360 ms, 430 ms), and, in the visual modality, the red circle appeared on the video screen for five different durations (300 ms, 450 ms, 600 ms, 750 ms, 900 ms). Participants were required to indicate whether the presented stimuli were short or long by pressing the appropriate response key. Feedback was not given.

Each session contained two blocks of 50 trials corresponding to five stimuli (= 5 durations), each delivered 10 times (intertrial interval = 2 s).

RESULTS

Demographic and neuropsychological variables

Differences between demographic characteristics of control and ADHD groups were tested using independent-sample t tests. As shown in Table 1, no significant differences existed in age, IQ scores, or working memory index. As expected, WURS scores were significantly different.

Results for temporal tasks

The classification data obtained in the duration bisection procedure may be quantified as the proportion of long responses the participant made at each signal duration for each modality and can be well described by a sigmoidal function. Sigmoidal functions were fitted to the response functions of each participant for each modality. This function allowed us to estimate the two dependent variables: the point of subjective equality (PSE) and the difference limen (DL). The PSE is the signal duration at which a participant is equally likely to classify the signal as short or long. It represents the subjective midpoint between the short and long anchor values that the participant learned in training. An increase in the PSE (a rightward shift of the curve) means that participants chose more often to respond "short"; inversely, a decrease in the PSE (a leftward shift of the curve) means that participants were biased towards selecting to respond "long". The PSE, reflecting a shift of the curve, therefore allows us to observe whether the participants presented a *bias* in their temporal judgements towards either an underestimation or an overestimation of durations. The DL is a measure of the "slope" of the participants' response function when plotted. It is calculated by subtracting the duration that the participant classifies as long 25% of the time from the duration that the participant classifies as long 75% of the time and dividing by two. It can be interpreted as a measure of participants' temporal precision because steep slopes are indicative of precise temporal processing whereas shallow slopes indicate greater variability in the interval-timing system. Both indices were calculated using a linear regression method.

The most interesting feature of these measures is that they allow for the detection of subtle differences between groups, differences that are missed by other measures. Indeed, DL and PSE can be different between groups indexing differences of judgements for the very close intermediate durations whereas no differences are observed for the anchor durations (see results observed in the training phase).

One ADHD patient was excluded because he anticipated more than 50% of responses in both modalities. In addition, in the auditory modality, one control subject and one ADHD patient

Table 1. *Demographic and neuropsychological variables for both groups*

Characteristic	ADHD ($N = 15$) Mean ± *SD*	Control ($N = 16$) Mean ± *SD*	*t*-value	*p*-value
Age (years)	21.6 ± 4	22.2 ± 1.6	0.55	.6
IQ	102.9 ± 10.6	100.9 ± 10.1	0.53	.59
WMI	90.5 ± 8.7	95.8 ± 12.8	1.39	.17
WURS	55.3 ± 10.9	18.7 ± 9.5	9.92	.0001

Note: ADHD = attention-deficit/hyperactivity disorder; IQ = intellectual quotient; WMI = Working Memory Index; WURS = Wender Utah Rating Scale.

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obtained percentages close to 50% of "short" responses, whatever the duration presented, preventing estimation of DL and PSE. Analyses were carried out on 15 control subjects and 13 ADHD subjects for the auditory modality, and on 16 control subjects and 14 ADHD subjects for the visual modality.

We first report comparisons between groups (using independent-sample *t* tests) in each modality, then a comparison of effect size between modalities (using paired-sample *t* tests).

Auditory modality

As illustrated by Figure 1, the two groups differed significantly for both the DL and for the PSE. Mean DL was larger for ADHD patients than for control subjects, $t(26) = 1.72$, $p < .05$, suggesting that ADHD patients were more variable in their judgements and had more difficulty in discriminating between the short and long stimuli. The mean PSE was less for the ADHD group than for the control group, $t(26) = 1.91$, $p < .05$. This indicates that for the intermediate targets, durations were judged as short more often by control subjects and were identified as long more often by the ADHD patients, who overestimated intermediate durations.

Visual modality

In this modality, the differences between groups were also significant for the DL and the PSE. Figure 2 shows (a) an increase in mean DL for

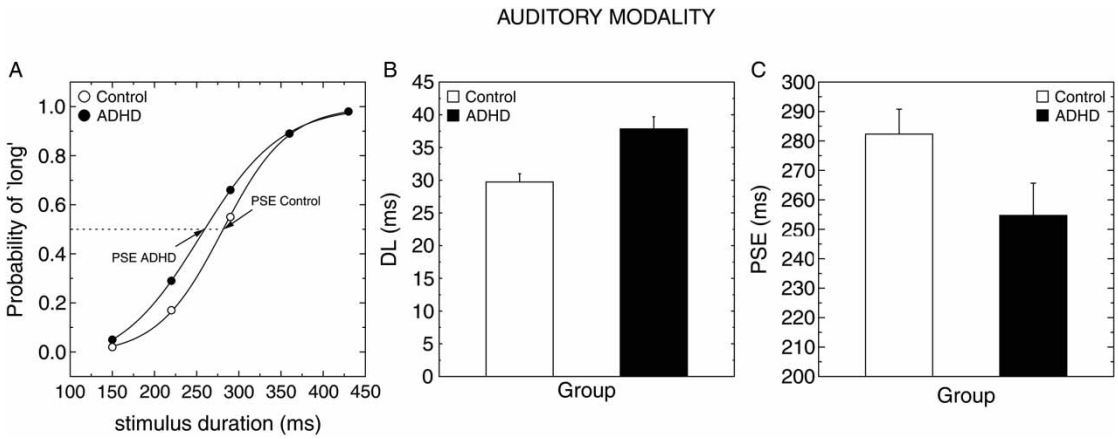

Figure 1. *Auditory temporal bisection task. (A): Mean probability of "long" responses as a function of the stimulus duration for control and attention deficit hyperactivity disorder (ADHD) groups. A logistic function is fitted to the average performance of the participants performing the bisection temporal task. Point of subjective equality (PSE) is indicated for control and ADHD groups. (B): Mean difference limen (DL in ms) for both groups. (C): Mean PSE (in ms) in both groups. A decrease in PSE means that patients overestimated durations.*

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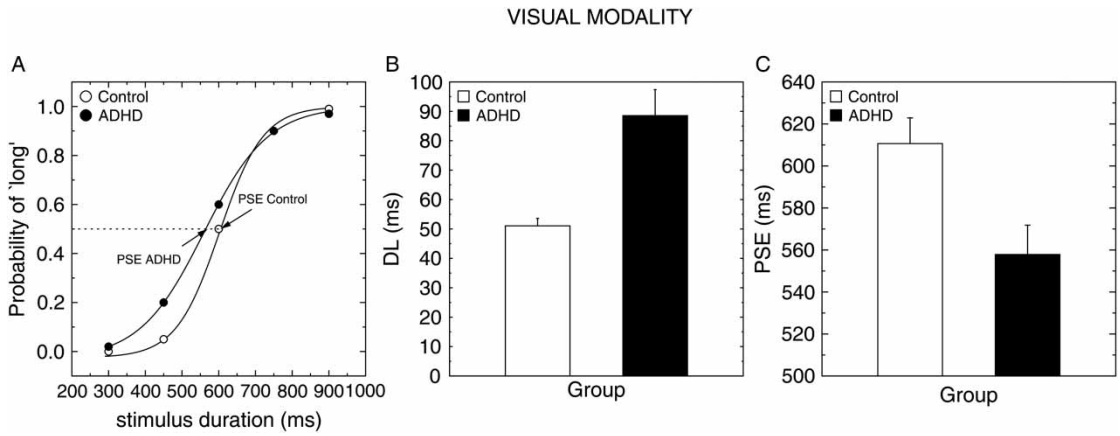

Figure 2. *Visual temporal bisection task. (A): Mean probability of "long" responses as a function of the stimulus duration for control and attention deficit hyperactivity disorder (ADHD) groups. A logistic function is fitted to the average performance of the participants performing the bisection temporal task. Point of subjective equality (PSE) is indicated for control and ADHD groups. (B): Mean difference limen (DL in ms) for both groups. (C): Mean PSE (in ms) in both groups. A decrease in PSE means that patients overestimated durations.*

ADHD patients compared to control subjects, $t(28) = 3.1$, $p < .001$, again suggesting that patients with ADHD were more variable in their judgement for intermediate durations, and (b) that mean PSE was less for the ADHD group in comparison to the control group, $t(28) = 2.3$, $p < .01$, demonstrating that ADHD patients also overestimated durations of intermediate intervals in the visual modality.

Comparisons between auditory and visual modalities

To compare effect size observed in auditory and visual modalities in subjects with ADHD, we calculated one index called size-PSE for each subject in each modality. Size-PSE expresses the percentage of overestimation (the size of the PSE shift) in subjects with ADHD compared to the mean PSE obtained in the control group; it corresponds to the following ratio: [(mean PSE of control group − subject PSE)/(mean PSE of control group)] × 100. To compare the variability between modalities, we used the Weber fraction (WF), which corresponds to the following ratio calculated for each subject: DL/PSE. It is a measure of timing variability that takes into account the duration being timed.

Table 2 presents these measures for both modalities. We observe that patients with ADHD overestimated durations to the same degree in both modalities (no difference on size-PSE) and that the variability adjusted to PSE was similar in both the visual and auditory modalities (no difference on WF).

In addition, we investigated whether temporal overestimations were correlated to working

Table 2. *Weber fractions and effect size of overestimation in each modality and results of statistical analyses comparing effect size between modalities*

Index	*Auditory modality mean* ± SD	*Visual modality mean* ± SD	t-*value*	p-*value*
WF	0.16 ± 0.09	0.16 ± 0.08	0.79	.44
size-PSE (%)	9.7 ± 15.1	8.6 ± 10.7	1.02	.33

Note: WF = Weber fraction; PSE = point of subjective equality; size-PSE = effect size of overestimation. Statistical analyses: paired *t*-tests.

memory index and/or WURS scores. For working memory index, no correlation was found in either of the concerned modalities (auditory modality: $r = -.03$; visual modality: $r = .34$); however, significant correlations were found between size-PSE and WURS scores in both modalities (auditory modality: $r = .58$, $p < .05$; visual modality: $r = .61$, $p < .05$).

DISCUSSION

This study provides further evidence that ADHD is associated with a deficit in temporal processing, even in the case of adults. Not only did adults with ADHD present larger perceptual variability, which suggests that they had more difficulty in performing the temporal bisection task, but these patients also overestimated duration intervals compared to control subjects. In addition, as similar deficits were obtained in both modalities tested, temporal deficit does not appear to be impacted by modality type.

In the duration bisection procedure, increased variability is revealed by a shallower slope of the psychophysical function, which is frequently interpreted as attentional in origin in the framework of the pacemaker–counter clock model. Different studies have shown that an increase in the variability of switch latency may be due to reduced attention (Allan, 1992; Droit-Volet, 2003; Whiterspoon & Allan, 1985) and, more specifically, to the function of attention known as alertness (Posner & Petersen, 1990). To detect the visual or the auditory stimulus as soon as it occurs, subjects have to increase their alertness and stay alert until the stimulus starts. If subjects have difficulties in maintaining a high level of alertness during trials, the variability of switch latency may increase, thus reducing temporal sensitivity. Consequently, we may assume that the lower sensitivity to duration in the bisection task found in individuals with ADHD might be in part due to the amount of noise produced by the switch closing of the internal clock.

Maintaining a high level of alertness is one function of attention considered as different from the capacity to maintain attention selectively on a stimulus, as is the case, for example, when attention is focused on an auditory or visual stimulus during the whole duration of the trial. The role of focused attention has also been pointed out in temporal judgements. It has been proposed that attention may determine the quality of pulse accumulation. Under full attention, the switch is supposed to close and to remain closed for the entire duration of the stimulus, whereas when less attention is being paid, the switch may oscillate or flicker between closed and opened states, which would lead to fewer pulses being accumulated and thus durations to be judged as shorter, as is the case when a temporal task is performed concurrently with an attention-consuming secondary task (Brown, 1997; Burle & Casini, 2001; Casini & Macar, 1997). In the present study, durations were estimated as longer by adults with ADHD than by control subjects—a result that therefore cannot be explained by a deficit of focused attention. These results can be related to those found by Pollak et al. (2009) who reported that the presence of a distractor did not impact time evaluation in adults with ADHD, contrary to the observations of Barkley and colleagues in children (Barkley, Koplowitz, Anderson, & McMurray, 1997). It is possible that adults with ADHD compensate for their attention deficit. Prox, Dietrich, Zhang, Emrich, and Ohlmeier (2007) have studied event-related potentials reflecting attentional processing in adults with ADHD. Their data suggest that adults with ADHD learn to gather their attention more strongly than healthy adults in order to achieve the same results and compensate for their impairment.

Alternatively, in the framework of the pacemaker–counter model, time overestimation may be explained by an acceleration of the pacemaker rate. If the clock runs faster, more pulses are accumulated, and temporal intervals seem longer, explaining the leftward shift observed in the PSE. Moreover, we observed that scalarity was respected between auditory and visual modality (with no difference between WF), for which we used two different duration ranges, which means

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that the effect was multiplicative with the duration values. This is congruent with an effect on the pacemaker rate (Burle & Casini, 2001; Penney, Gibbon, & Meck, 2000). Indeed, if the pacemaker runs faster, the effect has to be greater for longer than for shorter durations (i.e., proportional to the duration values). These data might support the hypothesis that a faster pacemaker rate could be at the origin of overestimations, but a faster than normal clock speed results in a shift in an estimate of duration only when the experience of time on the test trial is measured with a faster clock than that used to measure the reference duration during the training phase (Meck, 1996). For example, in the bisection-procedure task, if the reference durations are measured with a relatively slower clock speed during a training session, and on the test trials a faster clock is used, then more pulses would be accumulated during the same test duration, and the signal would seem longer than it really is, leading to overestimation. Hence the findings for patients with ADHD should be explained by differential clock speeds during the training session, and the test phase may be due to different motivational states. However, if the fast clock speed is used both when the reference duration is encoded and when the comparison duration is experienced, which seems a more prudent and likely explanation, then signal classifications are accurate, and neither under- nor overestimations are observed.

An alternative possibility is that the overestimations are a consequence of systematic memory distortions. In the bisection task, it is assumed that in each trial the subject compares a value stored in the accumulator during the current trial with values previously stored in reference memory and associated with the two anchor durations presented during the learning phase. If the transfer to reference memory is defective and systematically results in a loss of pulses, values stored in reference memory would be distorted short. As a consequence, durations presented in the current trial would be judged as longer than those that were actually presented. Moreover, some authors have proposed that memory representations of anchor durations are stored as distributions; therefore sampling from their distributions produces trial-by-trial variance (Droit-Volet & Wearden, 2001; Wearden, 1991). In this case, the variability of memory of the short and long standards would be a kind of sensitivity parameter controlling the slope of psychophysical functions: The fuzzier the memory of the short and long standards, the flatter the slope of the psychophysical function, which is the case in the present study. Therefore, it is possible that patients with ADHD constructed more variable representations of anchor durations in visual as in auditory modality.

Studies with functional neuroimaging techniques performed with ADHD children suggest dysfunction of the ventral and dorsolateral prefrontal cortex, the anterior cingulate, and neostriatum (Bush et al., 1999; Castellanos et al., 1996; Durston et al., 2003; Rubia et al., 1999, 2000). In addition, it has been reported that methylphenidate, which is highly effective in the treatment of ADHD and which exerts its effects via dopaminergic pathways, was able to normalize striatal circuitry function and could improve frontal activation in children and adolescents with ADHD (Shafritz, Marchione, Gore, Shaywitz, & Shaywitz, 2004; Vaidya et al., 1998). Similar to findings in childhood ADHD, it has been shown that prefrontal cortex, anterior cingulate cortex, and basal ganglia are also involved in adult ADHD (Ernst et al., 2003; Zametkin et al., 1990). Schneider et al. (2010) reported a functional magnetic resonance imaging (fMRI) study in which brain activation was investigated with a continuous performance test (CPT). They found not only impaired activation of frontostriatal and parietal attentional networks but also correlations between symptom severity and dysfunction of neuronal systems across adult subjects with a history of ADHD in childhood. Therefore timing dysfunctions observed in patients with ADHD may be due to disruption of frontal lobe structures known to be involved in memory.

This hypothesis of memory distortion also receives some support from work by Malapani and colleagues who demonstrated dysfunctional representation of memory for time by manipulating dopamine levels in patients with Parkinson

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disease (Malapani et al., 1998). Perhaps deficits in dopamine balance in patients with ADHD could also lead to temporal memory dysfunction.

A growing body of evidence in the literature of psychology of time, coming from functional neuroimaging studies as well as patient or animal studies, supports the idea that the basal ganglia, the cerebellum, the supplementary motor areas, and the prefrontal cortex would be the neural substrates of timing (for a review, see Coull, Cheng, & Meck, 2011). Basal ganglia, like the cerebellum, have already been proposed as playing a key role as a pacemaker or "internal clock" (Ivry & Spencer, 2004; Meck & Benson, 2002). Since all of these structures have been shown to be dysfunctional in adolescents and adults with ADHD (Noreika, Falter, & Rubia, 2013; Rubia et al., 2000, 2001; Teicher et al., 2000), one hypothesis among others could be that dysfunction of these brain regions might explain poor performance in timing. In this line, by using fMRI to study neural substrates of impaired sensorimotor timing in adults with ADHD, Valera et al. (2010) suggested that subsecond timing abnormalities would result from atypical activation of corticocerebellar and corticostriatal timing systems. Moreover, there are several studies showing that the treatment of ADHD with dopamine agonists, such as methylphenidate, both attenuates most timing deficits and restores the functioning of underlying fronto-striato-cerebellar networks (for review, see Noreika et al., 2013).

To conclude, this study confirms temporal deficits in adults with ADHD, and in the framework of the pacemaker model, the data suggest that the temporal deficit might result from an alertness impairment affecting the level of the switch that allows pacemaker pulses into an accumulator or from impairment of memory. It is interesting to note that time seems to be perceived as longer in patients with ADHD, which could lead to the illusion of time stretching. The illusion of time stretching might explain several behavioural characteristics expressed in ADHD. Some symptoms of impulsivity, such as impatience and difficulty in waiting for things that are desired, expressed as an aversion to delay and a preference for immediate reward (Sonuga-Barke, Saxton, & Hall, 1998; Sonuga-Barke et al., 1992), could result from this feeling of elongated time. This could also explain why individuals with ADHD quickly become bored with a task, unless they are doing something enjoyable, which should disrupt their attention from temporal aspects and so shorten passing time. In the same manner, some symptoms of hyperactivity such as constantly being in motion or difficulty doing quiet tasks or activities could also be due to the feeling that a long time period has already elapsed.

This study, however, contains at least two limitations. First, the generalization of our findings may be questionable, because our sample of participants only included combined-type ADHD. It would be interesting to investigate bisection temporal performance in different subtype ADHD patients, for example in predominantly inattentive subtype ADHD patients. Second, in this study, we used subsecond durations. A distinction is often made between the processing of durations of more or less than one second. Some authors propose that time estimation of suprasecond durations would be cognitively mediated, whereas measurement of subsecond durations is supposed to be of a highly perceptual nature and not accessible to cognitive control (Karmarkar & Buonomano, 2007; Michon, 1985; Rammsayer & Lima, 1991). Future studies using suprasecond durations are warranted. And finally, further different temporal tasks need to be carried out in order to confirm and generalize our results.

Manuscript received 30 October 2012
Revised manuscript received 22 July 2013
Revised manuscript accepted 4 September 2013
First published online 10 October 2013

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