Emotional distraction in boys with ADHD: Neural and behavioral correlates

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ABSTRACT

Although, in everyday life, patients with attention deficit hyperactivity disorder (ADHD) are frequently distracted by goal-irrelevant affective stimuli, little is known about the neural and behavioral substrates underlying this emotional distractibility. Because some of the most important brain responses associated with the sudden onset of an emotional distracter are characterized by their early latency onset and short duration, we addressed this issue by using a temporally agile neural signal capable of detecting and distinguishing them. Specifically, scalp event-related potentials (ERPs) were recorded while 20 boys with ADHD combined type and 20 healthy comparison subjects performed a digit categorization task during the presentation of three types of irrelevant, distracting stimuli: arousing negative (A−/C0), neutral (N) and arousing positive (A+). Behavioral data showed that emotional distracters (both A− and A+) were associated with longer reaction times than neutral ones in the ADHD group, whereas no differences were found in the control group. ERP data revealed that, compared with control subjects, boys with ADHD showed larger anterior N2 amplitudes for emotional than for neutral distracters. Furthermore, regression analyses between ERP data and subjects’ emotional ratings of distracting stimuli showed that only in the ADHD group, emotional arousal (ranging from calming to arousing) was associated with anterior N2: its amplitude increased as the arousal content of the visual distracter increased. These results suggest that boys with ADHD are more vulnerable to the distracting effects of irrelevant emotional stimuli than control subjects. The present study provides first data on the neural substrates underlying emotional distractibility in ADHD.

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1. Introduction

The ability to remain goal oriented in the face of irrelevant distracting stimuli is crucial for successful adaptive functioning. This ability is thought to depend on two closely interrelated and mutually dependent attentional mechanisms (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002). On the one hand, voluntary top-down processes are triggered and developed by knowledge, expectation and current goals (e.g., read a book for an exam). On the other hand, involuntary bottom-up processes are driven by stimulus features such as novelty or significance (e.g., a wasp that appears suddenly while reading the book). Interestingly, emotional stimuli, salient and signal events by definition, have been shown to be prominent distracters that can efficiently capture attention in a bottom-up fashion, thereby disrupting the focus on goal-relevant information (Carretié, Hinojosa, Martin-Loeches, Mercado, & Tapia, 2004; Carretié, Hinojosa, Mercado, & Tapia, 2005; Vuilleumier & Schwartz, 2001; Öhman, Flykt, & Esteves, 2001).

An increased susceptibility to distraction is currently one of the behavioral diagnostic criteria of attention-deficit/hyperactivity disorder (ADHD; American Psychiatric Association, 2000). Indeed, the presence of heightened levels of distraction in ADHD is believed to be associated with broad impairment across multiple domains, including cognitive functioning (e.g., disrupting the ability to maintain information in working memory: Higginbotham & Bartling, 1993; Marx et al., 2011), interpersonal relationships (e.g., making difficult to follow the sequence of rules in social activities: Maedgen & Carlson, 2000), academic or work performance (e.g., making careless mistakes in school or job activities: Shifrin, Procotor, & Prevatt, 2010), and health (e.g., increasing distraction-related accidents and associated injuries: Barkley & Cox, 2007). However, experimental evidence of enhanced distractibility in ADHD is equivocal. Whereas some behavioral and electrophysiological data suggest that individuals with ADHD are more distractible than healthy comparison subjects (Gumenyuk et al., 2005; Mason, Humphreys, & Kent, 2005; Radosh & Gittelman, 1981; Rosenthal...
& Allen, 1980), others have reported that patients with this disorder are not affected by irrelevant distracting stimuli to a greater extent than controls (Booth et al., 2005; Huang-Pollock, Nigg, & Carr, 2005; Jonkman et al., 2000; Meere & Sergeant, 1988). A recent study has even shown that, in certain circumstances, the presence of auditory distracters could improve the performance of children with ADHD (van Mourik, Oosterlaan, Heslenfeld, Konig, & Sergeant, 2007). In any case, it should be mentioned that research on this topic is scarce, particularly in comparison with the large body of data on the neural mechanisms underlying the reduced top-down inhibitory control in ADHD (Albrecht et al., 2008; Dimoska, Johnston, Barry, & Clarke, 2003; Liotti, Pliszka, Perez, Kothmann, & Woldorf, 2005; Pliszka, Liotti, & Woldorf, 2000; Rubia et al., 1999), which has been traditionally proposed as the core deficit of this disorder (Barkley, 1997). However, growing evidence indicates that this deficit in inhibitory control is not present among all patients with ADHD and, in some cases, is preceded and caused by other processing deficits (Banaschewski et al., 2004; Brandeis et al., 1998; McLoughlin et al., 2010; Willcutt, Doyle, Nigg, Faraoone, & Pennigton, 2005). This evidence has led to question whether inhibition is the central deficit in ADHD and to look for the involvement of other psychopathological processes, including bottom-up and affective mechanisms (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Nigg & Casey, 2005; Sergeant, 2005; Sonuga-Barke, 2002).

It should be also noted that previous studies on attentional deficits in ADHD have relied heavily on emotionally neutral visual distracters, such as letters, numbers and geometric shapes (Booth et al., 2005; Huang-Pollock et al., 2005; Jonkman et al., 2000; Mason et al., 2005). In real social situations, however, maintaining goal-directed attention in the face of salient affective distracters is often needed. Convergent evidence from hemodynamic and electrophysiological studies suggests enhanced neural responses to emotional stimuli relative to neutral ones, even when these stimuli are not consciously perceived (Carretié et al., 2005; Vuilleumier & Schwartz, 2001; Whalen et al., 1998). For example, a number of investigations have reported amplified responses to emotional visual events, involving structures such as the amygdala and the extrastriate visual cortex as well as early and late electrophysiological responses such as N2 and P3 (see reviews by Olofsson, Nordin, Sequeira, & Polich, 2008; Vuilleumier, 2005). Therefore, employing emotional stimuli may help to evoke clearer distraction effects in conditions simulating real social environments. Furthermore, the idea of incorporating emotional stimuli in the characterization of ADHD fits well with current models that emphasize that multiple psychopathological processes and neural pathways are implicated in this disorder, including cognitive (e.g., attention, inhibition and working memory) and affective (emotion and motivation) processes as well as top-down (voluntary) and bottom-up (involuntary) mechanisms (Castellanos et al., 2006; Nigg & Casey, 2005; Sergeant, 2005; Sonuga-Barke, 2002; see also Sonuga-Barke, De Houwer, De Ruiter, Ajzenstien, & Holland, 2004). From this perspective, the poor ability of ADHD patients to remain focused on a task in the presence of irrelevant emotional distracters could arise not only from a hypofunction of the brain processes associated with cognitive control of distraction, but also from a hyperfunction of brain processes related to the bottom-up response to affectively laden stimuli. In support of this, a recent fMRI study has shown that adolescents with ADHD displayed amygdalar hyperactivity during subliminal presentation of fearful faces (Posner et al., 2011b). However, to the best of our knowledge, no study has yet addressed the effect of emotional irrelevant stimuli on ongoing cognitive processes in children with ADHD.

Due to their high temporal resolution that allows neural processes to be tracked in milliseconds, event-related potentials (ERPs) are particularly useful for elucidating the neural basis underlying emotional distraction in ADHD. The main reason for this is that some of the most important brain responses associated with the sudden onset of an emotional distractor are characterized by their rapidity (early latency onset) and brevity (short duration), and thereby can only be detected by using a temporally agile physiological signal such as electroencephalography (EEG). One ERP component that seems particularly well suited for studying emotional distractibility in the visual modality is the anterior N2, a brain electrical response occurring between 200 and 400 ms after stimulus onset that presents its maximum amplitude over frontal scalp regions. Numerous studies have shown this component to be enhanced for unfamiliar, novel visual stimuli as well as for highly emotional events (Carretié et al., 2004; Chong et al., 2008; Daffner et al., 2000; Kenemans, Verbaeten, Melis, & Slangen, 1992; Liddell, Williams, Rathjen, Shevrin, & Gordon, 2004; Rozenkrants & Polich, 2008). Remarkably, it has recently been reported that, unlike subsequent positive components, the amplitude of the anterior N2 to this type of stimuli is neither modulated by the degree of task-relevance of the eliciting stimulus nor by the direction of subjects’ controlled attention (Chong et al., 2008; Tarbi, Sun, Holcomb, & Daffner, 2011; see also Carretié et al., 2004 and Liddell et al., 2004). Therefore, this component responds to novel and emotional events even when they are not relevant for the task and occur outside the focus of attention. In light of this evidence, this anterior N2, which is thought to be functionally distinct from the frontocentrically distributed control-related N2 mainly elicited by executive control paradigms (see Folstein & Van Petten, 2008 for a review on this issue), seems to reflect automatic detection of highly significant stimuli (Chong et al., 2008; Daffner et al., 2000; Liddell et al., 2004; Tarbi et al., 2011). To our knowledge, no study has examined this in ADHD.

Following the anterior N2, a large positive deflection over centro-parietal regions is often observed. This posteriorly distributed positivity has been variously called P3, P3b, LPP or LPC, and has generally been associated with more controlled stages of processing (Chong et al., 2008; Kenemans et al., 1992; Liddell et al., 2004). For instance, P3b is thought to reflect the processing of task-relevant events, including stimulus categorization/evaluation and memory updating (Donchin, 1981; Kok, 2001; Polich, 2007; Verleger, 1998). ERP studies of patients with ADHD have frequently shown a reduction in the amplitude of P3b to task-relevant stimuli (Barry, Johnston, & Clarke, 2003; Brandeis et al., 2002; Jonkman et al., 2000). Within the context of emotion research, this component (often termed LPP) has been shown to be sensitive to manipulations requiring voluntary control processes. Indeed, it has been been proposed as a neural marker of top-down emotion regulation in both adults and children (Dennis & Hajcak, 2009; Moser, Hajcak, Bukay, & Simons, 2006). Interestingly, a reduced amplitude of LPP has recently been found in patients with ADHD when they asked to inhibit their responses to negative emotions (Kochel, Leutgeb, & Schienele, 2012). Hereafter, we will use the term late positive complex (LPC) to describe this family of posteriorly distributed positivity associated to a greater extent than previous components with controlled and conscious processes.

The present study aimed at elucidating the neural and behavioral mechanisms underlying emotional distraction in children with ADHD. To this end, ERP and behavioral data were recorded from boys with ADHD combined type and healthy comparison controls while they performed a digit categorization task while three types of irrelevant, distracting stimuli were presented: arousing negative (A−), neutral (N) and arousing positive (A+). Specifically, behavioral measures consisted of reaction times (RTs) and error rates in the cognitive task. Distraction caused by the irrelevant emotional stimuli would be mirrored in an impoverishment of current task performance (i.e., longer RTs and/or higher error rates for emotional versus neutral distracters). Neural measures consisted
of scalp ERP analyses of N2 and LPC. In this case, emotional distraction would be reflected in alterations of one or both of these components. An enhancement in the anterior N2 would suggest that distraction is primarily related to an exaggerated bottom-up response to the saliency of distracters, whereas a reduction in the LPC would indicate that distraction is associated with deficits in a later, more controlled stage of processing. On the basis of evidence showing heightened distractibility in children and adolescents with ADHD when they are in real social situations (Barkley & Cox, 2007; Lawrence et al., 2002; Lorch et al., 2000), we hypothesized that boys with ADHD may show enhanced susceptibility to emotional distraction as compared to matched control subjects, both at the behavioral and electrophysiological levels.

2. Methods

2.1. Participants

Patients were 20 boys between 8 and 13 years recruited from the Child Neurology Unit of the Hospital Quirón, Madrid. They all had a formal diagnosis of ADHD combined type by a multidisciplinary team according to DSM-IV-TR criteria (American Psychiatric Association, 2000). The clinical diagnoses were then confirmed by administering the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children—Present and Lifetime Versions (K-SADS-PL; Kaufman et al., 1997; Ulloa et al., 2006). Three patients had an additional diagnosis of oppositional defiant disorder (ODD).1 ODD is a common comorbid psychiatric condition in ADHD (Jensen et al., 2001). No other psychiatric or neurological disorders were present in any of the children. Moreover, parents completed the ADHD Rating Scale-IV (ADHD-RS-IV; DuPaul, Power, Anastopoulos, & Reid, 1998) in order to obtain additional information on the current severity of their son’s ADHD symptoms. All children scored above the 93rd percentile on the total scale as well as on the inattention and hyperactivity-impulsivity subscales of the ADHD-RS-IV. The patients were either medication naïve (N = 4) or medication free for at least 36 h prior to recording. All medicated patients (N = 16) were receiving extended-release methylphenidate.

Control subjects were 20 healthy boys between 8 and 13 years, recruited from different local community schools. None of them had a history of neurological or psychiatric disorders or was taking medication. They scored below threshold on the ADHD-RS-IV in total scale and the subscales of inattention and impulsivity/hyperactivity (DuPaul et al., 1998). Specifically, eighteen control subjects scored at or below the 50th percentile on all ADHD-RS-IV subscales, whereas the remaining two subjects scored below the 80th percentile. Absence of ADHD or other comorbid psychiatric disorders was confirmed with a semi-structured clinical interview (Ulloa et al., 2006).

The ADHD and control groups were matched on average age and estimated IQ (see Table 1 for means, standard deviations and statistical test results). By contrast, both groups differed in the ADHD-RS-IV scores, with ADHD patients showing significantly greater inattention and hyperactivity-impulsivity scores than control subjects (Table 1). All children had an estimated IQ above 85 as measured by two WISC-IV subtests: Vocabulary and Block Design. These subtests both have shown to have an excellent reliability and correlate highly with the full-scale intelligence quotient (Sattler, 2001). Concretely, the estimated reliability of the WISC-IV subtests for our sample of children was 0.88, as determined by using the Guilford-Fruchter formula (p. 420, Guilford & Fruchter, 1973). All participants were right-handed, as determined by asking the child to demonstrate with which hand they perform each of the following activities: write, throw a ball, brush teeth, and eat soup with a spoon. Written informed consent was obtained from parents, with the child giving assent. Parents and children were informed that they could withdraw from the study at any time without consequences. Children received incentives for participation (a gift voucher of €15 and a small bag of sweets). The study had been approved by the Research Ethics Committee of the Universidad Autónoma de Madrid, where the experiment took place.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>ADHD group mean (SD)</th>
<th>Control group mean (SD)</th>
<th>t Test* (df = 38)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>20</td>
<td>20</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Male (%)</td>
<td>100</td>
<td>100</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Age (years)</td>
<td>11.35 (1.42)</td>
<td>10.65 (1.27)</td>
<td>±1.642</td>
<td>ns</td>
</tr>
<tr>
<td>IQ estimate (WISC-IV)</td>
<td>113.1 (12.04)</td>
<td>116.95 (11.81)</td>
<td>−1.021</td>
<td>ns</td>
</tr>
<tr>
<td>ADHD RS-IV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>41.65 (4.04)</td>
<td>7.3 (4.86)</td>
<td>±24.31</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Inattention</td>
<td>21.25 (2.59)</td>
<td>3.8 (2.97)</td>
<td>±19.81</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td>Hyperactivity/impulsivity</td>
<td>20.4 (3.05)</td>
<td>3.5 (2.63)</td>
<td>±18.78</td>
<td>p &lt; 0.001</td>
</tr>
</tbody>
</table>

Abbreviations: No, number of subjects; ADHD, attention-deficit/hyperactivity disorder; IQ, intelligence quotient; ADHD RS-IV, ADHD Rating Scale-IV (DuPaul et al., 1998); df, degree of freedom, ns, non significant; na, not applicable.

* Group differences were tested by means of two-sample t tests (alpha = 0.05).

1 All results described in this article remained the same when boys with ADHD plus ODD were excluded from the analyses.
differences between groups in the subjective feeling of valence and arousal caused by each distracter type. The complete set of stimuli used in the present study may be seen at http://www.uam.es/CEACO/sup/ADHD_ED12.htm. The cognitive task concerned the digit presented in the center of the background picture: children had to press, as fast and accurate as possible, one response button with the thumb of their right hand for odd numbers and another button with the thumb of their left hand for even numbers. The same combination of digits was repeated across conditions in order to ensure that task difficulty was the same for A−, N, and A+. Stimuli were presented in semi-random order in such a way that there were never more than three consecutive trials for the same emotional or numerical category. As illustrated in Fig. 1, each trial began with the presentation of the digit superimposed on the center of the picture (300 ms), followed by a white fixation cross on a dark background (1700 ms), so that the resulting onset asynchrony (SOA) was 2000 ms. An animation reproducing several trials of the experimental task as well as their temporal characteristics can be seen at http://www.uam.es/CEACO/sup/ADHD_ED12.htm. The experiment consisted of 60 trials per experimental condition (60 A−, 60 N, and 60 A+) which were divided into two blocks of 90 trials each. Thus, each picture used as distracter was repeated four times.

Before the beginning of the experiment, subjects completed a practice block of 16 trials, with neutral pictures as background distracters to ensure that task instructions were understood. They were asked to look continuously at the center of the screen and to refrain from blinking, as much as possible, during block runs in order to minimize eye–movement interference. The task was programmed using Inquisit Millisecond software (Millisecond Software, 2006) and presented through a RGB projector on a back-projection screen (48.8 × 65.6 cm). Participants were seated 100 cm from this screen in an electrically shielded, sound-attenuated, and video-monitored room.

2.3. EEG recording and preprocessing

EEG activity was recorded using an electrode cap (ElectroCap International) with 119 electrodes. Thirty electrodes were placed on the scalp in an extended 10–20 configuration: Fp1, Fpz, Fp2, AFz, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP3, CP2, CP6, P7, P3, Pz, P4, P8, O1, Oz, O2. All scalp electrodes were referenced to the nose tip. Electrooculographic (EOG) data were recorded supra- and infraorbitally (vertical EOG), as well as from the left versus right orbital rim (horizontal EOG). Electrode impedances were kept below 5 kΩ. An online bandpass filter of 0.3–40 Hz was applied. Recordings were continuously digitized at a sampling rate of 210 Hz for the entire duration of the recording session. The continuous recording was divided into 1000-ms epochs for each trial, beginning 200 ms before stimulus onset. Trials for which participants responded erroneously or did not respond were eliminated. Epochs containing eye movements or blinks over 100 μV in amplitude were deleted. For the rest of epochs, the EOG-artifact removal procedure described by Gratton, Coles, and Donchin (1983) was applied whenever EOG activity was observed. This artefact and error rejection procedure led to the average admission of 36.65 ± 9.33 (mean ± standard deviation) A− trials, 37.4 ± 8.68 N and 35.15 ± 9.75 A+ in the ADHD group, and 37.45 ± 7.72 A−, 37.55 ± 8.2 N and 37.50 ± 7.5 A+ in the Control group. The number of valid trials did not differ between groups (F(1, 38) = 0.2, p = 0.67) or experimental conditions (i.e., distracter types; F(2, 76) = 1.2, p = 0.31), and there was no group x condition interaction (F(2, 76) = 1.1, p = 0.33). The minimum number of trials accepted for averaging was 20 per subject and condition. Behavioral performance was recorded through a two-button keypad whose electrical output was continuously digitized at a sampling rate of 840 Hz.

2.4. Data analysis

All statistical analyses described below were carried out using the SPSS software package (Version 15.0; SPSS Inc, Chicago, USA). Repeated-measures ANOVAs including Group (two levels: ADHD and Control) as between subjects factor and Distracter type (three levels: A−, N, and A+) as within subjects factor were performed for behavioral and ERP data. Contrasts especially relevant for our purposes were those showing a significant interaction between Group and Distracter type. Significant interactions were further evaluated using simple effects with Bonferroni correction for multiple comparisons. For all ANOVAs, the Greenhouse–Geisser epsilon (ε) correction was applied to within-subjects measures. Uncorrected degrees of freedom, corrected ε values, and Greenhouse–Geisser ε values are provided, as recommended (Picton et al., 2000). Effect sizes are reported as partial eta-square (ηp2) for all significant effects. Although age differences between groups were not significant, children with ADHD were somewhat older than control subjects (Table 1). For this reason, significant ANOVA results were confirmed using age as a covariate. All dependent variables, except error rates, were normally distributed, as assessed by Shapiro–Wilk tests. Error rates were square root transformed before analysis to achieve a normal distribution.

2.4.1. Behavioral analysis

Performance in the digit categorization task was analyzed. To that aim, mean RTs (to correct trials only) and square root transformed error rates (i.e., non-responses –omissions– and incorrect button presses) were submitted to repeated-measures ANOVAs with Group and Distracter type as factors. In the case of RTs, outliers, defined as responses above 2000 ms or below 200 ms, were omitted in the analyses. As mentioned above, the RTs in the digit categorization task to each distracter type were normally distributed both in the ADHD and Control groups (A−: W = 0.93,
p = 0.12; N: W = 0.94, p = 0.25; A+: W = 0.94, p = 0.25 for the ADHD group; A–: W = 0.91, p = 0.08; N: W = 0.92, p = 0.13; A+: W = 0.92, p = 0.09 for the Control group).

2.4.2. ERP analysis

With the aim of reliably testing whether N2 and LPC were present in the ERPs, components explaining most of the variance in the temporal domain were detected and quantified through a covariance-matrix-based temporal principal component analysis (tPCA). tPCA constitutes a useful data-driven method to distinguish components along time, thus ruling out the potentials confounds when defining time windows of interest based on visual inspection of grand averages. Another advantage of tPCA is that it presents each ERP component with its ‘clean’ shape, extracting and quantifying it free of the influences of adjacent or latent components. Indeed, the waveform recorded at a site on the head over a period of several hundreds of milliseconds represents a complex superposition of different overlapping electrical potentials. Such recordings can stylize visual inspection (see e.g., Albert, Lópezm-Brinjoloja, & Carretié, 2013; Carretié et al., 2004; Spencer, Dier, & Donchin, 2001). In brief, tPCA computes the covariance between all ERP time points, which tends to be high between those time points involved in the same component and low between those belonging to different components (for further details see Dien & Frishkoff, 2005). The solution is therefore a set of factors made up of highly covarying time points, which ideally correspond to ERP components. Temporal factor score, the tPCA-derived parameter in which extracted temporal factors may be quantified, is linearly related to amplitude.

In the present study, tPCA was computed for 210 digitized voltage points (from −200 to 800 ms) as data matrix variables and 3600 cases resulting from the product of participants (40), conditions (3) and scalp electrodes (30). The decision on the number of variables and cases. The number of factors retained was determined as the number of real eigenvalues that were greater with those extracted from a random matrix having the same number of variables (3) and scalp electrodes (30). The decision on the number of factors to retain was also based on the PA, and extracted factors were submitted to Promax rotation with a kappa value of 3 as well.

Finally, repeated-measures ANOVAs on N2 and LPC spatial factor scores (linearly related to amplitudes) were performed with Group as between subjects factor and Distracter type as within subjects factor.

3. Results

3.1. Emotional assessments

Table 2 shows the means and standard deviations of valence and arousal for each group and each type of distracter. As previously described, ANOVAs were computed for both emotional dimensions, using Group as between-subjects factor and Distracter type as within-subjects factor. The main effect of Distracter type was significant both for valence (F(2, 76) = 634.5, p = 0.000; ε = 0.82, ηp2 = 0.94) and arousal dimensions (F(2, 76) = 257.6, p = 0.000, ε = 0.94, ηp2 = 0.58). Bonferroni post hoc contrasts indicated that A– and A+ showed different valences (p = 0.000) but not different arousal levels (p = 0.091). Moreover, both A+ and A– differed from N in arousal (A+ vs. N, p = 0.000; A– vs. N, p = 0.000) and valence (A+ vs. N, p = 0.000; A– vs. N, p = 0.000). The main effect of Distracter type remained significant after statistically controlling for age, both for valence (F(2, 74) = 13.4, p = 0.000, ε = 0.82) and arousal (F(2, 74) = 7.6, p = 0.001, ε = 0.94).

Table 2 shows that there were no differences between ADHD and healthy control groups in the subjective feeling of valence and arousal caused by each distracter type.

3.2. Behavioral data

Performance in the digit categorization task is shown in Table 2. Repeated-measures ANOVAs on RTs and error rates were performed using Group and Distracter type as factors. The main effect of Group was not significant for error rates (F(1, 38) = 0.8, p = 0.381). In the case of RTs, the main effect of Group was marginally significant (F(1, 38) = 4.2, p = 0.047, ηp2 = 0.1), showing that RTs were shorter in the ADHD than in the control group (means and standard errors: 689.72 ± 37.37 and 798.2 ± 37.37, respectively). The interaction of Group and Distracter type was not significant neither for valence (F(2, 76) = 0.7, p = 0.466, ε = 0.82) nor for arousal (F(2, 76) = 1.3, p = 0.283, ε = 0.94). These findings indicate that there were no differences between ADHD and healthy control groups in the subjective feeling of valence and arousal caused by each distracter type.
715.46 ± 31.02 and 772.46 ± 31.02, respectively; \( F(1, 37) = 1.6,\ p = 0.209 \). Therefore, although age differences between groups were not significant (Table 1), the fact that the children with ADHD were somewhat older than control children seems to be the reason for the group differences in RTs.

### 3.3. ERP data

Fig. 2 shows a selection of grand averages once the baseline value (pre-stimulus recording) had been subtracted from each ERP. Two main deflections were noticeable. The first was a negative component with an onset around 280 ms after distracter presentation (N2). This component shows its maximum amplitude over frontal and frontocentral electrode locations. The second deflection was a late positivity peaking around 585 ms after distracter onset (LPC). The largest amplitude of this positivity was observed at centroparietal locations. Fig. 3 represents the distribution of voltages of these components in the form of scalp maps for the ADHD and Control groups.

#### 3.3.1. Temporospatial PCA

As a consequence of the application of the tPCA using the PA as criterion of the number of factor to retain (Fig. 4A), five components were extracted from the ERPs (Fig. 5). Factor peak latency and topography characteristics associate Factor 1 (peaking at 280.95 ms) with the wave labeled N2 in grand averages and Factor 2 (peaking at 583.71) with that labelled LPC. These labels will be employed hereafter to make the results easier to understand. The sPCA subsequently applied to N2 and LPC temporal factor scores extracted three spatial factors for N2 and two for LPC (Fig. 6).
The decision on the number of spatial factors to select for these two ERP components was also based on the PA (Fig. 4B).

Repeated-measures ANOVAs on N2 and LPC spatial factor scores (directly related to amplitudes, as previously indicated) were then carried out for Group and Distracter type factors. The main effect of Group was not significant in any of the N2 spatial factors. In other words, amplitudes did not differ between groups in the anterior N2 ($F(1, 38) = 3.3, p = 0.079$), centroparietal N2 ($F(1, 38) = 0.06, p = 0.803$) or occipitally distributed N2 ($F(1, 38) = 0.05, p = 0.821$). However, a significant effect of the interaction of Group and Distracter type was obtained in the anterior spatial factor of N2 ($F(2, 76) = 5.7, p = 0.006, \eta^2_p = 0.13$). Specifically, post hoc tests of simple effects with Bonferroni correction for multiple comparisons showed that anterior N2 amplitudes were larger (more negative) for emotional distracters (both A+ and A/C0) than for neutral distracters in the ADHD group (A/C0 vs. N, $p = 0.000$; A+ vs. N, $p = 0.000$; A+ vs. A/C0, $p = 0.324$), whereas no differences were observed in the Control group (A/C0 vs. N, $p = 0.407$, A+ vs. N, $p = 0.124$, A+ vs. A-, $p = 0.324$), whereas no differences were observed in the Control group (A- vs. N, $p = 0.407$, A+ vs. N, $p = 0.124$, A+ vs. A-, $p = 0.853$). This interaction remained significant after controlling for age ($F(2, 74) = 6.9, p = 0.002, \eta^2_p = 0.16$). Age was significant as a covariate ($F(1, 37) = 5.3, p = 0.027, \eta^2_p = 0.12$). Concretely, the amplitude of the anterior N2 decreased linearly with age ($r = 0.21, p = 0.022$), which is consistent with previous studies showing age-related changes in the anterior N2 (Riis et al., 2009; Van Strien, Glimmerveen, Franken, Martens, & de Bruin, 2011). Neither the main effect of Group nor the interaction of Group and Distracter type was significant in

The decision on the number of spatial factors to select for these two ERP components was also based on the PA (Fig. 4B).

Repeated-measures ANOVAs on N2 and LPC spatial factor scores (directly related to amplitudes, as previously indicated) were then carried out for Group and Distracter type factors. The main effect of Group was not significant in any of the N2 spatial factors. In other words, amplitudes did not differ between groups in the anterior N2 ($F(1, 38) = 3.3, p = 0.079$), centroparietal N2 ($F(1, 38) = 0.06, p = 0.803$) or occipitally distributed N2 ($F(1, 38) = 0.05, p = 0.821$). However, a significant effect of the interaction of Group and Distracter type was obtained in the anterior spatial factor of N2 ($F(2, 76) = 5.7, p = 0.006, \eta^2_p = 0.13$). Specifically, post hoc tests of simple effects with Bonferroni correction for multiple comparisons showed that anterior N2 amplitudes were larger (more negative) for emotional distracters (both A+ and A–) than for neutral distracters in the ADHD group (A– vs. N, $p = 0.000$; A+ vs. N, $p = 0.000$; A+ vs. A–, $p = 0.324$), whereas no differences were observed in the Control group (A– vs. N, $p = 0.407$, A+ vs. N, $p = 0.124$, A+ vs. A–, $p = 0.853$). This interaction remained significant after controlling for age ($F(2, 74) = 6.9, p = 0.002, \eta^2_p = 0.16$). Age was significant as a covariate ($F(1, 37) = 5.3, p = 0.027, \eta^2_p = 0.12$). Concretely, the amplitude of the anterior N2 decreased linearly with age ($r = 0.21, p = 0.022$), which is consistent with previous studies showing age-related changes in the anterior N2 (Riis et al., 2009; Van Strien, Glimmerveen, Franken, Martens, & de Bruin, 2011). Neither the main effect of Group nor the interaction of Group and Distracter type was significant in
3.2. Conventional ERP analysis

In order to compare results from temporospatial PCA with traditional ERP waveform analysis, we also assessed the N2 and LPC as mean voltage amplitudes within the 200–400 ms and 500–700 ms intervals, respectively. Amplitudes were measured with respect to the average of the 200 ms pre-stimulus baseline. Scalp regions of interest were defined, and the average amplitude recorded by those electrodes forming each of these regions was computed. Time windows and scalp regions of interest were determined based on previous research as well as on visual inspection of grand averages and topographic map of the voltage distribution of each component (Figs. 2 and 3). For N2, a frontocentral region consisting of six electrodes (AFz, F3, Fz, F4, FC1, and FC2) was selected. For LPC, a centroparietal region comprising five electrodes (CP1, CP2, P3, Pz, and P4) was chosen. Supplementary Fig. 1 shows the selected electrode region for each component.

Repeated-measures ANOVAs on these two regions were then carried out for Group and Distracter type factors. Results were similar to those obtained using temporospatial PCA. For anterior N2, the main effect of Group was not significant (F(1, 38) = 2.1, p = 0.152). However, it was sensitive to the interaction of Group and Distracter type (F(2, 76) = 4.4, p = 0.016, \( \eta_p^2 = 0.09 \)). Bonferroni post hoc tests of simple effects showed that anterior N2 amplitudes were larger for emotional (both A− and A+) than for neutral distracters in the ADHD group (A− vs. N, p = 0.000; A+ vs. N, p = 0.000; A+ vs. A−, p = 0.441), but not in the Control group (A− vs. N, p = 1; A+ vs. N, p = 0.447; A+ vs. A−, p = 1). This interaction remained significant after controlling for age (F(2, 74) = 5.9, p = 0.005, \( \varepsilon = 0.98, \eta_p^2 = 0.14 \)). Neither the main effect of Group (F(1, 38) = 0.01, p = 0.902) nor the interaction of Group and Distracter type (F(2, 76) = 0.5, p = 0.621, \( \varepsilon = 0.87 \)) was significant in the centroparietally distributed LPC.

3.4. Relationship between emotional assessments and ERP data

Although it is reasonable to deduce from previous analyses that arousal more than valence explains results concerning the anterior N2 component in the ADHD group, since differences between emotional (both A+ and A−) and neutral distracters are clear, this trend required statistical confirmation. To this end, the associations between anterior N2 factor scores (equivalent to traditional amplitudes, as mentioned before) and subjects’ emotional ratings of distracting stimuli were analyzed via multiple regressions (enter method) in both groups. Anterior N2 amplitude was the dependent variable, and independent variables were valence and arousal ratings. In the ADHD group, arousal associated significantly with anterior N2 (F(2, 57) = 6.02, p = 0.004; \( \beta = -0.4, \rho = 0.002 \)), while valence did not (\( \beta = -0.09, \rho = 0.475 \)). Concretely, the linear association pattern between anterior N2 amplitudes and arousal presented a negative slope: the larger -more negative- the former, the greater the latter. By contrast, neither valence nor arousal was associated with anterior N2 amplitude in the control group (F(2, 57) = 0.3, p = 0.735; \( \beta = -0.06, \rho = 0.657 \) and \( \beta = -0.08, \rho = 0.531 \), respectively). Table 3 shows, for each group, the correlations between the independent variables, and between each independent variable and the dependent variable. The inclusion of age as an additional predictor variable did not alter the results of the regression analyses, neither for the ADHD nor for the control group.

4. Discussion

This is the first study, to our knowledge, to examine the effect of irrelevant emotional distractors on goal-directed processing in children with ADHD. Both behavioral and neural data indicate that boys with ADHD show enhanced susceptibility to emotional distraction with respect to typically developing healthy comparison subjects. At the behavioral level, we found that, in the ADHD group, emotional distracters were associated with longer RTs in the digit categorization task than neutral distracters. By contrast, no behavioral differences among distractors were found in the control group. At the electrophysiological level, we found that anterior N2 amplitudes were greater for emotional than for neutral distracters in ADHD children, whereas no differences were observed in healthy comparison subjects. Moreover, regression analyses between anterior N2 amplitudes and subjects’ emotional ratings of distracting stimuli showed that only in the ADHD group, arousal ratings were associated with anterior N2: its amplitude increased as the arousal content of the visual distracter increased. These data, therefore, suggest that boys with ADHD are more vulnerable to the distracting effects of task-irrelevant high-arousing emotional stimuli than healthy comparison subjects. This conclusion is in line with the fact that enhanced distractibility is observed in ADHD children when they are in real social contexts, such as school and home, where distracters are often affectively loaded. Likewise, present results provide further empirical support for the current inclusion of distractibility as one of the behavioral diagnostic criteria of ADHD (American Psychiatric Association, 2000).

The results of the current study suggest that anterior N2 is a useful neural index of emotional distraction in ADHD. Although the complete functional dissociation of frontally distributed N2 components is probably difficult to achieve (Albert et al., 2013; Kropotov, Ponomarev, Hollup, & Mueller, 2011), it has been
suggested that anterior N2 should be divided into, at least, the control-related N2 and the novelty/mismatch N2 (for a review see Folstein & Van Petten, 2008; see also Kropotov et al., 2011). The former is primarily elicited by executive control paradigms, such as the go/nogo, stop-signal and especially Eriksen flanker tasks (Buss, Dennis, Broker, & Sippel, 2011; Donkers & Van BoktL, 2004; Enriquez-Geppert et al., 2010; Nieuwenhuis et al., 2003; Randall & Smith, 2011; Van Veen & Carter, 2002). This anterior N2 is thought to index top-down control processing such as conflict monitoring (Donkers & Van BoktL, 2004; Enriquez-Geppert et al., 2010; Randall & Smith, 2011). The latter has been consistently associated with the rapid detection of novelty and significance using different distraction and oddball paradigms (Carretié et al., 2004; Chong et al., 2008; Daffner et al., 2000; Kenemans et al., 1992; Rozenkrafts & Polich, 2008; Tarbi et al., 2011). Notably, as in the present study, some of these investigations have shown larger anterior N2 amplitudes in response to novel and emotional stimuli even when attention was not engaged and directed to them (Carretié et al., 2004; Tarbi et al., 2011), suggesting that this N2 component is related to stimulus-driven attentional processes. The anterior N2 elicited by our experimental paradigm seems to be primarily related to bottom-up attentional mechanisms. Indeed, both categorical and dimensional analyses indicated that, in patients with ADHD, the amplitude of the anterior N2 was associated with the emotional content of distracters, suggesting that it was automatically driven by the salience of these task-irrelevant stimuli.

As indicated by the lack of a main effect of group, boys with ADHD showed similar N2 amplitudes to controls in response to distracters when emotional conditions were not taken into account. However, they diverged from controls in anterior N2 amplitudes associated with emotional compared to neutral distracters. These results highlight the importance of incorporating emotional stimuli into distraction paradigms in order to enhance the interference of task-irrelevant distracters on goal-directed behavior, reflecting what actually occurs in many real social situations. As mentioned before, only affectively neutral visual stimuli have been used previously in studies examining the neural substrates of attention functioning in ADHD (e.g., Booth et al., 2005; Huang-Pollock et al., 2005; Jonkman et al., 2000; Meere & Sergeant, 1988). On the other hand, the results of the present study suggest that the enhanced emotional distractibility seen in ADHD children seems to be more related to an exaggerated bottom-up response to the saliency of distracters rather than to a failure to implement top-down control processes to avoid distraction. In this vein, it should be pointed out that children with ADHD did not differ from controls with respect to LPC. In the present study, this component seems to reflect a more controlled stage of processing triggered by previous automatic processing (N2-associated), which would be in line with some previous studies on novelty/significance processing (Chong et al., 2008; Kenemans et al., 1992; Liddell et al., 2004). Centroparietally distributed late positivities, such as P3b, are often interpreted as reflecting limited-resource processing of task-relevant information, such as stimulus categorization and allocation of attention resources for memory updating (Donchin, 1981; Kok, 2001; Polich, 2007; Verlger, 1998). In the context of emotion research, increasing evidence suggests that the LPC is sensitive to top-down manipulations of attention. Indeed, it has been proposed as a neural correlate of top-down emotion regulation, both in adults and children (Dennis & Hajcak, 2009; Moser et al., 2006). Thus, one of these studies has found that the amplitude of the centroparietal LPC decreased when subjects were asked to intentionally suppress their affective responses to high arousing emotional stimuli (Moser et al., 2006). Taking into consideration the results of these studies, current results with respect to LPC may indicate that the enhanced levels of emotional distraction observed in our patients with ADHD were not related to deficits in more controlled and conscious stages of emotional/cognitive processing. These findings are of critical relevance for the current debate regarding the nature (top-down vs. bottom-up) and extent (present or not) of attentional deficits in ADHD (Friedman-Hill et al., 2010; Gumenyk et al., 2005; Huang-Pollock et al., 2005; Sonuga-Barke et al., 2004).

Dysfunction of top-down inhibitory control has long been theorized to be the central feature of ADHD (Barkley, 1997). Convergent data for impaired inhibitory control in ADHD have been found in studies using functional brain measures (Albrecht et al., 2008; Dimoska et al., 2003; Liotti et al., 2007; Pliszka et al., 2000; Rubia et al., 1999). These studies have generally reported decreased activation of fronto-striatal brain regions and reduced amplitudes of the frontally distributed N2 related to top-down processing (i.e., the N2 primarily associated with conflict monitoring) while ADHD patients were engaged in non-emotional executive tasks such as the go/nogo or stop-signal tasks. Considering this strong evidence, impairments in top-down cognitive processing and its neurobiological basis were thought to be the cause of distractibility in ADHD (Barkley, 1997). Thus, from this perspective, the enhanced distractibility in patients with ADHD would be associated with impairments in the ability to monitor and resolve conflict evoked by distracter stimuli, by incapacity either to enhance task-relevant representations or to inhibit task-irrelevant information. It should be noted, however, that the deficit in top-down inhibitory control is not present among all patients with ADHD and cannot explain alone the great heterogeneity of the disorder (Banaschewski et al., 2004; Castellanos et al., 2006; Sonuga-Barke, 2002; Willcutt et al., 2005). Abnormalities in other brain regions beyond the fronto-striatal circuit (including mesolimbic and visual networks: Ahrends et al., 2011; Castellanos & Proal, 2012; Vaidya & Stollstorff, 2008) and impairments in other psychological processes beyond inhibitory control (including bottom-up and affective mechanisms: Brotman et al., 2010; Herrmann et al., 2011; Pluchta et al., 2009; Posner et al., 2011b) are also present among patients with ADHD. Interestingly, some of these studies have found amygdalar hyperactivation in patients with ADHD during delayed reward and emotion processing (Brotman et al., 2010; Maier et al., 2013; Pluchta et al., 2009; Posner et al., 2011b), even when the emotional stimulation was presented subliminally (Posner et al., 2011b). The amygdala seems to play a crucial role in the bottom-up or involuntary response to emotional stimuli (Vuilleumier, 2005; Vuilleumier & Schwartz, 2001; Whalen et al., 1998). In light of this recent evidence and as suggested by present results, we propose that distractibility in ADHD might also arise from an abnormal involuntary response to affective stimuli.

The results of the present study should be interpreted in light of several limitations. Firstly, the clinical group was restricted to boys with a clinical diagnosis of ADHD combined subtype. Further investigations should include girls and other subtypes to determine whether the findings of the current experiment can be generalized across different populations with ADHD. Secondly, most of the patients of the present study were not medication-naive (only four of the boys with ADHD had no prior history of any medication use). It would be interesting to replicate this study in medication-naive patients as well as to examine the effect of medication on neural and behavioral mechanisms underlying emotional distraction in ADHD. Interestingly, some recent evidence suggests that stimulant medication normalizes emotional processing in individuals with ADHD by attenuating abnormal activity within affective brain mechanisms (Posner et al., 2011a, 2011b). Therefore, the effects observed in the present study would probably be intensified rather than attenuated when investigated on a medication-naive sample. Finally, this study exclusively explored the timing and topographic characteristics of the neural processes underlying emotional distractibility in ADHD. Future studies examining the
origin of these neural processes within the brain are needed to provide a more complete picture of the neural substrates underlying emotional distraction in ADHD.

Notwithstanding its limitations, the present study represents an important new step toward the integration of cognitive and affective neuroscience to obtain a comprehensive understanding of neurobiological basis of ADHD. By capitalizing on the high temporal resolution of the ERPs, the results of the present experiment provide insight into the timing of the neural processes underlying emotional distractibility in ADHD. Firstly, we found that, in comparison with healthy controls, boys with ADHD showed an increased susceptibility to emotional distraction. Secondly, we observed that the poor ability of ADHD children to remain goal orientated in the face of distracting irrelevant stimuli seems to be more related to an excessive bottom-up response to emotionally laden distracters than to the hypofunction of top-down brain mechanisms. These results emphasize the view of ADHD as a complex disorder in which top-down and bottom-up mechanisms as well as cognitive and affective processes are involved.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandc.2013.06.004.

References


