

# Binge Drinking Affects Brain Oscillations Linked to Motor Inhibition and Execution

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**Introduction:** Neurofunctional studies have shown that binge drinking (BD) patterns of alcohol consumption during adolescence and youth are associated with anomalies in brain functioning. Recent evidence suggests that event-related oscillations (EROs) may be an appropriate index of neurofunctional damage associated with alcoholism. However, there is no study to date that has evaluated the effects of BD on oscillatory brain responses related to task performance. The purpose of the present study was to examine brain oscillations linked to motor inhibition and execution in young binge drinkers (BDs) compared to age-matched controls. **Methods:** Electroencephalographic activity was recorded from 64 electrodes while 72 university students (36 controls and 36 BDs) performed a visual Go/NoGo task. EROs along with the Go-P3 and NoGo-P3 event-related potential (ERP) components were analysed. **Results:** While no significant differences between groups were observed regarding ERPs, ERO analysis showed that BDs displayed a lower oscillatory response than controls in delta and theta frequency ranges during Go and NoGo conditions. **Conclusions:** Findings are congruent with ERO studies showing reduced delta and/or theta oscillations in alcoholics during Go/NoGo tasks. Thus, BDs appear to show disruptions in neural oscillations linked to motor inhibition and execution similar to those observed in alcohol-dependent subjects. Finally, these results are the first to evidence that oscillatory brain activity may be a sensitive indicator of underlying brain anomalies in young BDs, which could complement standard ERP measures.

**Key words** Alcohol, Binge Drinking, Event-Related Potentials, Event-Related Oscillations, Response Inhibition.

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## 1. Introduction

Alcohol is the most widely used psychoactive substance in the world (*World Health Organization*, WHO, 2014). Binge drinking (BD), formally defined as the consumption of five or more drinks for men and four or more for women on the same occasion within a 2-h interval (*National Institute of Alcohol Abuse and Alcoholism*, NIAAA, 2004; Courtney and Polich, 2009), is a highly prevalent pattern of alcohol consumption in adolescents and young people in most Western countries. As such, around one out of three young Europeans and North Americans are binge drinkers (29% of Europeans aged 15 to 25 years and 39% of North Americans between 18 and 25 years) (Eurobarometer, 2010; SAMHSA, 2103), which has been associated with major social and health consequences such as unsafe sexual activity, motor vehicle crashes, violent behaviour, poor school performance, increased risk for cardiovascular impairments and hepatic injury, etc. (Brewer and Swahn, 2005; Goslawski et al., 2013; Llerena et al., 2015; Miller et al., 2007; Naimi et al., 2003; Valencia-Martín et al., 2008).

Adolescence and youth are periods of critical development in which the brain undergoes significant structural and functional changes (Casey et al., 2010; Giedd and Rapoport, 2010). These transformations in functioning and brain morphology mainly involve the prefrontal cortex (PFC) and other high-order association areas (Gogtay et al., 2004; Lebel and Beaulieu, 2011) and have been linked to meaningful enhancements in several cognitive processes such as attention, working memory, inhibitory control or decision making (Blakemore and Robbins, 2006; Hooper et al., 2004; Luna and Sweeney, 2004; Velanova et al., 2009; Yurgelun-Todd, 2007). Consequently, alcohol consumption during these periods of transition to adulthood is of particular concern given that excessive drinking might disrupt the neuromaturational processes of regions that are still maturing and therefore impair the cognitive functions partially supported by them (Squeglia et al., 2009).

Inhibitory control, i.e., the ability to suppress inappropriate responses or impulsive reactions with the aim of monitoring behaviour according to long-term goals (Allom et al., 2015; Diamond, 2013), deserves special attention given that this cognitive function has been related to individuals' capacity to regulate alcohol consumption (Fillmore, 2003; Smith et al., 2014). Indeed, weak inhibitory control may predispose individuals to develop addictive behaviours, including alcohol abuse (López-Caneda et al., 2014a; Perry and Carrol, 2008). Specifically, poor response inhibition has been associated with BD in

young social drinkers (Henges and Marczinski, 2012) as well as with more alcohol-related problems and greater risk of alcohol dependence in adolescents (Nigg et al., 2006; Rubio et al., 2008). Likewise, acute alcohol intake may lead to impulse control deficits (Loeber and Duka, 2008; Rose and Duka, 2007) as well as to disruptions in brain functioning related to inhibitory control (Nikolau et al., 2013; Euser and Franken, 2012).

Young BDs have also shown lower performance on neuropsychological tests assessing inhibitory ability compared to age-matched controls (Czapla et al., 2014; Poulton et al., 2016). At the same time, electroencephalographic (EEG) recordings during Go/NoGo and Stop Signal tasks point to abnormalities in the event-related potentials (ERPs) linked to response inhibition in social and heavy drinkers (López-Caneda et al., 2012, 2014b; Petit et al., 2012; Smith and Mattick, 2013). These anomalies affect essentially the NoGo-P3 component, a positive waveform occurring between 300-700 ms after stimulus onset that has a maximum amplitude at fronto-central sites and has been functionally associated with response inhibition (Kok et al., 2004; Wessel and Aron, 2015). Thus, heavy social drinkers exhibited delayed NoGo-P3 latencies in alcohol-related contexts, which was considered an index of prioritizing processing related to alcohol that might lead to inhibitory deficits (Petit et al., 2012). Furthermore, BDs also showed increased amplitude in NoGo-P3 and Stop-P3 (an analogous component to NoGo-P3 evoked during the Stop Signal task), suggesting the activation of additional/compensatory neural resources that would allow BDs to efficiently carry out the response inhibition (López-Caneda et al., 2012; Smith and Mattick, 2013).

There is considerable evidence suggesting that ERP waveforms emerge from superimposed neuroelectric oscillations induced by sensory or cognitive processes framed within dynamic ongoing EEG activity (Karakas et al., 2000; Klimesch et al., 2004). These oscillations, when analysed in the context of stimulus-related brain function, are frequently called event-related oscillations (EROs). The study of EROs enables the measurement (frequency-specific) of oscillatory activity in neural circuits that is temporally related to the sensory and cognitive processing of stimuli (Başar et al., 2001a). EROs are commonly classified according to the “natural frequencies” of the brain (Başar et al., 2001b), i.e., delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30-70 Hz). Despite their functional meanings often being task-specific, certain frequency bands within oscillatory responses may underlie different cognitive functions. In particular, research has shown a close relationship between delta and theta responses and inhibitory control processes evoked during the Go/NoGo paradigm (Harper et al.,

2014, 2016; Kirmizi-Alsan et al., 2006; Lavalley et al., 2014; Yamanaka and Yamamoto, 2010). However, the relationship between delta and theta oscillations and cognitive functions are not exclusive to response inhibition, as they have also been associated with a myriad of other cognitive processes such as perception, attention, error monitoring, memory and decision making (Cohen et al., 2009; Güntekin and Başar, 2016; Sauseng et al., 2010; Yordanova et al., 2004).

EROs have been shown to be sensitive to both normal and abnormal cognitive functioning in humans (Başar and Güntekin, 2013). Regarding alcoholism, several studies have reported attenuated delta and/or theta oscillations in alcohol-dependent patients during Go/NoGo tasks to both Go and NoGo stimuli, which has been interpreted as reflecting deficient inhibitory and attentional processing (Colrain et al., 2011; Kamarajan et al., 2004; Pandey et al., 2016). However, even though oscillatory responses have proven to be a useful tool for studying the neural response linked to inhibition in alcoholics, and that neural oscillations during resting states have been shown to be sensitive to the BD pattern (Correas et al., 2015, 2016; Courtney and Polich, 2010), to our knowledge there is no study that has evaluated EROs in young BDs. Bearing this in mind, the objective of this study was to determine whether young BDs would also exhibit impairments in oscillatory signals, particularly in delta and theta frequencies within the time window corresponding to Go- and NoGo-P3 components, i.e., the electrophysiological signals linked to execution and inhibition of a motor response. Furthermore, although our primary interest was in the EROs, we also examined the Go-P3 and NoGo-P3 signals of the ERPs in order to compare time-domain and frequency-domain measures.

Given that this is the first study that directly compares EROs in these two groups, our *a priori* hypothesis is based on the results from alcohol-dependent subjects. Thus, we hypothesize that delta/theta oscillations linked to response inhibition will be modulated by the BD pattern. Specifically, we predict that young BDs will display reduced oscillatory activity in delta/theta frequency ranges during response inhibition processes as compared to age-matched controls with low or no alcohol consumption.

## **2. Materials and Methods**

### **2.1 Participants**

Seventy-two students from the Complutense University of Madrid (Spain) participated in the study. Participants were selected on the basis of their responses to a questionnaire that included the Spanish validated version of the Alcohol Use Disorder Identification Test (AUDIT) (Guillamón et al., 1999). Participants were asked to keep a record of daily alcohol consumption by indicating the type of drink, the quantity and the intensity of drinking. Blood alcohol concentration (BAC) was calculated based on the information of the drinking episodes of the last six months according to the following formula:

$$BAC = \left( \frac{G}{W \times bw} \right) - mr \times DP$$

where  $G$  corresponds to grams of alcohol consumed on one occasion (the occasion of greatest consumption in the last month);  $W$  is body weight (kilograms);  $bw$  or body water is a constant related to the water content of the human body, with value 0.68 for males and 0.55 for females;  $mr$  is the metabolism rate with a value of 0.15 for males and 0.18 for females; and  $DP$  is the drinking period (hours). Taking into account the NIAAA's BD definition, where "a binge is a pattern of drinking alcohol that brings BAC to 0.08 grams per cent or above" (NIAAA, 2004), participants reaching  $BAC \geq 0.08$  g/dL at least once during the last month were classified as BDs. On the other hand, the control group consisted of students who have never reached an alcohol concentration of 0.08 grams. Consequently, 36 participants were classified as BDs (19 females) and 36 as controls (16 females); 20 of the controls (8 females) were abstainers.

Impulsivity was assessed by the Barratt Impulsiveness Scale (BIS-11; Patton et al., 1995) and psychopathological symptoms were measured by the Symptom Checklist-90 revised questionnaire (SCL-90-R; Derogatis, 1983). Likewise, participants were questioned about their use of other drugs such as tobacco, cannabis, cocaine, amphetamines and ecstasy (MDMA).

Exclusion criteria were: non-corrected sensory deficits, any episode of loss of consciousness for more than 20 minutes, history of traumatic brain injury or neurological disorder, personal history of psychopathological disorders (according to DSM-IV-TR criteria), family history of alcoholism or substance abuse in first degree relatives, consumption of medical drugs with psychoactive effects (e.g., sedatives or anxiolytics) during the week previous to the assessment, AUDIT scores  $\geq 20$ , and use of illegal drugs except cannabis.

## 2.2 Procedure

Participants were asked to abstain from consuming alcohol for at least 24 h before the experiment. They were submitted to a Breathalyzer test, and the assessment was only performed after verifying 0% breath alcohol level. Additionally, subjects were instructed not to smoke, or drink tea or coffee for at least 3 h before the assessment.

Participants performed a Go/NoGo task. They were instructed to fixate on a small cross located centrally on a LCD monitor. Squares or circles (green or blue) with a visual angle of  $3^\circ \times 3^\circ$  were equiprobably presented (50/50) during 100 ms in the centre of the screen with an 1100-1500 ms interstimulus interval (offset-onset). Figures were presented in a randomized order in two series of 200-225 stimuli around four minutes each. Subjects had to press a button (50% with their right hand and the other 50% with their left hand) as fast as possible to the Go trials (green circle and blue square) and not to respond to the NoGo trials (blue circle and green square).

All participants gave written informed consent and received monetary compensation for their participation. The experiment was undertaken in compliance with Spanish legislation and the Code of Ethical Principles for Medical Research Involving Humans Subjects outlined in the Declaration of Helsinki.

## **2.3 Data Analysis**

### *2.3.1 Analysis of behavioral and demographic data*

Only responses occurring between 100 and 1000 ms after the onset of a Go stimulus were considered to be correct responses. No-responses to NoGo stimuli were scored as correct inhibitions. Reaction time (RT) and percentage of correct responses and correct inhibitions were analysed by a Student's t-test for independent samples. The same statistical analysis was applied to demographic data.

### *2.3.2 Electroencephalographic recording*

The electroencephalogram (EEG) was recorded using a 64-channel ActiCap system (Brain Products, Munich, Germany). Electrodes were Ag/AgCl active electrodes with integrated circuit of noise suppression and they were located according to the 10/10 system (*American Clinical Neurophysiology Society, ACNS, 2006*). All active electrodes were referred to the nose tip and grounded with an electrode placed at Fpz. Vertical and horizontal electrooculogram activity was recorded to control for potentials evoked by eye

movements and blinks. According to impedance levels allowed by the ActiCap system, electrode impedances were kept below 20 k $\Omega$ . EEG signals were continuously amplified and digitized at a rate of 500 Hz, and filtered on-line with a 0.01–100 Hz band pass filter.

### *2.3.3 Event-Related Potential Analysis*

For the ERP analysis, data were processed with BrainVision Analyzer software (Version 2.1). The EEG signal was corrected for vertical and horizontal ocular artifacts by the procedure developed by Gratton et al. (1983). It was then digitally filtered off-line with a 0.1–30 Hz bandpass filter and segmented into epochs of 1000 ms (from -100 to 900 ms). Baseline correction was applied; epochs exceeding  $\pm 80\mu\text{V}$  at any scalp electrode were rejected and EEG epochs corresponding to incorrect responses (omissions or false alarms) were excluded. The number of retained trials was similar across the two conditions (Go and NoGo) for both groups.

ERP waveforms were extracted by averaging across trials for each condition. The averaged ERPs were analysed with a semiautomatic peak detection procedure and subsequently reviewed and manually corrected for each of the midline electrode sites of interest (MESOIs) (Andrew and Fein, 2010), these being Fz, FCz, Cz, CPz, and Pz. The nature of the task (four different stimuli with equal-probability for each of them) entails a noteworthy difficulty for response selection, which may lead to two P3 subcomponents (Falkenstein et al., 1994, 1995; Fox et al., 2000). In the present study we measured both early-P3 and late-P3. These subcomponents were identified in the averaged waveforms elicited by Go and NoGo stimuli as the largest positive peak between 300- 450 ms (early-P3) and between 500-600 ms (late-P3) after stimulus onset. Amplitude ( $\mu\text{V}$ ) and latency (ms) values of both components were obtained for each of the MESOIs. A mixed-model ANOVA with two between-subject factors (Group: control and BD; Gender: male and female) and two within-subject factors (Condition: Go and NoGo; Electrode: five MESOIs) was used to examine the data separately for each subcomponent (alpha level  $\leq 0.05$ ). Where appropriate, degrees of freedom were corrected by the Greenhouse-Geisser estimate, and post hoc paired comparisons were performed with the Bonferroni adjustment for multiple comparisons, also with an alpha level  $\leq 0.05$ .

### *2.3.4 Time-Frequency Analysis*

Along with ERP analysis, time-frequency analysis was carried out, which required some specific data pre-processing steps. For this analysis, the EEG signal was digitally filtered



off-line with a 0.1–70 Hz bandpass filter and then corrected for ocular artifacts by the same procedure used for the ERPs. The EEG signal was re-referenced to the averaged reference and segmented into epochs of 2000 ms, from 500 ms pre-stimulus to 1500 ms post-stimulus. Epochs exceeding  $\pm 80\mu\text{V}$  at any scalp electrode were rejected and, as with the ERPs, EEG epochs corresponding to incorrect responses were excluded.

Time-frequency decomposition was performed on MATLAB R2015a (v8.5.0.197613, MathWorks) by first multiplying the result of the Fast Fourier Transform (FFT) of the EEG data by the FFT of different complex Morlet wavelets, and then computing the inverse FFT (iFFT) of the result. 32 Morlet wavelets were created in logarithmically spaced steps from 1 Hz to 40 Hz, and with 3 cycles at the lowest frequency up to 10 at the highest frequency (also in logarithmically spaced steps). The iFFT yielded a complex estimate at each frequency  $f$  and time point  $t$  (with steps of 10 ms). To obtain the power spectrogram, the squared absolute value of the complex estimate in each  $tf$  point was computed. Resulting power values were normalized by transforming the power change of each  $tf$  point to dB, relative to the mean power in the baseline interval (from -300 to -100 ms) of each frequency, using the formula:  $\text{dB}_{tf} = 10 \log_{10}(\text{signal}_{tf} / \overline{\text{baseline}_f})$ ; where the bar over baseline indicates the mean of the baseline interval.

The resulting time-frequency values (total ERO power) were assessed statistically using the nonparametric cluster-based random permutation method (Maris & Oostenveld 2007). The clustering used 4000 iterations and was performed on time-frequency data for each condition (Go and NoGo) and for each of the MESOIs included in the ERP analysis. To create a null-hypothesis distribution, subjects were randomized across groups in each iteration, and then two-tailed independent samples t-tests were performed for each time-frequency point. The cluster with the maximum absolute sum of t-values among all significant ( $p < .01$ ) pixels was saved. When all permutations were completed, the t-values of the saved clusters were arranged in ascending order. A cluster was considered significant if the sum of t-values of significant pixels in the real t-tests was below the 2.5 percentile or above the 97.5 percentile in the sorted permutation t-values.

[INSERT TABLE 1 ABOUT HERE]

### **3. Results**

#### **3.1 Demographic results**

Demographic data are summarized in Table 1. There were no significant differences between groups regarding age, handedness, regular use of cannabis (several times a week or every day), age of onset of regular use of alcohol, general severity index (GSI) of the SCL-R or BIS-11 scores (neither in total scores nor in the three second order factors: attentional, motor and nonplanning). Groups differed significantly in total AUDIT score ( $p = .001$ ), regular use of tobacco (several times a week or every day) ( $p < .001$ ), and BAC ( $p = .001$ ).

### **3.1 Behavioural results**

Behavioural data are summarized in Table 2. Groups did not differ in any of the behavioural variables analysed (RT, percentage of correct responses and percentage of correct inhibitions).

[INSERT TABLE 2 ABOUT HERE]

### **3.2 ERP results**

The grand averages of ERPs for each group in both conditions are shown in Figure 1. Analysis of the early-P3 amplitude showed significant effects for Condition factor [ $F(1,68) = 42.26, p < .001$ ], with larger amplitude in the Go than in the NoGo condition, and also for Electrode factor [ $F(4,272) = 56.53, p < .001$ ], with the largest amplitude at Pz. Analysis of P3 latency only showed significant effects for Electrode factor [ $F(4,272) = 8.15, p < .001$ ], with the shortest latency at CPz. Regarding the late-P3, amplitude analysis only revealed significant effects for Condition ( $F(1,68) = 4.3; p = .042$ ) and Electrode ( $F(4,272) = 93.5; p < .001$ ) factors, showing larger amplitude in the Go than in the NoGo condition and the largest amplitude at Pz. Significant effects were also found in the latency analysis for the Condition ( $F(1,68) = 4.42; p = .039$ ) and Electrode ( $F(4,272) = 4.23; p = .002$ ) factors, showing longer latencies in the Go than in the NoGo condition and the shortest latency at Pz. There were no main effects or interactions involving group or sex in either amplitude or latency for any of the two subcomponents.

[INSERT FIGURE 1 ABOUT HERE]

### **3.3 Time-frequency results**

The time-frequency representation and the energy curves for each group in both conditions are shown in Figures 2 and 3 respectively. Statistical analysis showed significant differences between groups during the Go condition in central and parietal locations. Specifically, BDs displayed lower total power in delta and theta frequencies compared to controls at Cz ( $p = .022$ ; time window = 260-660 ms; frequency range = 2.8-8.0 Hz) and Pz ( $p = .013$ ; time window = 440-900 ms; frequency range = 2.3-5.5 Hz) electrodes. Regarding the NoGo condition, significant effects were found in frontal and parietal locations. Specifically, BDs exhibited lower delta and theta power than controls at Fz ( $p = .004$ ; time window = 350-820 ms; frequency range = 1.9-4.5 Hz) and Pz ( $p = .002$ ; time window = 350-900 ms; frequency range = 2.6-7.3 Hz) electrodes. In both conditions, the significant clusters showed maximal differences within the time range corresponding to Go-P3 and NoGo-P3 components, i.e., around 300-700 ms after the Go/NoGo signal onset (see Figure 2).

[INSERT FIGURE 2 ABOUT HERE]

[INSERT FIGURE 3 ABOUT HERE]

#### **4. Discussion**

This is the first study to examine oscillatory brain activity in young people with a BD pattern of alcohol consumption. Results reveal that BDs showed significantly lower delta and theta EROs during Go and NoGo conditions in comparison with the control group. These differences were localized in central and parietal regions for Go trials and in frontal and parietal regions for NoGo trials.

The results of the present study are consistent with previous ERO studies in chronic alcoholics during visual Go/NoGo tasks (Colrain et al., 2011; Kamarajan et al., 2004; Pandey et al., 2016), where significant differences between healthy controls and alcohol-dependent patients were observed in delta and theta oscillations during Go and NoGo conditions. In the first study, Kamarajan et al., (2004) reported reduced delta and theta oscillatory activity in abstinent chronic alcoholics that was more prominent in NoGo trials in the frontal region. The authors proposed that this decrease might be indicative of

disruption of the neural circuit responsible for inhibitory control and that this deficit might constitute an endophenotypic marker for alcoholism. Another study from the same research group showed lower evoked delta, theta and alpha power in alcoholics compared to controls for Go and NoGo stimuli (Pandey et al., 2016). Again, the results were interpreted as suggestive of neurofunctional deficits during inhibition and execution of a response. Finally, Colrain et al., (2011) observed attenuated delta oscillations in alcoholics during response inhibition, which was related to reduced white matter integrity in the cingulate bundles. According to the authors, the lower delta power observed in alcoholics compared to controls might emerge as a consequence of degradation of fronto-parietal pathways involved in inhibitory processing.

The present data examining EROs in young BDs extend previous findings reported in abstinent chronic alcoholics given that BDs, similarly to alcohol-dependent patients, displayed decreased delta and theta activity associated with response inhibition and response activation. Regarding these frequency bands, it has been argued that it is not possible to assign a single function to a given type of oscillatory activity since brain functions arise from series of superimposed oscillations in different frequency ranges (Başar et al., 2001a; Sauseng et al., 2007). Thus, delta and theta oscillations have been linked to multiple processes including perception, attention, signal detection, error monitoring, reward processing, memory, inhibition and decision making (Başar-Eroglu and Demiralp, 2001; Cohen et al., 2009; Güntekin and Başar, 2016; Marco-Pallarés et al., 2008; Sauseng et al., 2010; Yamanaka and Yamamoto, 2010; Yordanova et al., 2004). Even so, a number of studies have demonstrated that these frequency bands play an important and definite role in inhibitory control processes. Accordingly, increased delta and/or theta power has been reported for successful compared to failed inhibitions (Wessel and Aron, 2013, 2014) for withholding compared to execution of a response (Lavalley et al., 2014; Nigbur et al., 2011), as well as when a greater number of preceding Go stimuli are presented before the NoGo stimuli, which involve greater inhibitory effort (Harper et al., 2016). Likewise, delta and/or theta oscillations elicited by NoGo stimuli are reduced in subjects with high-risk for different disinhibitory spectrum disorders such as attention-deficit/hyperactivity disorder (Krämer et al., 2009) or alcoholism (Kamarajan et al., 2006), suggesting that weaker low-frequency oscillations linked to response inhibition may predispose individuals to develop alcoholism and/or other disinhibitory disorders.

Based on these findings and the results reported from studies on alcohol-dependent patients, it can be suggested that the reduced delta and theta power observed in the present study may reflect deficient oscillatory activity in young BDs during response inhibition. Furthermore, the finding that group differences were mostly detected within the time window corresponding to the NoGo-P3 –a component typically associated with motor inhibition (Smith et al., 2008; Wessel and Aron, 2015)- along with the fact that only the NoGo condition showed significantly lower delta and theta power in BDs compared to controls at the frontal region –the main region engaged in inhibitory control processes (Wiecki and Frank, 2013)- seems to strengthen the hypothesis that BD may be associated with functional anomalies in the neural oscillations linked to inhibitory responses.

Furthermore, this study has also shown abnormal oscillatory delta and theta activity in young BDs during response execution. Delta and theta power reductions in Go trials were localized in central and parietal sites and were maximal within the time range of Go-P3. These frequency bands have been considered the major contributors to the P3 signal (Başar-Eroglu et al., 1992; Demiralp et al., 2001). Go-P3 is functionally equivalent to the P3b component typically obtained in oddball tasks, which has been related to target detection involving both attention and memory processing (Polich, 2007). Thus, ERO anomalies in delta and theta oscillations during the Go condition might suggest dysfunctions in neurophysiological mechanisms underlying attentional and working-memory processes, which is a common finding in chronic alcoholics (Jones et al., 2006; Pandey et al., 2016).

Likewise, several studies have demonstrated that BDs perform poorly in inhibition-related neuropsychological tests such as Go/NoGo (Czapla et al., 2014), Stop-Signal (Nederkoorn et al., 2009), Monetary Incentive Control (Poulton et al., 2016) and Stroop tasks (Hallgren et al., 2013), indicating weaker inhibitory ability in subjects with a BD pattern compared to age-matched controls. In turn, some ERP studies evaluating inhibitory control in young BDs seem to point to functional disruptions in the neural responses associated with response inhibition. As such, anomalies in latency (Petit et al. 2012) and amplitude (López-Caneda et al., 2012; Smith and Mattick, 2013) of NoGo-P3 and Stop-P3 have been observed in young binge and social drinkers while trying to withhold a response.

Nevertheless, not all studies conducted on BDs have found these effects, since some recent reports (using also a visual GoNoGo task) have failed to show group

differences in these electrophysiological components linked to inhibition and execution responses (Watson et al., 2014, 2016). The present study also failed to find differences in Go- and NoGo-P3 responses, i.e., these components seemed not to be significantly affected by BD, which is contrary to what was observed in a previous study from our laboratory with a different sample (López-Caneda et al., 2012). One possible explanation for the absence of significant differences between groups in the Go- and NoGo-P3 components concerns the fact that subjects in our first study had been drinking alcohol for a longer time than BDs of the present study. In this regard, anomalies in NoGo-P3 only emerged after more than two years maintaining the BD pattern (López-Caneda et al., 2012). Thus, it is possible that the present study has failed to show time-domain differences between groups because impairments in ERPs might not be apparent in early stages of BD. However, electrophysiological differences might emerge when frequency-domain measures are used. In this vein, studies on offspring of alcoholics and high-alcohol preferring mice have shown stronger differences between groups for ERO signals than for P3 amplitude (Criado and Ehlers, 2009; Rangaswamy et al., 2007), suggesting that ERO measures are a more stable and useful marker in the study of alcoholism and related disorders (Gilmore et al., 2010; Pandey et al., 2012). Altogether, it can be suggested that ERO analysis may be able to detect electrophysiological anomalies linked to BD in youths when performing a Go/NoGo task that are not identifiable by standard time-domain analyses.

An additional question that arises from the present results is why ERO measures might provide unique information beyond the ERP amplitude measures. While ERPs contain information about time- and phase-locked activity, total ERO power measures contain contributions from both phase-locked and nonphase-locked activity and, consequently, provide independent information to that obtained from the ERP amplitude measures (Pfurtscheller and Lopes da Silva, 1999). Thus, these nonphase-locked oscillations –also known as induced activity or event-related synchronization/desynchronization (ERS/ERD)-, which cannot be extracted by traditional time-domain analyses, might account for the group differences observed in the present study. This possibility has been already reported from studies with alcohol-dependent patients and with offspring of alcoholics, from which has been proposed that ERO measures may provide additional or even more sensitive group discriminators than the ERPs (Andrew and Fein, 2010; Jones et al., 2006; Rangaswamy et al., 2007).

However, further inquiries regarding EROs in BD population are required to address this issue.

Finally, this study has some limitations that encourage us to be cautious when interpreting the results. On one hand, the limited sample size (although suitable for an EEG study) could undermine the reliability of results. Therefore additional research must be conducted in order to verify or refute the present results. On the other hand, the nature of this study does not allow us to determine whether these anomalies in EROs precede the BD pattern or, conversely, arise as a consequence of heavy alcohol drinking. In this sense, studies on offspring of alcoholics have found that such high-risk youths exhibit decreased power in delta and/or theta bands during the GoNoGo task (Kamarajan et al., 2006), as well as during oddball (Rangaswamy et al., 2007) and gambling (Kamarajan et al., 2015) tasks, suggesting that these effects might constitute a biological marker of vulnerability to alcoholism, rather than being a consequence of alcohol consumption. However, in the present study, in which individuals with a family history of alcoholism were excluded and where no differences were found among groups in impulsivity (as measured by BIS-11), no anomalous ERPs or EROs before the onset of alcohol consumption were expected, although longitudinal studies including *future* BDs without prior alcohol consumption are needed to test this hypothesis.

In summary, the present study is the first ERO study to report abnormal neural activity related to response execution and inhibition during a Go/NoGo task in young BDs. Specifically, this study showed weaker oscillatory responses in delta and theta bands during both response inhibition and response execution in the BD group as compared to age-matched control group mainly within the time window of 300-700 ms poststimulus. This finding is congruent with previous ERO studies in chronic alcoholics using visual Go/NoGo tasks, where lower delta and/or theta oscillations were reported in alcohol-dependent patients compared to healthy controls (Colrain et al., 2011; Kamarajan et al., 2004; Pandey et al., 2016). Thus, BDs appear to show disruptions in neural oscillations similar to those observed in subjects with alcohol dependence. The reduced delta and theta EROs might reflect impairments in the neural circuit involved in both the activation and inhibition of a response. This outcome might constitute a new manifestation of functional anomalies in inhibitory control and attentional/working memory processes in BDs, which could not be disclosed by means of traditional time-domain methods. These findings are particularly valuable since they are the first to evidence that oscillatory brain

activity may be a sensitive indicator of underlying brain anomalies in young BDs which could complement standard ERP measures.

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## Tables

Table 1. Demographic and drinking characteristics of the Control and Binge Drinking groups.

	Controls	Binge Drinkers
N (females)	36 (19)	36 (16)
Age	18.08 ± 0.28	18.08 ± 0.28
Handedness (right/ambidextrous/left)	32/3/1	33/2/1
Caucasian ethnicity (%)	100	100
Regular tobacco smokers	0	6*
Regular use of cannabis	0	0
Age of onset of regular drinking	16.56 ± 1.12	14.72 ± 1.18
Blood alcohol concentration (BAC) in a drinking day (g/dL)	0.01 ± 0.02	0.17 ± 0.09*
BIS-11 total score	60.19 ± 8.73	63.25 ± 9.12
GSI score	0.30 ± 0.17	0.30 ± 0.14
Total AUDIT score	0.94 ± 1.44	7.44 ± 1.29*

\*p ≤ .05 significant differences between groups.

Table 2. Performance scores in the Control and Binge Drinking groups (mean  $\pm$  SD).

<i>Behavioral Performance</i>	<i>Controls</i>	<i>Binge Drinkers</i>
Response Time (ms)	489.8 $\pm$ 49.19	512 $\pm$ 60.06
% Correct Responses	95.93 $\pm$ 5.42	95.14 $\pm$ 3.96
% Correct Inhibitions	90.79 $\pm$ 5.42	92.28 $\pm$ 5.65

## Figure Legends

**Fig. 1** Grand average of event-related potentials for Control (blue line) and Binge Drinking (red line) groups in response to Go and NoGo stimuli. Averages are presented for Fz, Cz and Pz electrodes.

**Fig. 2** Time-frequency representation of Go and NoGo conditions for Control and Binge Drinking groups at Cz and Pz (Go condition) and Fz and Pz (NoGo condition) electrodes. The area embedded within each frame represents the frequency ranges and the time window that showed significant between-group differences.

**Fig. 3** Energy curves of delta and theta power during Go and NoGo conditions. Curves correspond to the grand averages of the mean power values in delta and theta frequency bands. Data are presented for electrodes with significant between-group differences: Cz and Pz (Go condition); Fz and Pz (NoGo condition).