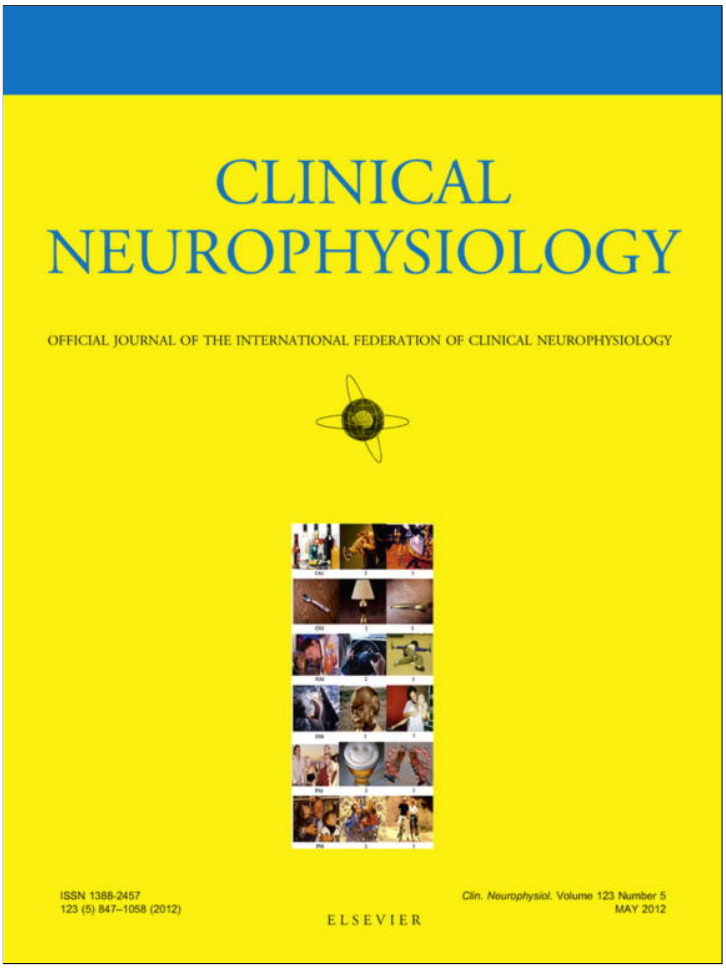

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Cerebral effects of binge drinking: Respective influences of global alcohol intake and consumption pattern

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HIGHLIGHTS

- Binge drinking leads to striking cerebral alterations, as indexed by event-related potentials.
- Young binge drinkers present early and global electrophysiological impairments, affecting low-level (perception and attention) as well as high-level (decision) cognitive stages.
- The specific consumption pattern observed in binge drinking (i.e., alternating intense intoxications and withdrawal episodes) is particularly deleterious for the brain.

ABSTRACT

Objective: Binge drinking is a major health concern, but its cerebral correlates are still largely unexplored. We aimed at exploring (1) the cognitive step at which these deficits appear and (2) the respective influence of global alcohol intake and specific binge-drinking consumption pattern on this deficit.
Methods: On the basis of a screening phase (593 students), 80 participants were selected and distributed in four groups (control non-drinkers, daily drinkers, low and high binge drinkers). Event-related potentials (ERPs) were recorded while performing a simple visual oddball task.
Results: Binge drinking was associated with massive ERP impairments, starting at the perceptive level (P100/N100 and N170/P2) and spreading through the attentional (N2b/P3a) and decisional (P3b) ones. Moreover, these deficits were linked with global alcohol intake and also with the specific binge-drinking consumption pattern.
Conclusions: Binge drinkers presented early and global ERP deficits, affecting basic and high-level cognitive stages. Moreover, we showed that binge drinking is deleterious for the brain because of alcohol consumption *per se*, and also because of its specific consumption pattern.
Significance: The present results show that binge-drinking habits lead to striking brain consequences, particularly because of the repeated alternation between intense intoxications and withdrawal episodes.

1. Introduction

Binge drinking, globally defined as the alternation between uncontrolled alcohol intake and abstinence periods, has become increasingly prominent during the past decade among young adults (Johnston et al., 2007). Forty percent of the 18–24-year-old people now fulfil criteria for binge drinking (D'Alessio et al., 2006; Kuntsche et al., 2004; Wechsler et al., 1999), which leads to deleterious effects: poorer academic results, less adequate social integration (Jennison, 2004; Read et al., 2007) and also cognitive impairments for visuospatial (Brumback et al., 2007), attentional (Giancola, 2002; Zeigler et al., 2005), memory (Blume et al., 2000) and executive (Goudriaan et al., 2007; Hartley et al., 2004; Johnson et al., 2008) abilities.

Anatomical and functional cerebral impairments associated with chronic alcoholism have been extensively described (e.g., Brooks, 2000; Chanraud et al., 2007; George et al., 2001; Meyerhoff et al., 2004). However, while the medical, social and cognitive consequences of binge drinking are clearly established, its cerebral correlates are still largely unexplored. Young binge drinkers seem particularly at risk concerning alcohol's brain impact, as animal

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studies showed that (1) the adolescent brain is in a critical period of development and is particularly sensitive to alcohol (Barron et al., 2005; Ehlers and Criado, 2010); and (2) binge drinking, characterised by the rapid alternation of intoxication and abstinence, leads to multiple withdrawals that are particularly deleterious for the brain (Obernier et al., 2002; Pascual et al., 2007).

Despite these arguments suggesting that binge-drinking habits should lead to negative brain effects, very few studies explored cerebral structure or functioning in this population. One recent study described electroencephalographic (EEG) modifications among binge drinkers during passive recording (i.e., EEG without any cognitive task, Courtney and Polich, 2010). Moreover, several works focussed on young chronic alcoholics who were not binge drinkers (e.g., De Bellis et al., 2000, 2005; McQueeny et al., 2009; Schweinsburg et al., 2005), and others explored binge drinking's cerebral effects among animals (White et al., 2000, 2002; Yttri et al., 2004) or specific human populations (e.g., polysubstance abusers or Native Americans, Ehlers et al., 2007). However, only four studies specifically explored the functional cerebral correlates of binge drinking in a general population and during a cognitive task, by means of event-related potentials (ERP) or functional magnetic resonance imaging (fMRI). These studies showed marked cerebral impairments in binge drinking: delayed latencies for P3b and the late positive component (Crego et al., 2009, 2010; Maurage et al., 2009a) and decreased occipito-hippocampal activations (Schweinsburg et al., 2010). These explorations constituted a crucial first step but presented several shortcomings:

(a) As they used complex cognitive tasks, it is unclear whether the cerebral abnormalities observed are part of a global brain impairment (also present for basic cognitive tasks) or whether brain functioning is only impaired when high-level cognitive processing is needed.
(b) As they focussed on specific ERP components and brain areas, several cerebral regions and electrophysiological components are still unexplored. Concerning ERP, earlier results cannot establish whether the cerebral alterations are specific for late components or already present earlier in the cognitive processing stream, as it has been described among alcoholics (i.e., perceptive, attentional and decisional stages). The timing of appearance of these deficits across the successive processing stages remains unexplored.
(c) Earlier studies only proposed a limited control of biasing variables. Particularly, binge drinkers with present nicotine dependence, recent marijuana use or sub-clinical psychopathological co-morbidities (e.g., depression, anxiety and alexithymia) have been included in these studies. As these uncontrolled characteristics modify cerebral functioning (e.g., Aftanas and Varlamov, 2007; Rossignol et al., 2008), the brain alterations described earlier could be explained partially by these co-morbidities rather than by binge drinking itself.
(d) Most importantly, earlier works were based on a simple comparison between binge drinkers and control non-drinkers (or very low drinkers). When a deficit is observed, this comparison does not allow distinguishing whether this impairment is due to the global quantity of alcohol intake (common to several populations such as binge, heavy or daily drinkers) or to the specific binge-drinking consumption pattern (i.e., rapid alternation between excessive consumption and abstinence periods).

A classical ERP paradigm (i.e., visual oddball) with four groups (non-drinkers, daily drinkers, low binge drinkers and high binge drinkers) was used here to overcome these limits and to answer four main questions:

(a) Is binge drinking leading to global cerebral dysfunction or only to specific alterations during complex cognitive tasks? By avoiding any strong implication of high-level cognitive functions (e.g., executive functions or high working memory load), the present paradigm allowed determining whether the brain impairment is generalisable to low-level cognitive processing, as it has been repeatedly observed in chronic alcoholism (Fein et al., 2009; Verma et al., 2006).
(b) Is the cerebral deficit limited to late ERP components or present throughout the cognitive processing stream? While earlier studies focussed on late waveforms, we explored the ERP correlates of every visual processing stage: general perceptive (P100/N100, Hillyard et al., 1973), specific face processing (N170/P2, Bentin et al., 1996), attentional (N2b/P3a, Knight, 1991; Patel and Azzam, 2005) and decisional (P3b, Polich, 2007; Sutton et al., 1965) stages (Rugg and Coles, 1995). This allowed specifying the timing of appearance of cerebral disturbances (i.e., at which cognitive stage they begin and how they spread throughout following steps).
(c) Are binge-drinking cerebral alterations partly due to co-morbid variables? The present study offered a strict control of co-morbidities.
(d) Is binge drinking deleterious for the brain because of alcohol consumption *per se* (i.e., global quantity of alcohol intake, 'quantitative effect') or because of its specific consumption mode (i.e., intoxication-withdrawal alternations, 'qualitative effect')? The comparison between low and high binge drinkers (i.e., same consumption pattern but different alcohol intakes) determined the influence of alcohol quantity, while the comparison between low binge drinkers and daily drinkers (i.e., same global intake but different consumption modes) clarified the specific influence of binge-drinking consumption.

2. Methods

2.1. Participants

A total of 593 students at the Catholic University of Louvain (Belgium) filled in a questionnaire assessing psychological measures and alcohol–drug consumption characteristics. On this basis, 80 students were selected, fulfilling the following criteria: no positive personal or family history of alcohol dependence, absence of past or current other drug consumption (including tobacco, marijuana and any medication), very low alcohol consumption and total absence of binge-drinking habits before starting university studies, no major medical or central nervous system problems, no visual impairment and low depression–anxiety scores. All participants were right-handed. According to their alcohol consumption during the last year (i.e., mean number of alcohol doses per drinking occasion (DPO), mean number of drinking occasions per week (NOW), consumption speed in doses per hour (CS) and mean number of alcohol doses per week (DPW)), students were then distributed among four groups (see Table 1): controls (CR, DPO <2; NOW <0.5; CS <1; DPW <2); daily drinkers (DD, 3–5 DPO; 5–7 NOW; CS <2; 15–29 DPW); low binge drinkers (B1, 5–12 DPO; 2–3 NOW; CS >3; 15–29 DPW); high binge drinkers (B2, DPO >10; 3–4 NOW; CS >3; DPW >30). Groups were balanced for age (age range: 19–24 years in each group), gender (11 males in each group) and education. All participants were assessed for psychological measures: state and trait anxiety (State-Trait-Anxiety Inventory (STAI A-B), Spielberger et al., 1983), depression (Beck Depression Inventory (BDI), Beck and Steer, 1987), interpersonal problems (Inventory of Interpersonal Problems (IIP), Horowitz et al., 1988) and alexithymia (Toronto Alexithymia Scale (TAS-20), Bagby et al., 1994). All subjects were asked to abstain from

Table 1
Demographic and alcohol consumption characteristics of control (CR), daily drinkers (DD), low binge drinkers (B1) and high binge drinkers (B2) groups: mean (SD).

	CR ($N = 20$)	DD ($N = 20$)	B1 ($N = 20$)	B2 ($N = 20$)
Age	21.6 (2.39)	22.1 (2.2)	21 (2.16)	21.2 (1.96)
Gender ratio (female/male)	9/11	9/11	9/11	9/11
Educational level[a]	15.8 (2.23)	16.2 (3.71)	15.1 (2.49)	15.3 (2.37)
Age at first alcohol consumption	13.38 (3.64)	13.5 (2.31)	12.7 (3.48)	13.15 (1.69)
Consumption during secondary school[b]	0.84 (0.98)	1.13 (1.37)	0.92 (0.79)	1.07 (1.71)
Age when starting regular consumption	NA	18.15 (1.46)	17.94 (1.26)	18.21 (1.21)
Duration of binge drinking habits (in months)	NA	NA	34.3 (4.54)	32.9 (6.39)
Consumption speed[c,d]	0.91 (0.25)	1.61 (1.58)	3.59 (1.55)	4.1 (1.62)
Number of doses per week[d]	0.85 (3.36)	19.5 (8.48)	21.5 (10.79)	42.9 (23.21)
Mean number of occasions per week[d]	0.25 (0.91)	6.11 (1.34)	2.33 (0.89)	3.53 (1.12)
Mean consumption per occasion[d]	1.12 (1.34)	3.97 (2.27)	9.75 (4.6)	13.2 (5.34)
Number of times drunk[d]	0.05 (0.22)	3.56 (8.92)	13.8 (7.84)	29.36 (17.83)

NA = not applicable.
[a] In number of years of education completed since starting primary school.
[b] In doses per week.
[c] In doses per hour.
[d] During the last year.

any alcohol consumption for at least 5 days before testing (which was postponed if this criterion was not fulfilled). Participants were provided with full details regarding the study and gave their written informed consent. The study was approved by the ethical committee of the Faculty of Psychology and has been conducted in accordance with the Declaration of Helsinki.

2.2. Task and procedure

A face-detection task (visual oddball paradigm) was used. This task is a useful tool to detect cerebral alterations among psychopathological populations (Campanella and Philippot, 2006) and comprises one regularly repeated frequent stimulus (female or male face) and four deviant rare ones. Rare faces differed from the frequent ones for luminosity (RLum, i.e., the same face but with higher general luminosity), identity (RId, i.e., a face depicting another person), eyes (REyes, i.e., the same face with eyes closed) or for a detail (RDet, i.e., the same face but presenting a slightly different nose or mouth). The stimuli were constructed using FaceGen Modeller (Singular Inversions Inc., 2008). Four basic neutral faces (two males) were elaborated and then modulated to obtain four rare stimuli. The experiment thus comprised 20 stimuli (4 faces $\times$ 5 stimuli), which were placed on a white background and resized to a 15 $\times$ 7.5 cm format (visual angle: 8 $\times$ 4°) using Photoshop 6.0.

Participants were presented with 16 blocks of 103 stimuli each (78 frequent, 25 rare), lasting for 160 s. The total number of stimuli was 1648 (1248 frequent ones, 100 for each rare condition). Only one frequent face was presented within each block (i.e., four blocks for each frequent face). The order of the 16 blocks randomly varied across participants. During ERP recordings, participants sat in a dark room on a chair placed 1 m from the screen with their head restrained in a chin rest. Each face was presented for 500 ms. A black screen (random duration: 800–1300 ms) was displayed between faces. From stimulus onset, participants had 1300 ms to indicate the occurrence of a rare stimulus by pressing a button with their right forefinger. Response time and percentage of correct answers were recorded. In view of the very low percentage of incorrect answers, only correct answers (i.e., detection of rare stimuli) were considered for analysis of reaction times (RTs) and ERP.

2.3. EEG recording and analysis

EEG was recorded by 32 electrodes mounted in an electrode Quick-Cap. Electrode positions included the standard 10-20 system locations and intermediate positions. Recordings were taken with a linked mastoid physical reference but re-referenced using a common average. The EEG was amplified by battery-operated ANT® amplifiers with a gain of 30,000 and a band-pass of 0.01–100 Hz. Impedance was kept below 5 kΩ. EEG was recorded continuously (sampling rate: 500 Hz) and the vertical electro-oculogram (VEOG) was recorded bipolarly from electrodes placed on the supraorbital ridge of both eyes. Data were analysed using Eeprobe (ANT software). Trials contaminated by EOG artefacts (mean: 8%) were manually eliminated off-line. Epochs were created starting 200 ms prior to stimulus onset and lasting for 1500 ms. Data were filtered (30 Hz low-pass filter). Three parameters were coded for each stimulus: (1) stimulus identity (2 males and 2 females); (2) stimulus type (Frequent/RLum/Rid/REyes/RDet) and (3) response type (keypress for deviant stimulus, no keypress for frequent stimulus). A time window was first determined for each ERP component (P100-N100:90–160 ms; N170-P2:160–210 ms; N2b-P3a:300–450 ms; P3b:450–650 ms). Peak selection was then conducted: For each participant and each component, individual peak amplitudes and maximum peak latencies were obtained for the ERPs resulting from the rare stimuli waveforms (P100/N100/N170/P2/P3b) or from the frequent minus rare stimuli subtraction waveform (N2b/P3a) and from several electrodes separately: Oz-O1-O2-T5-T6 for P100/N170/N2b (Joassin et al., 2004); Cz-C3-C4 for N100/P2 (Coull, 1998); Fz-F3-F4 for P3a (Polich, 2007); and Pz-P3-P4 for P3b (Polich, 2004). These values were tested using repeated measures of analysis of variance (ANOVA; Greenhouse–Geisser correction was applied when appropriate), *post hoc* least significant difference method (LSD) tests and *post hoc* *t*-tests (for group comparisons) and two-tailed Pearson correlations. Bonferroni correction was applied for multiple comparisons. Statistical Package for Social Sciences (SPSS) 17 was used to perform these analyses.

3. Results

3.1. Demographic and alcohol consumption characteristics

As described in Table 1, no group differences were found for gender, age ($F(3,76) = 1.06$; NS), educational level ($F(3,76) = 0.34$; NS), age at first alcohol consumption ($F(3,76) = 0.82$; NS), secondary school mean alcohol consumption ($F(3,76) = 0.21$; NS). Moreover, the drinking groups (i.e., DD–B1–B2) did not differ concerning the age at which they started drinking alcohol regularly ($F(3,57) = 0.49$; NS).

Nevertheless, groups differ concerning:

(1) Number of drinking occasions per week ($F(3,76) = 55.48$; $p < .001$): CR were lower than the other groups (DD: $t(19) = 12.34$; $p < .001$; B1: $t(19) = 6.92$; $p < .001$; B2: $t(19) = 10.16$; $p < .001$), DD was higher than B1 ($t(19) = 5.76$; $p < .001$) and B2 ($t(19) = 5.34$; $p < .001$) and B1 was lower than B2 ($t(19) = 3.94$; $p < .001$). In summary, DD > B2 > B1 > CR.

(2) Number of doses per occasion ($F(3,76) = 44.55$; $p < .001$): CR were lower than the other groups (DD: $t(19) = 6.23$; $p < .001$; B1: $t(19) = 7.71$; $p < .001$; B2: $t(19) = 9.83$; $p < .001$], B2 were higher than DD ($t(19) = 5.04$; $p < .001$) and B1 ($t(19) = 4.76$; $p < .001$) and B1 were higher than DD ($t(19) = 3.07$; $p < .01$). In summary, B2 > B1 > DD > CR.

(3) Number of doses per week ($F(3,76) = 3\ 2.07$; $p < .001$): CR were lower than the other groups (DD: $t(19) = 7.82$; $p < .001$; B1: $t(19) = 8.1$; $p < .001$; B2: $t(19) = 8.97$; $p < .001$) and B2 were higher than DD ($t(19) = 4.59$; $p < .001$) and B1 ($t(19) = 3.26$; $p < .01$). In summary, B2 > B1 = DD > CR.

(4) Alcohol consumption speed ($F(3,76) = 32.01$; $p < .001$): CR were lower than the other groups (DD: $t(19) = 5.13$; $p < .001$; B1: $t(19) = 9.23$; $p < .001$; B2: $t(19) = 10.39$; $p < .001$), B2 were higher than DD ($t(19) = 5.15$; $p < .001$) and B1 [$t(19) = 2.94$; $p < .01$], and B1 were higher than DD [$t(19) = 3.11$; $p < .01$]. In summary, B2 > B1 > DD > CR.

(5) Number of drunkenness episodes during the last year [$F(3,76) = 5.98$; $p = .001$]: CR were lower than the other groups [DD: $t(19) = 4.54$; $p < .001$; B1: $t(19) = 10.91$; $p < .001$; B2: $t(19) = 11.13$; $p < .001$], B2 were higher than DD [$t(19) = 6.74$; $p < .001$] and B1 [$t(19) = 5.49$; $p < .001$], and B1 were higher than DD [$t(19) = 2.04$; $p < .05$]. In summary, B2 > B1 > DD > CR.

3.2. Control measures

As described in Table 2, no group differences were observed concerning depression [$F(3,76) = 0.04$; NS], trait [$F(3,76) = 0.38$; NS] or state [$F(3,76) = 0.34$; NS] anxiety, interpersonal problems [$F(3,76) = 0.45$; NS] and alexithymia [$F(3,76) = 1.12$; NS].

Table 2
Psychopathological measures in control (CR), daily drinkers (DD), low binge drinkers (B1) and high binge drinkers (B2) groups: mean (S.D.).

	CR ($N = 20$)	DD ($N = 20$)	B1 ($N = 20$)	B2 ($N = 20$)
BDI[a]	2.94 (3.82)	3.01 (2.81)	3.15 (3.07)	3.21 (3.01)
STAI[b]A	30.65 (6.47)	32.95 (6.49)	33.3 (11.67)	31.89 (8.66)
STAI[b]B	36.25 (9.19)	38.55 (9.38)	37.3 (9.1)	39 (9.71)
IIP[c]	0.91 (0.46)	1.06 (0.52)	1.07 (0.54)	1.02 (0.46)
TAS-20[d]	45.32 (11.43)	50.2 (13.29)	47.25 (11.91)	50.68 (9.07)

[a] DI = Beck Depression Inventory (Beck and Steer, 1987).
[b] STAI = State and Trait Anxiety Inventory (Spielberger et al., 1983).
[c] IIP = Inventory of Interpersonal Problems (Horowitz et al., 1988).
[d] TAS-20 = Twenty-item Toronto Alexithymia Scale-II (Bagby et al., 1994).

3.3. Behavioural data

As no differences (performance or RTs) were found between the four identities, the results obtained for each identity were collapsed. Behavioural results are presented in Table 3. A 4 × 4 analysis of variance (ANOVA) with stimulus type as within-factor and group as between-factor was carried out for performance and RTs.

3.3.1. Performance

No effect was found for group [$F(3,76) = 0.39$; NS], or for group X stimulus type interaction [$F(9228) = 0.64$; NS], but there was a stimulus type main effect [$F(3228) = 143.03$; $p < .001$]: RDet led to lower performance than the other stimuli [Rid: $t(79) = 12.55$; $p < .001$; Reyes: $t(79) = 12.45$; $p < .001$; RLum: $t(79) = 11.53$; $p < .001$] and RLum led to lower performance than Rid [$t(79) = 6.09$, $p < .001$] and Reyes [$t(79) = 5.93$; $p < .001$].

3.3.2. RTs

No effect was found for group [$F(3,76) = 1.44$; NS], or for group X stimulus type interaction [$F(9228) = 1.52$; NS], but there was a stimulus type main effect [$F(3228) = 405.58$; $p < .001$]: RDet led to longer RTs than the other stimuli [Rid: $t(79) = 23.62$; $p < .001$; Reyes: $t(79) = 23.02$; $p < .001$; RLum: $t(79) = 9.8$; $p < .001$] and RLum led to longer RTs than Rid [$t(79) = 25.77$; $p < .001$] and Reyes [$t(79) = 21.45$; $p < .001$].

3.4. ERP data

Two 3(5) × 4 × 4 ANOVAs (one for amplitude, one for latency) were computed separately for each component of interest (i.e., P100, N100, N170, P2, N2b, P3a and P3b), with electrode (i.e., 3 or 5 according to the component: F3-Fz-F4 for P3a; C3-Cz-C4 for N100 and P2; P3-Pz-P4 for P3b; and T5-O1-Oz-O2-T6 for P100, N170 and N2b) and stimulus type (i.e., RLum, RDet, Reyes and Rid) as within-factors, and group (i.e., controls, daily drinkers, low binge drinkers and high binge drinkers) as between-factor. As the electrode effect was not the central focus of this study and as no (electrode × group) interaction effect was found, these results will not be reported. Moreover, as no group × stimulus type interaction effects were found, and as group differences were the main interest of our study, general effects (i.e., main effect of stimulus type) will be presented first, followed by group differences. ERP results are presented in Table 4 and Figs. 1 and 2.

3.4.1. General effects (i.e., not related to group differences)

Similar results were found for every ERP component (i.e., P100, N100, N170, P2, N2b, P3a and P3b), namely a significant main effect of stimulus type in amplitude and latency. As these results are similar across components, they will be summarised here by describing the threshold *F*-values and *p*-values (i.e., the minimal significant values observed across the different components). A main effect of stimulus type was thus found for every ERP

Table 3
Behavioral results of control (CR), daily drinkers (DD), low binge drinkers (B1) and high binge drinkers (B2) groups: performance (% of correct response) (S.D.) and reaction times (ms) (S.D.).

Group	Performance				RTs			
	RLum	RId	REyes	RDet	RLum	RId	REyes	RDet
CR ($N = 20$)	97.9 (2.1)	99.8 (0.4)	99.7 (0.5)	71.5 (21.6)	520 (46.2)	470 (43.5)	473 (47.1)	582 (66.7)
DD ($N = 20$)	96.2 (5.9)	99.5 (1.3)	99.2 (1.7)	74.1 (17.8)	556 (39.4)	490 (40.1)	487 (41.4)	591 (57.9)
B1 ($N = 20$)	95 (5.1)	99.8 (0.5)	99.6 (0.7)	72.9 (18.9)	569 (56.8)	502 (53.9)	502 (58.3)	602 (67.7)
B2 ($N = 20$)	97.8 (3.1)	99.1 (1.8)	99.2 (1.4)	78.1 (15)	543 (47.2)	492 (44.5)	494 (54.1)	595 (67.1)

RLum = Rare Luminosity; RId = Rare Identity; Reyes = Rare Eyes closed; RDet = Rare Detail.

Table 4
Electrophysiological results: Mean latencies (ms (SD)) and amplitudes (μv (SD)) across stimulus types and electrodes for P100, N100, N170, P2, N2b, P3a and P3b components, among control (C), daily drinkers (DD), low binge drinkers (B1) and high binge drinkers (B2) groups.

		P100		N100		N170		P2		N2b		P3a		P3b	
		Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
C (*N* = 20)		134 (7.2)	9.52 (2.9)	133 (7.2)	−4.79 (1.6)	185 (12.5)	−4.59 (2.9)	189 (12)	1.28 (1.4)	293 (20.4)	−5.46 (1.2)	300 (24.1)	3.70 (1.0)	481 (42.1)	5.53 (1.47)
DD (*N* = 20)		137 (9.1)	8.25 (2.3)	136 (10.6)	−4.14 (1.5)	187 (11.4)	−3.32 (2.6)	192 (15)	0.83 (1.3)	298 (27.5)	−4.42 (1.5)	311 (28.5)	3.51 (1.1)	506 (28.1)	5.25 (2.02)
B1 (*N* = 20)		136 (10.6)	7.32 (3.4)	136 (10.9)	−3.7 (1.2)	186 (15.5)	−2.03 (2.4)	193 (22)	−0.2 (1.1)	297 (17.7)	−3.91 (0.9)	310 (22.8)	3.74 (0.8)	517 (26.6)	4.12 (1.21)
B2 (*N* = 20)		144 (7.1)	6.69 (3.1)	146 (9.8)	−3.64 (1.5)	193 (17.2)	−1.08 (2.3)	200 (20)	−0.5 (1.4)	314 (27.5)	−4.04 (1.5)	338 (41.9)	3.41 (1.3)	525 (32.4)	3.95 (1.53)
Group Differences[a]	*F*-values	4.76	3.42	6.4	3.07	1.28	11.88	1.2	7.33	3.07	5.86	6.04	0.37	6.9	5.48
	p-values	<.01	<.05	<.001	<.05	N.S.	<.001	NS	<.001	<.05	<.001	<.001	N.S.	<.01	<.01
	t-tests	C = B1 = DD < B2	C > B1 = B2	C = DD = B1 < B2	C > B1 = B2		C = DD > B1 > B2		C = DD > B1 > B2	C = B1 = DD < B2	C > DD = B2 = B1	C = B1 = DD < B2	/	C < B1 = B2	C = DD < B2

[a] *F*-values for main group effect [*F*(3,76)], *p*-value for main group effect and significant group differences shown by *post hoc t*-tests.

component in latency [$F(3228) > 2.94$; $p < .05$] and amplitude [$F(3228) > 7.08$; $p < .001$]: RDet led to longer latencies than the other stimuli [RId: $t(79) > 3.34$; $p < .001$; REyes: $t(79) > 3.29$; $p < .001$; RLum: $t(79) > 2.91$; $p < .01$], and RLum led to longer latencies than Rid [$t(79) > 3.13$; $p < .001$] and Reyes [$t(79) > 2.97$; $p < .01$]. Moreover, RDet led to smaller amplitudes than the other stimuli [Rid: $t(79) > 7.59$; $p < .001$; REyes: $t(79) > 3.98$; $p < .001$; RLum: $t(79) > 2.2$; $p < .05$], and RLum led to smaller amplitudes than Rid [$t(79) > 6.34$; $p < .001$] and Reyes [$t(79) > 3.06$; $p < .01$].

3.4.2. Group effects

3.4.2.1. P100.

- *Latencies:* A group effect was found [$F(3,76) = 4.76$; $p < .01$]. B2 had longer latencies than the other groups [CR: $t(19) = 4.96$; $p < .001$; DD: $t(19) = 2.54$; $p < .05$; B1: $t(19) = 2.71$; $p < .05$].
- *Amplitudes:* A group effect was found [$F(3,76) = 3.42$; $p < .05$]. CR had higher amplitudes than B1 [$t(19) = 2.58$; $p < .05$] and B2 [$t(19) = 2.81$; $p < .05$].

3.4.2.2. N100.

- *Latencies:* A group effect was found [$F(3,76) = 6.4$; $p = .001$]. B2 had longer latencies than the other groups [CR: $t(19) = 4.67$; $p < .001$; DD: $t(19) = 3.14$; $p < .01$; B1: $t(19) = 3.05$; $p < .01$].
- *Amplitudes:* A group effect was found [$F(3,76) = 3.07$; $p < .05$]. CR had higher amplitudes than B1 [$t(19) = 2.6$; $p < 0.05$] and B2 [$t(19) = 2.21$; $p < .05$].

3.4.2.3. N170.

- *Latencies:* No group effect was found [$F(3,76) = 1.28$; NS].
- *Amplitudes:* A group effect was found [$F(3,76) = 11.88$; $p < .001$]. B2 had lower amplitudes than the other groups [CR: $t(19) = 5.51$; $p < .001$; DD: $t(19) = 4.4$; $p < .001$; B1: $t(19) = 2.66$; $p < .05$], and B1 had lower amplitudes than CR [$t(19) = 3.95$; $p = .001$].

3.4.2.4. P2.

- *Latencies:* No group effect was found [$F(3,76) = 1.2$; NS].
- *Amplitudes:* A group effect was found [$F(3,76) = 7.33$; $p < .001$]. B2 had lower amplitudes than the other groups [CR: $t(19) = 4.36$; $p < .001$; DD: $t(19) = 2.71$; $p < .05$; B1: $t(19) = 2.11$; $p < .05$], and B1 had lower amplitudes than CR [$t(19) = 2.92$; $p = .01$] and DD [$t(19) = 2.2$; $p = .05$].

3.4.2.5. N2b.

- *Latencies:* A group effect was found [$F(3,76) = 3.07$; $p < .05$]. B2 had longer latencies than the other groups [CR: $t(19) = 3.47$; $p < .01$; DD: $t(19) = 2.23$; $p < .05$; B1: $t(19) = 2.38$; $p < .05$].
- *Amplitudes:* A group effect was found [$F(3,76) = 5.86$; $p = .001$]. CR had higher amplitudes than the other groups [DD: $t(19) = 3.32$; $p < .01$; B1: $t(19) = 4.87$; $p < .001$; B2: $t(19) = 3.44$; $p < .001$].

3.4.2.6. P3a.

- *Latencies:* A group effect was found [$F(3,76) = 6.04$; $p < .001$]. B2 had longer latencies than the other groups [CR: $t(19) = 3.86$; $p = .001$; DD: $t(19) = 2.52$; $p < 0.05$; B1: $t(19) = 2.64$; $p < 0.05$].
- *Amplitudes:* No group effect was found [$F(3,76) = 0.37$; NS].

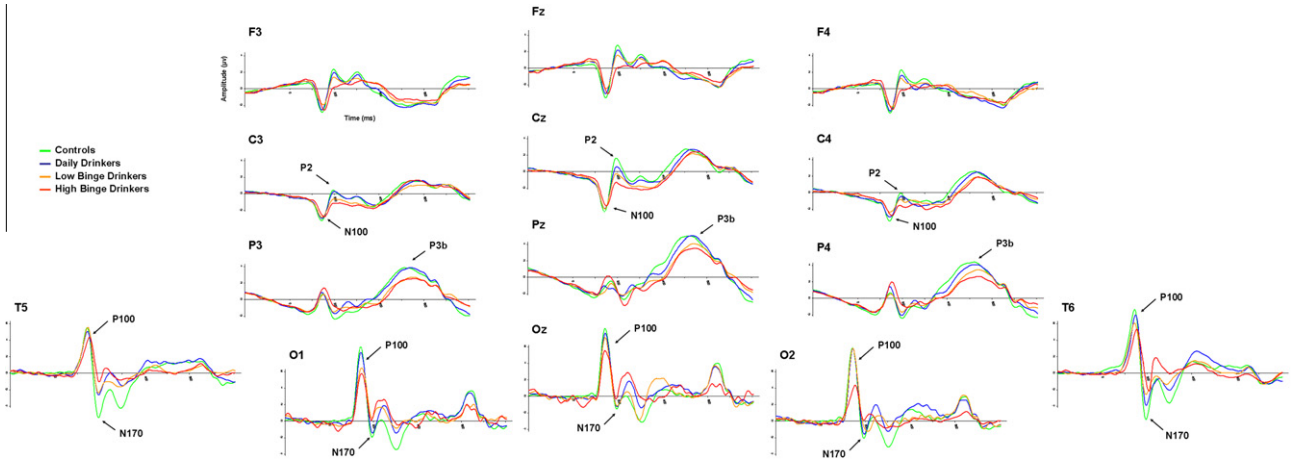

Fig. 1. Illustration of the electroencephalographic results for the rare stimuli, among controls (in green), daily drinkers (in blue), low binge drinkers (in orange) and high binge drinkers (in red). The waveforms are based on the collapsing of ERP data across stimulus types and show the ERP components associated with the rare stimuli (P100, N100, N170, P2, P3b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

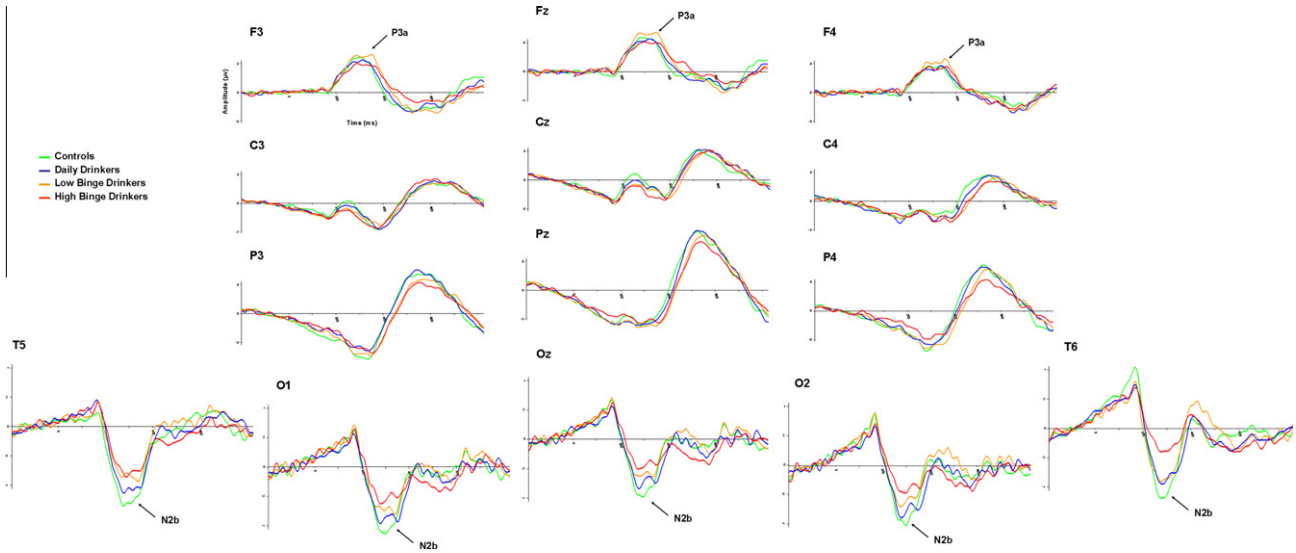

Fig. 2. Illustration of the electroencephalographic results associated with the subtraction between rare and frequent stimuli, among controls (in green), daily drinkers (in blue), low binge drinkers (in orange) and high binge drinkers (in red). The waveforms are based on the collapsing of ERP data across stimulus types and show the ERP components resulting from this subtraction (N2b, P3a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4.2.7. P3b.

- *Latencies:* A group effect was found [$F(3,76) = 6.9$; $p < .001$]. CR had shorter latencies than B1 [$t(19) = 3.25$; $p < .01$] and B2 [$t(19) = 4.13$; $p < .01$], and DD had shorter latencies than B2 [$t(19) = 2.39$; $p < .05$].
- *Amplitudes:* A group effect was found [$F(3,76) = 5.48$; $p < .01$]. CR and DD had higher amplitudes than B1 [CR–B1:$t(19) = 3.84$; $p < .01$; DD–B1: $t(19) = 2.12$; $p < .05$] and B2 [CR–B2: $t(19) = 4.06$; $p < .01$; DD–B2: $t(19) = 2.21$; $p < .05$].

3.5. Complementary analyses

(a) *Gender effect:* Gender was included as a covariate in ANOVAs. No gender influence was found for any experimental result ($p > 0.05$ for every test).

(b) *Influence of psychopathological scores:* Pearson's correlations (within each group and across groups) were computed between questionnaire scores and experimental results (behavioural and ERP). No significant correlations were found ($\rho < 0.16$; $p > 0.21$).

4. Discussion

While the deleterious cerebral correlates of binge-drinking habits among adolescents and young adults have been strongly suggested for a long time (particularly on the basis of animal studies), the specific exploration of these brain impairments only started very recently among humans. The few studies which focussed on this topic during the last 2 years led to crucial preliminary data by confirming the proposition of brain impairment associated with the repeated excessive consumption of alcohol over short periods of time. Nevertheless, many aspects of the links between binge drinking and cerebral functioning remain unclear. The present study used a strictly controlled ERP design with four experimental groups to answer several questions. More specifically, the simple visual oddball paradigm, which did not imply high level cognitive functions and evaluated the whole cognitive stream, was an effective tool to explore: (1) the generalisation of the impairment to basic cognitive task; (2) the timing of appearance and evolution of this impairment throughout the successive

processing stages; (3) the role played by co-morbidities; and (4) the respective responsibility of global alcohol intake and specific binge-drinking consumption pattern in this deficit.

As groups were simultaneously balanced for control measures (including duration of alcohol consumption habits) and distinguishable concerning binge drinking (i.e., DPO, CS, DPW and drunkenness episodes), it has been possible to test the quantitative (B1–B2 comparison) and qualitative (B1–DD comparison) brain effects of binge drinking. Using this tightly controlled experimental design, the present study evidenced that binge drinking is associated with a coherent pattern of cerebral impairments as indexed by delayed latencies (reflecting a reduced information processing speed, i.e., a slowed neuronal functioning and/or a delayed transmission between neural sources for the cognitive function associated with this component) and reduced amplitude (indexing a less intense information processing, i.e., a reduction of the neuronal population implied and/or a reduced firing intensity of the neurons associated with this cognitive function) of ERP components (see Rugg and Coles, 1995 for an exhaustive discussion concerning the interpretation of ERP components' delayed latencies or reduced amplitudes). These brain functioning alterations start very early along the cognitive stream, as basic visual processing waveforms (i.e., P100 and N100) are already impaired in amplitude (for both binge drinker groups) and latency (for B2). This initially reduced processing of visual information, then extends throughout the successive stages of cognitive processing, as shown by (1) reduced amplitude of specific face processing components (N170/P2) in both binge drinker groups; (2) reduced amplitude (for B1 and B2) and delayed latency (for B2) of the attention allocation complex (N2b/P3a) and finally (3) highly impaired decisional level (P3b) in latency and amplitude (for B1 and B2). Table 4 gives a general overview of these ERP results, which are clearly in line with previous ones (Crego et al., 2009, 2010; Courtney and Polich, 2010; Maurage et al., 2009a; Schweinsburg et al., 2010) demonstrating a strong harmful effect of binge-drinking habits on the brain. Moreover, they extend these earlier results by describing new electrophysiological correlates of binge-drinking habits.

4.1. Generalisation of the deficit to low-level cognitive tasks

As earlier studies used complex tasks to evaluate the cerebral effects of binge drinking, it was up to now impossible to decide whether these effects were specific for high-level cognitive functions (i.e., high working memory load and executive functions) or were indexing a general brain functioning deficit, independent of the cognitive functions implied in the task. The present data, showing ERP deficits among binge drinkers as compared to controls non-drinkers in a very simple task which does not involve high level cognitive processing, generalise earlier results to low-level cognitive processing (i.e., perceptive level) and confirm the hypothesis of a general brain functioning alteration associated with binge drinking.

This generalisation is notably interesting because low-level cognitive function impairments have been repeatedly observed in chronic alcoholism (e.g., Fein et al., 2009; Verma et al., 2006), and the observation of such deficits in binge drinking confirms the parallelism between these two alcohol-related problems. More specifically, our results strengthen the 'continuum hypothesis' (e.g., Enoch, 2006) suggesting that binge drinking and chronic alcoholism have to be considered as two stages of the same phenomenon, leading to parallel deficits, rather than as independent pathologies (e.g., Courtney and Polich, 2010; Wagner and Anthony, 2002). In other words, binge drinkers seem to present the same pattern of impairments as chronic alcoholics, the difference being quantitative (i.e., deficits are more marked in chronic alcoholism) and not qualitative (i.e., deficits affect the same cognitive functions).

4.2. Generalisation of the deficit throughout the cognitive stream

While earlier results focussed on late ERP components and only showed a deficit for specific waveforms (i.e., N2, P3b and LPC), our design explored all the successive visual processing stages to spot the timing of appearance and evolution of the deficits. We showed that binge drinking does not only affect late components, but is also associated with deficits starting very early and then extending to later processing stages. Binge drinking is linked with reduced and slowed down cerebral activity during the whole cognitive processing stream. More precisely:

- P100/N100 present reduced amplitude among B1 and B2 groups, and delayed latency among B2 group. As this ERP complex is associated with early primary perception (Heinze and Mangun, 1995), these results are the electrophysiological marker of a basic visual processing deficit in binge drinking, with a reduced and slowed (for intense binge drinking) neuronal activation associated with early processing of visual stimuli. Binge drinking thus leads to perceptual deficits at the cerebral level. It is worth underlining that the perceptive impairment is in line with an earlier study (Crews et al., 2007) proposing that binge drinking is particularly harmful for the visual cortex, as this region is characterised, during late adolescence, by a high vulnerability due to important remodelling and plasticity.
- N170/P2 presents reduced amplitude among B1 (and even more among B2) as compared to CR and DD. As N170/P2 index the specific perceptual processing of human faces (Bentin et al., 1996), these results show a shallower processing of human faces in binge drinking: These stimuli, presenting a high social value, are less deeply processed in binge drinking (and particularly in intense binge drinking). Nevertheless, as no deficit was observed for latencies, the specific processing of faces seems to have a preserved speed. It can thus be hypothesised that face processing in binge drinking has a normal speed but a lower intensity as compared to control participants. This observation of a face-processing deficit in binge drinking makes sense in view of the well-established face-processing impairments in alcohol dependence (particularly for emotional facial expressions, e.g., Philippot et al., 1999; Maurage et al., 2009b) and should thus be further explored in the future, notably using emotional faces.
- N2b/P3a present reduced amplitude among DD, B1 and B2 as compared to CR (for N2b), and delayed latencies among the B2 group. This is the only observation of a difference between the DD and CR groups, suggesting that moderate but daily alcohol consumption could lead to mild cognitive impairments at the attentional level, as the N2b/P3a complex reflects the voluntary switch of attention towards stimuli changes (Rossignol et al., 2008). These partial results should be confirmed, but it underlines the fact that daily drinking could have significant (while moderate) effects on attention. More centrally, binge drinking clearly leads to altered attentional processing at the electrophysiological level, which is totally in line with earlier studies showing attention impairments in binge drinking at the behavioural level (e.g., Giancola, 2002; Zeigler et al., 2005). In line with what had been observed for earlier components, moderate binge drinking only leads to a reduction of neuronal firing intensity (i.e., reduced amplitude) while intense binge drinking leads to both decreased intensity and processing speed, underlining the presence of a quantitative effect of binge drinking (see below for a more thorough discussion on this question).

– P3b presents delayed latencies and reduced amplitudes for B1 and B2. This late component is related to executive processing, as it is considered to reflect the decisional processes and mark the 'closure' of the processes linked to the stimulus, just before the motor response (Polich, 2004). The general deficit observed among binge drinkers for this component is an electrophysiological confirmation of the several descriptions of memory and executive impairments in binge drinking, for decision making, inhibition or flexibility (e.g., Blume et al., 2000; Goudriaan et al., 2007; Hartley et al., 2004): binge drinking leads to slowed and reduced executive functioning, and these alterations (particularly concerning inhibition) could be responsible for the inability to control alcohol consumption and for the evolution towards alcohol dependence.

Moreover, the early appearance and later spreading of this ERP deficit on the cognitive stream, which had already been suggested in our earlier study (Maurage et al., 2009a), makes sense in view of the continuum hypothesis. Indeed, ERPs have been used for decades among alcoholics, leading to strongly established results which allow reliable comparison with binge drinkers. Most electrophysiological studies among alcohol dependent patients focussed on P3b, showing marked amplitude and latency impairments (see Hansenne, 2006; Porjesz and Begleiter, 2003 for reviews). However, more recent explorations (e.g., Maurage et al., 2007; Nicolas et al., 1997) showed that earlier components also present amplitude and latency abnormalities in alcoholism, and particularly those associated with visuospatial and perceptive abilities (i.e., P100, N100 and N170) and with attentional processing (N2b/P3a). The parallelism between these results obtained among alcoholics and the present ones among binge drinkers undoubtedly supports the continuum hypothesis: binge drinking leads to comparable (while less marked) cerebral effects than chronic alcoholism. Moreover, it should be noted that the perceptive abnormalities (P100/N100) appear quite specific to alcohol-related problems, as they are not found in other psychiatric populations (e.g., depressive or psychopathic patients). This suggests a specific neurotoxic effect of alcohol consumption as compared to the brain-related deficit associated with other psychiatric states.

4.3. Influence of co-morbidities and consumption variables

The strict control of potentially biasing variables was also a central aim of the present study. Indeed, as other drug dependence (including cannabis or tobacco) and psychiatric pathologies (mainly depression and anxiety) are known to be frequently associated with binge drinking (Deas, 2006; Toumbourou et al., 2005), and as these co-morbidities have an influence on cognition and cerebral activities (see for example Ceballos, 2006 for review), these characteristics had to be controlled to avoid any possible alternative explanations of the results. While these variables have only been partially controlled in earlier studies, the present design excluded any influence of other drug consumption (by using cannabis and tobacco as exclusion criteria) and psychopathological co-morbidities (by using clinical depression and anxiety as exclusion criteria and by evaluating sub-clinical depression, anxiety and alexithymia's influence on the results). When these characteristics are controlled for, binge drinkers still present a marked electrophysiological deficit, thus showing that the cerebral impairment is indeed due to alcohol consumption itself.

4.4. Distinct effects of alcohol consumption quantity and alcohol consumption pattern

As underlined earlier, the inclusion of four groups with different alcohol consumption patterns allowed a multiple comparison design. The simple comparison between control non-drinkers and binge drinker groups allowed exploring the general electrophysiological consequences of binge drinking (see above for a detailed discussion of these general differences). However, two other comparisons are of first importance in our design:

(1) *Quantitative effect (B1–B2 comparison):* B1 and B2 were both characterised by a binge-drinking consumption pattern (rapid CS, high DPO and numerous drunkenness episodes), but B2 had a more intense consumption (higher NOW, DPO and DPW). A B1–B2 difference would thus index the 'quantitative effect' (i.e., influence of alcohol quantity, independent of consumption mode). As expected in view of animal studies, results showed this 'quantitative effect': B2 participants were impaired for nearly every ERP component's latency and amplitude (except for N170/P2 complex latency and for P3a amplitude) while B1 ones presented a more contrasted pattern (general amplitude impairment but preserved latency except for P3b). The cerebral consequences of binge drinking are thus dose dependent: moderate binge drinking mainly affects ERP amplitudes, while massive binge-drinking habits lead to a generalised ERP impairment (amplitude and latency). The 'quantitative effect' thus seems to be associated with a reduction of neuronal processing speed, as moderate binge drinkers show preserved ERP latencies while intense binge drinking (i.e., B2) leads to delayed neuronal transmission.

(2) *Qualitative effect (B1–DD comparison):* B1 and DD were similar for global alcohol consumption, but B1 had a typical binge-drinking consumption with far more concentrated alcohol intakes (less NOW but more DPO). A difference between these groups on experimental measures would thus demonstrate the specific influence of a binge-drinking pattern (independently of total alcohol intake), that is, a 'qualitative effect'. This study was the first to explore this effect among humans, and the results are unambiguous: While DD did not show any ERP impairment (except marginally reduced N2b amplitude), B1 participants had a significant amplitude reduction throughout every ERP complex, indexing a less intense information processing at perceptive, attentional and decisional stages. The main result of this study is thus to show a qualitative effect associated with binge drinking. This phenomenon is of course deleterious for the brain not only because of general alcohol consumption (as it had been observed in earlier studies), but also for its specific consumption pattern. Consuming the same global amount of alcohol is more harmful for the brain when this consumption is more concentrated (i.e., less NOW but more DPO). As it had been shown earlier among animals (see Hunt, 1993 for a review), the binge-drinking consumption mode (based on repeated alternations between acute intoxication and withdrawal periods) is thus particularly neurotoxic, independently of the total number of doses consumed.

These electrophysiological impairments were observed in the absence of any behavioural difference (even for the high binge drinkers). This is perfectly in line with earlier studies exploring binge-drinking cerebral correlates (Crego et al., 2009, 2010; Maurage et al., 2009a; Schweinsburg et al., 2010). Cerebral dysfunctions appear earlier than detectable behavioural impairments. It suggests that cognitive effects of binge drinking (up to now mostly evaluated on the basis of behavioural studies) could have been underestimated. This underlines the usefulness of neuroimaging techniques to correctly evaluate an alteration that is still undetectable at the behavioural level.

5. Conclusion

The frequency and intensity of binge-drinking habits have been highly growing during the past decade (Gill, 2002), this behaviour becoming a central social and medical concern. It is thus crucial to better understand this disorder, notably concerning its cognitive and cerebral consequences. This study is the first to (1) describe an early and global ERP deficit among binge drinkers, starting from very basic cognitive stages and then spreading towards higher level processing; (2) show that binge drinking is not only deleterious for the brain because of alcohol consumption itself, but also because of the specific consumption pattern in binge drinking which is made of repeated and fast alternation between extreme acute intoxication and abstinence periods. This suggests that binge-drinking consequences for the brain are early and marked, and that binge-drinking consumption mode is particularly harmful. These deficits, and their similarities with those observed among chronic alcoholism, call for an urgent and massive exploration of binge drinking, particularly among adolescents and young adults, and for the development of ambitious information and therapeutic programmes (Grenard et al., 2007; Weitzman et al., 2004).

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