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Neurobiological and Cognitive Profile of Young Binge Drinkers: a Systematic Review and Meta-Analysis

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Abstract

This review provides the first systematic and quantitative synthesis of the literature examining the relationship between binge drinking, cognition, brain structure and function in youth aged 10 to 24 years. PubMed, EMBASE, Medline, PsychINFO and ProQuest were searched for neuroimaging, neurophysiological, and neuropsychological studies. A total of 58 studies (21 neuroimaging, 16 neurophysiological, 21 neuropsychological) met the eligibility criteria and were included in the review. Overall, abnormal or delayed development of key frontal executive-control regions may predispose youth to binge drink. These abnormalities appear to be further exacerbated by the uptake of binge drinking, in addition to alcohol-related neural aberrations in reward-seeking and incentive salience regions, indexed by cognitive deficits and maladaptive alcohol associations. A meta-analysis of neuropsychological correlates identified that binge drinking in youth was associated with a small overall neurocognitive deficit ($g = -0.26$) and specific deficits in decision-making ($g = -1.70$), and inhibition ($g = -0.39$). Using the Grades of Recommendation, Assessment, Development, and Evaluation (GRADE) Evidence Profile, the certainty in outcomes ranged from very low to low. Future prospective longitudinal studies should address concomitant factors, exposure thresholds, and age-related vulnerabilities of binge drinking, as well as the degree of recovery following discontinuation of use.

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Compliance with Ethical Standards

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Keywords

Alcohol; Binge drinking; Neurodevelopment; Brain structure; Brain function; Cognition

Introduction

Adolescence (10 to 19 years) and young adulthood (20 to 24 years) are unique transitional periods associated with age-related neural and cognitive changes (Crews, He, & Hodge, 2007; Spear, 2013). Behaviourally, this period is characterised by heightened exploration, risk-taking, sensation-seeking, and socialisation (Steinberg, 2010). Together, these factors contribute to a young person's increased propensity to experiment and engage in risk-taking behaviours, including alcohol and other drug use, and consume elevated levels of alcohol relative to that of adults (Macpherson, Magidson Jessica, Reynolds Elizabeth, Kahler Christopher, & Lejuez, 2010).

Adolescent drinking frequently consists of heavy binges separated by periods of abstinence, often clustering around social events (Bräker, Göbel, Scheithauer, & Soellner, 2015). Binge drinking is defined as a pattern of alcohol use that brings blood alcohol concentration (BAC) levels to 0.08 g/dL, which typically occurs after the consumption of four or more standard alcoholic drinks for females and five or more drinks for males, over a 2 h period (Substance Abuse and Mental Health Services Administration, 2016; National Institute on Alcohol Abuse and Alcoholism, 2018). This episodic pattern of drinking is most common among adolescents in Western countries. For instance, in the United States (US), 4%, 9% and 14% of 14, 16 and 18 year olds, respectively, reported binge drinking in the previous 2 weeks (Johnston et al., 2019). Similarly in Australia, 2%, 9% and 17% of 14, 16 and 17 year olds reported binge drinking in the previous week (White & Williams, 2016). Across 35 European countries, an average of 35% of secondary school students, aged 16 years, reported binge drinking in the previous month, with the highest prevalence in Austria, Cyprus, and Denmark, where more than 50% of students reported this drinking pattern (Kraus et al., 2016). The prevalence of binge drinking sharply increases from adolescence to young adulthood, with 38% of 18 to 25 year olds in the US (Substance Abuse and Mental Health Services Administration, 2017), 42% of 18 to 24 year olds in Australia (Australian Institute of Health and Welfare, 2017) and 42% of 16 to 24 year olds in the United Kingdom (UK; Office for National Statistics, 2018) reporting binge drinking at least monthly. These statistics are concerning because early alcohol use and binge drinking are associated with a myriad of short- and long-term negative consequences including blackouts, hangovers, and alcohol poisoning (Hermens & Lagopoulos, 2018; Labhart, Livingston, Engels, & Kuntsche, 2018), alcohol and drug use disorders (Dwyer-Lindgren & Bertozzi-Villa, 2018), other mental health problems (Teesson et al., 2010; Welsh et al., 2017), risky sexual behaviours (Townshend, Kambouropoulos, Griffin, Hunt, & Milani, 2014), injuries (Rehm & Shield, 2014), increased risk of violence exposure (Oosterhoff, Kaplow, & Layne, 2016), and suicide (Pompili et al., 2010).

A variety of factors undoubtedly contribute to the elevated levels of alcohol consumption in adolescence and young adulthood, and maturational changes in the brain are likely to play a

central role. Subcortical limbic regions that modulate reward, emotion, and impulsive motivations mature during mid-adolescence (14 to 17 years), prior to the development of prefrontal top-down executive control circuits in early adulthood (21 to 24 years; Shulman et al., 2016). This imbalance in brain region development is thought to create a reward bias which enhances a young person's affinity towards novel and risky activities, including alcohol use (Casey, Jones, & Hare, 2008; Steinberg, 2010). There is growing evidence that aberrant neural and cognitive developmental trajectories may cause some adolescents to be at an even greater risk of alcohol initiation (Squeglia et al., 2017). Furthermore, alcohol use during adolescence and young adulthood also appears to cause gradual attrition of cognitive functions and aberrant neural development trajectories (Spear, 2018). Since binge drinking is the dominant pattern of use among young people, it is critical that we investigate how this pattern of drinking is related to abnormalities in the developing brain and explore the associated negative consequences of binge drinking during a vulnerable developmental period.

The current evidence on the association between binge drinking and neurodevelopment during adolescence and young adulthood has been previously summarised in several narrative reviews (e.g., Petit, Maurage, Kornreich, Verbanck, & Campanella, 2014, Cservenka & Brumback, 2017, Spear, 2018, Hermens & Lagopoulos, 2018) and two systematic reviews (see Ewing, Sakhardande, & Blakemore, 2014 for a review of neuroimaging studies and Carbia, López-Caneda, Corral, & Cadaveira, 2018 for neuropsychological studies). Overall, these reviews have concluded that there were a number of structural (smaller grey and white matter volume, and lower white matter integrity), functional (abnormal activation during executive functioning and verbal encoding tasks, and latency differences during cognitive tasks in P1, N1, P3, P3b and P450) and cognitive (impairments in attention, executive functions, and verbal, non-verbal and spatial working memory) differences associated with binge drinking in youth. However, previous systematic reviews are limited by 1) the inclusion of concurrent substance use which may confound the specific effects of binge drinking, 2) providing no quantitative synthesis of the literature, 3) not disentangling the antecedents and consequences of binge drinking by synthesising prospective longitudinal studies, and 4) only including adolescents aged 10 to 19 years despite continued brain development until the mid-20s (i.e., Ewing et al., 2014). To date, there has also been limited systematic and quantitative synthesis of results across the cognitive and neuroscience fields. We are not aware of any systematic review which has integrated neuroimaging, neurophysiological, and neuropsychological data. Integrating this data is crucial because the refinement of cognitive processes is interleaved with the maturation of neural structure and function, and together these processes make an important contribution to excessive alcohol consumption (Spear, 2018).

The aim of this systematic review is to provide an update on the rapidly expanding neuroimaging, neurophysiological, and neuropsychological literature on binge drinking and neurodevelopment, understand the causal relationship between neural structure and function, cognition, and binge drinking, address limitations of previous systematic reviews, and conduct the first meta-analysis of these studies. By assessing this literature collectively, we will be able to provide a broader understanding of the impact binge drinking has on brain development and behaviour. Identifying antecedents of drinking will inform early detection

and the development of prevention and early intervention initiatives. While understanding the consequences of binge drinking is crucial for targeted cognitive and physiological treatment efforts.

Methods

Search Strategy and Study Eligibility

This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P) and Meta-Analysis of Observational Studies in Epidemiology (MOOSE) guidelines. The protocol was registered with the PROSPERO International Prospective Register of Systematic Reviews of the University of York (registration number: CRD42018086856) and has been previously published (Lees et al., 2018). Search terms were combinations of medical subject headings (MeSH) describing the participants (adolescent, teenager, youth, emerging adult, young adult), the exposure variable (alcohol, binge drinking, ethanol), and the assessment methods measuring the outcomes of interest [neuroimaging, brain imaging, magnetic resonance imaging (MRI), functional MRI (fMRI), diffusion tensor imaging (DTI), magnetic resonance spectroscopy (MRS), neurophysiological, electroencephalography (EEG), event-related potentials (ERP), neuropsychological, cognitive, verbal working memory tests, episodic memory tests, visuospatial working memory tests, verbal fluency tests, executive function tests, digit symbol substitution tests, reaction time, attention]. See the Supplementary Online Appendix File for the search strategy in Table 6.

Relevant literature from PubMed, EMBASE, Medline, PsychINFO and ProQuest was systematically searched to identify neuroimaging, neurophysiological, and neuropsychological studies that assessed the impact of binge drinking on neurodevelopment and neuropsychological task performance in adolescents and young adults, where the majority of participants were aged 10 to 24 years at first assessment. Studies were excluded if the majority of participants were significantly involved in substances other than alcohol (i.e., >5 cannabis use per month, >25 lifetime other drug use occasions), or if any participants had been clinically diagnosed with an alcohol use disorder, or any psychiatric, neurological, or pharmacological condition to ensure that outcomes were specific to binge drinking. Studies were included if participants also met criteria for moderate (for females: 1–3 drinks on any single day and ≤ 7 drinks per week; for males: 1–4 drinks on any single day and ≤ 14 drinks per week) or heavy drinking (for females: >3 drinks on any single day and/or > 7 drinks per week; for males: >4 drinks on any single day and/or > 14 drinks per week) with binges (National Institute on Alcohol Abuse and Alcoholism, 2018). Peer-reviewed cross-sectional and longitudinal neuroimaging, neurophysiological, and neuropsychological studies that provided original data were included. Reviews, reports and information in books or letters were not included. Further details of the search strategy and selection criteria are available in the Appendix File (Table 5) and the published protocol (Lees et al., 2018).

Systematic literature searches were conducted by reviewer one (BL) in April 2018 to assess publications from database inception to April 1, 2018. A snowballing technique was applied where the reference list of identified articles was screened for suitable studies. Reviewer one

screened all titles and abstracts from the peer-reviewed databases to determine eligibility for inclusion in the review. Reviewer two (LM) independently screened a random selection of 25% of abstracts to ensure accuracy in the study selection. Inter-rater reliability for abstracts of potentially eligible studies was high (96% agreement), Cohen's kappa (k = 0.803). Full-text versions of the potentially eligible studies were independently assessed by both reviewers to further determine eligibility for inclusion. Again, there was high inter-rater reliability of studies to be included in the review (87% agreement), k = 0.743. Consultation was held between the reviewers at the time of abstract screening and full-text assessment to reconcile the differences of opinion, and consensus in study selection was reached.

Meta-analyses were only conducted if the available data met established criteria (Muller et al., 2018) that requires all included experiments use the same search coverage (i.e., the same brain coverage, EEG and ERP components, neurocognitive domains) and that there were a sufficient number of studies included in the analysis (i.e., >17–20 experiments; Eickhoff et al., 2016). There was large heterogeneity in the EEG and ERP components measured for varying neurocognitive domains in neurophysiological studies, and there was insufficient data in neuroimaging structural (9 MRI, 1 DTI, 1 MRS studies) and functional experiments (10 fMRI studies). Therefore, a narrative synthesis was conducted. There was sufficient homogenous data to conduct a meta-analysis for neuropsychological studies (n = 42). Only observational, cross-sectional studies were included in the meta-analysis. Longitudinal studies were not included in the meta-analysis because reliable estimates were indeterminate. There were only six longitudinal studies reporting neuropsychological data, and there was large heterogeneity in length of follow-up (i.e., 1–60 months) and methods of reporting data, that is, baseline drinking criteria differed, where some studies reported no alcohol use at baseline and binge at follow-up, while others reported on continued binge behaviours. However, cross-sectional data (binge drinking vs. non-binge drinking participants) from longitudinal studies formed part of the meta-analysis of neuropsychological studies where available. Further details of the meta-analysis methods are provided in the Appendix File.

Data Extraction

Following the PRISMA guidelines, data on study information, participant characteristics, alcohol characteristics, and study characteristics were extracted into a table (see Table 1). The amount of alcohol in standard drinks differed across regions (i.e., US vs Europe) and this was noted during extraction. Standard drinks were converted to US criteria (14 g of pure alcohol per standard drink) to ensure consistency in reported results. The significant results for all neuroimaging, neurophysiological, and longitudinal neuropsychological studies were extracted into tables and classified according to the study type (see Tables 8, 9 and 10 in the Appendix File). All data was presented in terms of differences identified in the binge drinking sample compared to the non-binge drinking sample. Meta-analysis data presented in this review and a corresponding data dictionary is available on the Open Science Foundation website (https://osf.io/nx9cv/). To examine the effect of binge drinking on cognitive domains, reviewer one (BL) classified neuropsychological tasks into domains based on established theoretical principles of cognitive function (American Psychiatric Association, 2013; Schneider & McGrew, 2018), following widely known sources (see

Strauss, Sherman, & Spreen, 2006; Lezak, Howieson, Bigler, & Tranel, 2012) and previous reviews (Scott et al., 2018; Carbia et al., 2018). These domains were behavioural inhibition in impulsivity tasks, decision-making, delay discounting, expressive language, immediate memory, inhibition, long term memory, mental flexibility, planning, processing speed, recent memory, receptive language, recognition of emotions, sustained attention, visual perceptual, visuoconstructional, and working memory. Various frame-works exist that categorise these domains into overarching cognitive constructs, such as executive functions or fluid reasoning [e.g., the Diagnostic and Statistical Manual of Mental Disorders cognitive domains (American Psychiatric Association, 2013), the Cattell-Horn-Carroll taxonomy (Schneider & McGrew, 2018), and the Research Domain Criteria constructs (Cuthbert & Kozak, 2013)]. Due to inconsistencies across these frameworks, analyses were only conducted at the domain level. See Table 7 in the Appendix File for tests in each cognitive domain.

Statistical Analyses

Comprehensive Meta-Analysis Version 3.0 (Borenstein, Hedges, Higgins, & Rothstein, 2014) was used to compute effect sizes for individual studies, domains, and an overall effect for neurocognition, as well as determine the sampling variance of each effect size and the risk of bias. Random-effects models were adopted to account for wide variations in participant characteristics and methodological factors. The standardised mean difference was used as the measure of effect size and the Hedges correction for small sample bias (Hedges' *g*; 0.2 = small, 0.5 = medium, 0.8 = large) was applied (Hedges, 1985). Measures where low scores indicated better performance were adjusted so that a negative g statistic indicated worse performance in the binge drinking group. Most studies with neurocognitive behavioural measures reported on multiple cognitive tasks with multiple outcomes, indexing multiple cognitive domains. In cases where a study reported on more than one outcome for a single task indexing a single domain, the summary score was used (e.g. the Iowa Gambling Task net score) or a composite score was calculated (e.g. the 2-dot and 6-dot accuracy scores for the Visual Working Memory Task were averaged to calculate a composite score). In cases where a study used two cognitive tasks for one domain (e.g. the Digit Span Backward and N-Back Tasks, indexing working memory), the tasks were grouped together, and the average effect size was calculated. Finally, for the overall analysis of neurocognition, which included all domains, studies that reported on multiple domains were grouped together, and the average effect size was calculated.

To test for small study effects and the potential for publication bias, a funnel plot and trim and fill analysis were conducted. The funnel plot provided a visual sense of the relationship between effect size and precision (see Fig. 2 in the Appendix File). To quantify the amount of bias captured by the funnel plot, Egger's linear regression method was used for each domain (Egger, Smith, Schneider, & Minder, 1997, Sterne, Egger, & Smith, 2001). The Duval and Tweedie trim and fill method (Duval & Tweedie, 2000) for random-effects analyses provided an estimate of potential missing effects and yielded an effect size estimate after the bias had been taken into account.

Methodological Quality

The methodological quality of the studies was assessed using the Grades of Recommendation, Assessment, Development, and Evaluation (GRADE) approach (Brozek et al., 2009). In this rating system, observational studies receive a very low quality score and are upgraded only when there are no important threats to validity, there are large magnitude effects, a dose response is present, or when all plausible confounding factors are working against the direction of the observed effect (Ryan & Hill, 2016). Factors that reduce the quality of evidence include study limitations (risk of bias), inconsistency of results, indirectness of evidence, and imprecision. Risk of bias for neuroimaging and neurophysiological studies was considered against critical study limitations, including i) failure to apply appropriate eligibility criteria, ii) utilisation of flawed measurement of outcomes, iii) failure to adequately control for confounding variables, and iv) for longitudinal studies, inadequate procedures to follow-up participants (Schünemann, Brożek, Guyatt, & Oxman, 2013). Risk of bias for neuropsychological studies was measured in the meta-analysis through Egger's linear regression method (Egger et al., 1997, Sterne et al., 2001). Unexplained heterogeneity of results was assessed through examination of variance in point estimates across studies, and the Q, I^2, tau and tau^2 statistics in the meta-analysis (Schünemann et al., 2013). Directness of evidence is a measure ensuring research directly compares the study populations of interest (i.e., participants aged 10 to 24 years) with the correct dose (i.e., binge drinking) and outcomes of interest (i.e., cognitive, functional or structural measures), and compares these findings to a suitable control (i.e. non-binge drinking participants). Imprecision of results occurs when studies have included relatively few participants, and this leads to wide confidence intervals. Imprecision was assessed using the Optimal Information Size approach, where the total number of participants included in each outcome measure must be larger than the number of participants generated by a conventional sample size calculation for a single adequately powered trial, using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007).

Results

Characteristics of Studies

There were 58 eligible studies (Fig. 1, Table 1), including 21 neuroimaging studies (12 of which reported neuropsychological data), 16 neurophysiological studies (10 of which reported neuropsychological data), and 21 neuropsychological-only studies. There were seven neuroimaging, six neurophysiological, and six neuropsychological-only longitudinal studies. Of these longitudinal studies, six neuroimaging, one neurophysiological, and three neuropsychological-only studies conducted baseline assessments prior to the onset of regular alcohol use or binge drinking.

Studies were published between 2004 and 2018. There was considerable growth in the number of published studies, particularly for neuroimaging and neuropsychological-only studies. For neuroimaging studies, 81% were published after 2012, and 57% have been published since the last systematic review (between 2014 and 2018). Seventy-six per cent of neuroimaging studies were conducted in the US, 14% were conducted in the UK, 5% were conducted in Belgium, and 5% were conducted in China. For neurophysiological studies,

there has been a steady number of published papers with 50% published between 2009 and 2012, and 50% published between 2013 and 2017. Sixty-three per cent were conducted in Spain, 31% were conducted in Belgium, and 6% were conducted in the US. For neuropsychological-only studies, there was a recent spike in publications with 35% of studies being published in 2016 and 2017. Forty-three per cent were conducted in Spain, 24% were conducted in the UK, 14% were conducted in the US, 5% were conducted in Canada, and 5% were conducted in Korea.

Methodological Considerations

Using the GRADE Evidence Profile, the certainty in outcomes ranged from very low to low (Table 2). The majority of studies were observational (98%; 39 cross-sectional studies, 19 prospective cohort longitudinal studies) and one fMRI study was an interventional pre-post design (2%). Twelve outcomes (60%), including behavioural inhibition only, decision-making, delay discounting, expressive language, inhibition, planning, processing speed, recent memory, receptive language, visual perceptual, visuoconstructional, and recognition of emotions received a very low certainty score. There was serious concern of risk of bias for decision-making ($t = 2.57$, $p < 0.05$), inhibition ($t = 2.50$, $p < 0.05$), and processing speed ($t = 2.27$, $p < 0.05$), as measured by Egger's test. There was serious concern regarding inconsistency of results for decision-making, inhibition, processing speed, and recent memory, where I^2 was between 75 and 100%. Finally, there was serious concern of imprecision in results for behavioural inhibition only, delay discounting, expressive language, planning, receptive language, visual perceptual, visuoconstructional, and recognition of emotions, where the number of participants included in the review was smaller than the required number of participants generated from a sample size calculator for a single adequately powered trial. Eight outcomes (40%), including brain electrical activity, functional neural activity, immediate memory, long term memory, mental flexibility, neural structure and connectivity, sustained attention, and working memory were upgraded from very low to low because there were either no important threats to validity (i.e., risk of bias, inconsistency in results, indirectness of evidence, imprecision of results, publication bias). The indirectness of evidence was not serious for any outcome.

Longitudinal Studies

Longitudinal studies provided insight into the cause-effect relationship between structural and functional brain differences, neurocognitive deficits, and binge drinking in adolescents and young adults. The following section reports on observed group differences between future binge drinking and non-binge drinking participants that predated heavy episodic use and perhaps represent vulnerability factors that promote greater consumption of alcohol following initiation of use. This is followed by a synthesis of studies that reported neural and cognitive consequences of binge drinking, and the results following abstinence from binge patterns of drinking.

Pre-Existing Aberrations

Six of ten longitudinal neuroimaging, neurophysiological, and neuropsychological studies that examined youth prior to binge drinking have provided evidence of neural and cognitive differences in adolescents and young adults that later predict the uptake of binge drinking

over a 9-month to 13-year period. A structural neuroimaging study, which captures static images of the brain in an MRI scanner, observed 40 adolescents for three years, where the mean age was 15 years at baseline and 17.6 years at follow up (Squeglia et al., 2014). The researchers found that individuals who later transitioned to heavy drinking with regular binges (n = 20) recorded smaller baseline brain volume in regions important for executive functions and reward processing [anterior cingulate cortex (ACC), inferior frontal gyrus, cingulate gyrus], and less right cerebellar white matter at baseline, when compared to participants who did not engage in binge drinking. A second structural imaging study examined 265 substance-naïve adolescents aged 12 to 14 at baseline and followed them annually for up to 13 years (maximum age 27; Brumback et al., 2016). They found that the surface area of the right dorsolateral prefrontal cortex (PFC) at baseline predicted the number of subsequent binge drinking occasions, with smaller surface area indicating more binges.

Functional neuroimaging studies, which measure neural activity in response to a task, have also provided insight into the vulnerability markers of youth at heighted risk of binge drinking. The standard variable of interest used in fMRI studies is blood-oxygen-level dependent (BOLD) signal which measures the regional differences in cerebral blood flow and volume to delineate regional neural activity. A three-year functional neuroimaging study of 40 participants aged 15 years at baseline measured changes in BOLD signal response to a visual working memory task (Squeglia, Pulido, et al., 2012). During the three-year follow-up period (mean age at follow-up = 18.1 years), 20 participants initiated regular heavy alcohol use and met criteria for binge drinking. At baseline, these participants exhibited less BOLD signal to cognitive challenges than continuous non-drinkers in regions associated with working memory and other executive functions, including the right inferior parietal lobule and the left medial frontal gyrus. In this study, lower baseline BOLD signal in these regions predicted a higher number of subsequent peak drinks during binge sessions and a higher number of drinking days. A second functional neuroimaging study assessed response inhibition, using an event-related Go/No-Go task, in 28 participants who were aged 11.7 to 16.7 years at baseline (Wetherill et al., 2013). At the three-year follow-up, 14 participants had initiated heavy drinking with binges (m = 18.5 years) and these participants exhibited less BOLD response at baseline during the Go/No-Go task in cortical (frontal, parietal) and subcortical regions (putamen, cerebellum) implicated in processes of working memory and response inhibition, when compared to individuals who did not initiate binge drinking.

Neurophysiological measures have also been used to investigate the relationship between neural activity and binge drinking. An EEG measures the electrical brain wave patterns by using electrodes attached to the scalp, and an ERP is the measured electrical response to a specific task or event. One nine-month longitudinal study measured the ERP components of 36 first-year university students aged 18 years in an auditory task based on emotional valence detection (Maurage et al., 2009). This study found that individuals who initiated binge drinking by age 19 exhibited delayed P1, N2 and P3b latencies indexing deficits in perceptive and decisional processes at baseline, when compared to those who did not initiate binge drinking. Importantly, the extent of these latency delays were proportional to the severity of binge drinking behaviour. Finally, one neuropsychological study observed 181 adolescents over a one-year period and participants who transitioned to binge drinking by

age 17 exhibited poorer performance on the Iowa Gambling Task at baseline compared to non-bingeing participants (Xiao et al., 2009). Poorer task performance, reflecting poorer decision-making ability, predicted consumption of a greater number of drinks over the following year.

In summary, longitudinal studies have provided evidence that smaller brain volume in frontal regions, less cerebellar white matter, smaller prefrontal surface area, less brain activation in frontoparietal regions during inhibition and working memory tasks, slowed cerebral activity, and poorer decision-making ability were associated with a greater likelihood of initiating binge drinking during adolescence or young adulthood.

Consequences of Binge Drinking

Twelve neuroimaging, neurophysiological, and neuropsychological studies provide evidence that binge drinking during adolescence and young adulthood has structural and functional neural consequences. A structural neuroimaging study observed 135 adolescents aged 15 years at baseline over a 3.5-year period (Squeglia et al., 2015). Over the follow-up period, 75 participants (mean age at follow-up = 19.6 years) initiated heavy drinking and met binge drinking criteria. Disrupted brain volume maturation was observed for these participants with greater neocortical, frontal and temporal grey matter volume reductions, and attenuated white matter growth of the pons and corpus callosum at follow-up, when compared to low drinkers who had consumed a maximum of 4 drinks in the previous year. In this study, male and female drinkers exhibited similar deviations in neural developmental trajectories. As part of the National Consortium on Alcohol and Neurodevelopment in Adolescence (NCANDA) study, Pfefferbaum et al. (2018) examined 483 participants aged 12 to 21 years over a two-year period. Of the adolescents and young adults who initiated alcohol use, 65 met criteria for moderate drinking with a mean age of 16.7 years and an average of 3.7 lifetime binges, and 62 met criteria for heavy drinking with a mean age of 17.1 years and an average of 15.8 lifetime binges. Following relatively low levels of binge drinking, the participants exhibited accelerated reductions in grey matter volume in frontal regions important for executive control, including the causal middle and superior frontal gyrus, and the posterior cingulate cortex. Furthermore, the neuroimaging study by Squeglia et al. (2014), which followed 40 adolescents aged 15 for three years, reported accelerated grey matter volume reductions in cortical (left inferior and middle temporal gyrus; important in visual object recognition and language comprehension) and subcortical (left ventral diencephalon, left caudate, brainstem; important for sensory integration, motor control, feedback processing, reward and habit learning) regions in adolescents who initiated heavy drinking with binges (m = 18 years), compared to adolescents who remained non- or low-drinkers over the follow-up period (m = 17.2 years).

The functional neuroimaging study by Wetherill et al. (2013) also identified neural consequences of binge drinking. From baseline to follow-up, participants aged 18.5 years who initiated heavy drinking exhibited increases in response inhibition BOLD contrast, while non- or low-drinkers aged 17.6 years showed attenuated responses. At follow-up, heavy drinkers reported greater response inhibition activity than non-or low-drinkers in cortical (middle frontal, right inferior parietal) and subcortical (left cerebellar tonsil)

structures in order to successfully inhibit prepotent responses. As previously noted, the functional neuroimaging study by Squeglia, Pulido, et al. (2012) reported less brain activation during a working memory task among binge drinkers prior to the onset of alcohol use. Following alcohol uptake, binge drinking adolescents aged 18.5 years showed increased BOLD response, whereas non-drinkers aged 17.7 years exhibited attenuated activation when compared to baseline in frontoparietal executive control regions. Therefore, the group differences in BOLD response identified at baseline were no longer present at follow-up.

Five neurophysiological longitudinal studies have followed continuous binge drinking participants over a period of one to six years. These studies did not assess participants prior to binge drinking uptake, and therefore, conclusions can only be drawn about the consequences of chronic binge drinking patterns rather than the effect of the uptake of binge drinking. Lopez-Caneda and colleagues conducted multiple two-year studies and assessed the transitional period from adolescence (18 to 19 years) to young adulthood (20 to 21 years) in three separate neurophysiological publications (Lopez-Caneda et al., 2012; Lopez-Caneda et al., 2013; Lopez-Caneda et al., 2014). The 2012 and 2014 studies utilised the Go/No-Go Task to measure response inhibition and the 2013 study utilised a Visual Oddball Task to measure complex attention. Lopez-Caneda et al. (2012) followed 48 participants while Lopez-Caneda et al. (2014) followed 57 participants. Both studies reported increased P3 amplitude, related to working memory and inhibitory control, in the central, parietal and frontal regions, as well as increased activation in the PFC and insula during inhibiting responses at follow-up in continuous binge drinkers, compared to non- or low-drinkers. Lopez-Caneda et al. (2013) followed 57 continuous binge drinkers and reported increased P3b amplitude in the central and parietal regions during attentional control at both evaluation times, with a more pronounced difference after two years of consistent binge drinking. A larger P3b amplitude was associated with an earlier onset of regular drinking, and greater frequency and quantity of binge drinking. These findings from Lopez-Caneda and colleagues suggest that continuous binge drinking may have a cumulative effect on brain activity and the anomalous activity may reflect degradation of underlying attentional and executive functioning mechanisms. A one-year study by Petit, Kornreich, et al. (2014) observed 30 young adults, aged 22 at baseline, during a Visual Oddball Task with alcohol-related cues. Continuous binge drinking over the follow-up period was associated with the emergence of electrophysiological abnormalities affecting visual (decreased P1 amplitude) and decision making processing (decreased P3 amplitude) for non-alcohol related stimuli, compared to non-binge drinkers. At follow-up, binge drinkers showed enhanced P3 amplitude to alcohol-related stimuli, suggesting the emergence of a bias towards alcohol with continuous binge drinking behaviour. Finally, Folgueira-Ares et al. (2017) assessed 50 young adults (m = 20.6 years) during an associative memory task, measuring recent memory, and reported that consistent binge drinking over a two-year period was associated with increased vertex positive potential (VPP) amplitude in the central region and increased difference due to memory effect (DM) amplitude in the centro-parietal and parieto-occipital regions for incorrect delayed memories, when compared with controls. Despite the absence of behavioural differences, these results indicate that consistent binge drinking is associated with anomalous processing during the encoding memory phase.

In terms of neurocognitive functioning, two longitudinal studies assessed youth before and after binge drinking initiation, and three longitudinal studies followed continuous binge drinking participants. A one-year study observed 116 young adolescents with a mean age of 14.5 years at baseline (Jones et al., 2017). A subsample began binge drinking during the follow-up period and the authors observed that higher total life-time drinks predicted escalated impulsive choice in a delay discounting task, when compared with adolescents who did not initiate binge drinking during the same period. A second neuropsychological study followed 89 young adolescents, with a mean age of 13.7 years at baseline, for one to five years (Squeglia et al., 2009). For females who transitioned into moderate to heavy drinking with binges, more past year drinking days predicted a greater reduction in visuoconstructional functioning as measured by the Complex Figure Task, and for males who transitioned into binge drinking, more past year hangover symptoms predicted worsened sustained attention as measured by the Digit Vigilance Test, when compared to females and males who remained non- or low-drinkers. A study by Mota et al. (2013) observed 89 young people with a mean age of 18.7 years at baseline over a two-year period and found consistent binge drinking was associated with poorer immediate and delayed recall, retention and working memory at age 20.5 years. Finally, two papers reported on a sample of participants who were followed-up for a six-year period during the ages of 18 to 23 years (Carbia, Cadaveira, Caamano-Isorna, et al., 2017, Carbia, Cadaveira, Lopez-Caneda, et al., 2017). Consistent binge drinking over the six-year period was associated with poorer immediate and delayed recall compared to stable non-binge drinkers, and this deficit remained stable over the follow-up period (Carbia, Cadaveira, Caamano-Isorna, et al., 2017). In this study, male and female drinkers exhibited similar deficits in episodic memory. Meanwhile, the second publication by Carbia, Cadaveira, Lopez-Caneda, et al. (2017) investigating working memory reported deficits in working memory span among binge drinkers compared to non-binge drinkers at baseline, however these participants (n = 76) showed some improvement over the following four years.

Together, these findings indicate that following the uptake of binge drinking, adolescents and young adults report accelerated grey matter volume reductions in cortical (neocortical, frontal, temporal, cingulate) and subcortical regions (ventral diencephalon, caudate, brainstem), attenuated growth in white matter structures, aberrations in frontoparietal brain activity during executive functioning tasks, and deficits in delay discounting, visuoconstructional functioning, and sustained attention. Consistent binge drinking over a period of one to two years had a cumulative impact on brain wave activity during tasks of inhibition, complex attention and recent associative memory, as well as when exposed to alcohol-related cues. Consistent binge drinking over a period of two to six years was associated with poorer learning, and long-term, episodic and working memory.

Discontinuation of Binge Drinking

Five studies reported on young people who discontinued binge drinking over a follow-up period of one month to six years. A functional neuroimaging study observed 38 adolescents, aged 16 to 19 years (Brumback et al., 2015). At baseline, binge drinkers exhibited greater BOLD response than controls when observing alcohol versus non-alcoholic beverage images, and following one-month of monitored alcohol abstinence, BOLD response was

similar between bingers and controls. A neurophysiological study evaluated ERP components in 57 university students at ages 18 to 19 and 20 to 21 during an inhibition task (Lopez-Caneda et al., 2014). Participants who had stopped binge drinking during the follow-up period displayed an intermediate position where their P3 amplitude, reflecting cognitive processing demand, was larger than control but smaller than continuous binge drinkers. Three neuropsychological studies have reported on the discontinuation of binge drinking. The first study followed youth, with a mean age of 18.8 years at baseline, over a two-year period and found that youth who stopped binge drinking by approximately age 21 improved their long-term memory performance. While the same participants' performance was superior to youth who continued to binge drink over the follow-up, these participants continued to perform worse than the non-drinkers (Mota et al., 2013). On the other hand, a second sample reported in two papers (Carbia, Cadaveira, Caamano-Isorna, et al., 2017; Carbia, Cadaveira, Lopez-Caneda, et al., 2017), found no improvement in immediate recall or long-term memory performance in the short-term (approximately two years). However, long-term abandonment of binge drinking (two to four years) led to improvements in immediate recall which matched performance in continuous non-binge drinking youth, and improvements in long-term memory which reflected an intermediate position between binge and non-drinkers (Carbia, Cadaveira, Caamano-Isorna, et al., 2017). Furthermore, the participants who discontinued binge drinking behaviour reported an intermediate position between binge drinking and non-binge drinking participants in working memory performance (Carbia, Cadaveira, Lopez-Caneda, et al., 2017). Overall, this suggests that some neural and cognitive effects of binge drinking appear to reduce after discontinuation. However, performance of discontinuers does not match those who have never engaged in binge drinking. Further details of all prospective longitudinal studies are provided in the Appendix File.

Cross-Sectional Studies

The following section reports on neural and cognitive group differences observed between binge drinkers and non- or low-drinkers in cross-sectional studies, where causality cannot be determined. The neuroimaging and neurophysiological evidence is presented first in a narrative synthesis, followed by a meta-analysis of neuropsychological findings.

Structural Differences

A total of eight structural neuroimaging studies reported on aberrations associated with binge drinking in adolescence or young adulthood. Lisdahl et al. (2013) examined 106 adolescents aged 16 to 19 years, of which 46 had engaged in binge drinking in the month prior to testing. They found that higher peak drinks (i.e., where participants met binge drinking criteria) predicted lower global white matter volume in the left hemisphere, and lower grey and white matter volume in the right hemisphere. Another study examined 76 young adults (m = 21.3 years) and identified sex differences (Kvamme et al., 2016). Compared to non- or low-drinkers, male bingers reported lower cortical volume and female bingers showed higher volume in cortical (prefrontal, inferior- and mid-temporal, motor, somatosensory) and subcortical (striatal) regions, which are important for executive functions, reinforcement of behaviour and reward, and movement. In terms of cortical thickness, a study by Squeglia, Sorg, et al. (2012) examined 59 adolescents aged 16 to 19

years and reported sex differences where male binge drinkers exhibited decreased cortical thickness while female binge drinkers exhibited increased cortical thickness in regions of the cognitive control frontal cortex, when compared to non-binge drinking participants. Furthermore, a study of 54 young people aged 18 to 24 reported decreased cortical thickness in the mid-ACC and posterior cingulate cortex among binge drinkers (Mashhoon et al., 2014). Cross-sectional baseline data from the NCANDA consortium showed that the number of binges in the previous year predicted decreased frontal and parietal cortical thickness (regions implicated in executive functions) in binge drinking youth with an average age of 18.6 years (Pfefferbaum et al., 2016). One cross-sectional MRS study, examining neurochemical changes, examined 54 young adults with a mean age of 21.7 years, and found greater binge drinking was associated with decreased grey matter voxel content, decreased Gamma-Aminobutyric Acid (GABA; an inhibitory neurotransmitter) and N-acetyl aspartate/creatine (NAA/Cr; a marker of neuronal integrity) in the ACC which is relevant to executive functioning, and increased white matter voxel content in the ACC (Silveri et al., 2014). This study further stratified the 23 binge drinkers into subgroups based on whether they had experienced alcohol induced black-outs ($n = 14$) or no black-outs ($n = 9$), and concluded that the observed group differences were driven by binge drinking individuals who had experienced black-outs. Finally, one cross-sectional DTI study of 28 adolescents was included in this review (McQueeny et al., 2009). DTI is an MRI technique sensitive to the movement of water, and a common outcome variable of this technique is fractional anisotropy which is sometimes reported as a measure of white matter integrity. This study reported lower fractional anisotropy in binge drinkers aged 18 years, reflecting poorer integrity in major white matter pathways throughout widespread regions of the brain, including the corpus callosum, internal and external capsules, coronal radiata, longitudinal fasciculus, and the cerebellar white matter tracts.

Overall, structural neuroimaging studies have found that binge drinking is associated with lower global grey and white matter volume, lower grey matter voxel content, decreased cortical thickness in frontal regions, decreased GABA and NAA/cr in the ACC, and poorer white matter integrity throughout the brain. Sex differences have been identified, where male binge drinkers have shown decreased volume and cortical thickness, while female binge drinkers have displayed the inverse.

Functional Differences

Five fMRI studies measured brain activity during executive functioning tasks, including working memory, inhibition, and decision-making. One study examined 32 young adults (m = 21.3 years), and measured working memory with a Two-Back Task in binge and non-binge drinkers (Campanella et al., 2013). Analyses revealed higher bilateral activity in the pre-supplementary motor area in binge drinkers than matched controls. In this study, the number of drinks per occasion was positively correlated with higher BOLD response in the dorsomedial PFC, which is important for stimulus perception and incentive salience, and the number of drinking occasions per week was predictive of higher BOLD activity in subcortical regions important for mental flexibility, including the cerebellum, thalamus, and insula. A second fMRI study also reported greater BOLD activity in the supplementary motor area, as well as regions of the frontal gyrus and inferior parietal gyrus in heavy and

binge drinkers aged 15 to 19 years (n = 20) compared to non-drinkers (n = 20) during a visual working memory task (Squeglia, Pulido, et al., 2012). A third fMRI study measured brain functioning during a spatial working memory task in 95 adolescents aged 16 to 19 years and those who met criteria for binge drinking reported decreased BOLD response in frontal regions important for working memory, compared to non-binge drinking participants (Squeglia et al., 2011). Sex differences were reported, where female binge drinkers exhibited lower BOLD responses and male binge drinkers exhibited greater BOLD responses to the spatial working memory tasks in the frontal, ACC, temporal and cerebellar cortices, when compared with non-drinking controls. A fourth study measured inhibition in 41 participants aged 18 to 22 years and found that heavy and binge drinking participants exhibited greater BOLD activation in the frontal cortex and ACC (implicated in inhibitory control and decision-making), and insula (implicated in incentive salience, reward and habit circuitry) during the no-go responses in the alcohol-related Go/No-Go task, when compared to non-binge drinking participants (Ames et al., 2014). Finally, Xiao et al. (2013) assessed 28 adolescents (m = 17.1 years) using the Iowa Gambling Task. Binge drinking was associated with abnormal decision-making, reflected by greater BOLD activity in subcortical regions underpinning emotion and reward processing, including the left amygdala and bilaterally in the insula.

One fMRI study measured brain activity during affective processing, and a second study measured activity during presentation of alcohol cues. Maurage et al. (2013) observed 24 young adults (m = 23.8 years) during a Two-Alternative Choice Task that aimed to capture affective processing and recognition of emotions. They found that binge drinkers showed greater BOLD response in the right middle frontal gyrus and lower BOLD activity bilaterally in the superior temporal gyrus which is important for processing of affective changes, when compared to low-drinkers. Finally, Brumback et al. (2015) examined 38 adolescents aged 16 to 18.9 years during an Alcohol Cue Reactivity Task and found greater BOLD activity in cortical (ACC) and subcortical regions implicated in reward, decision-making and movement, including the dorsal striatum, globus pallidus, cerebellum and parahippocampal gyrus, in binge drinkers when compared to controls.

Two EEG and one magnetoencephalography (MEG) study have examined differences between binge and non-binge drinking young people. The MEG is a non-invasive technique which measures the magnetic fields of neural activity. A study of 96 participants with a mean age of 20.6 years reported an association between binge drinking and increased mean spectral power reflecting a hyperactive central nervous system when compared to non-binge drinkers (Courtney & Polich, 2010). Additionally, they observed an association between extreme binge drinking (i.e., 10+ drinks on a single occasion; Johnston et al., 2008) and greater delta power when compared to regular-binge drinking. López-Caneda et al. (2017) assessed 80 adolescents with a mean age of 18.1 years and reported greater beta density (parahippocampus, fusiform gyrus; eyes open) and theta density (cuneus, lingual gyrus; eyes closed) in binge drinking participants when compared to non-binge drinkers, reflecting neurofunctional deficits in inhibitory control processes. Finally, Correas et al. (2015) examined 73 adolescents aged 18 and reported higher theta power (occipital) and functional connectivity (frontal-parietal), beta connectivity (frontal-temporal), and delta connectivity (frontal-temporal) among binge drinkers. In this study, binge drinking compared to non-

binge drinking participants also exhibited lower alpha power (temporal, occipital) and connectivity (frontal-temporal), which has an important functional role in the inhibitory process.

Four neurophysiological studies have measured ERP components during tasks of complex attention. One study, reported in two papers, assessed 95 young people aged 18 to 20 years and showed lower overall activation in the PFC (indicative of neurofunctional deficits in executive functions), a smaller late positive component in the frontal and central regions (Crego et al., 2010), and greater N2 amplitude (reflecting higher levels of attentional effort) in the central and parietal cortex in binge drinkers compared to controls (Crego et al., 2009). Lannoy et al. (2017) assessed 40 young adults (m = 20.7 years) and reported slower error processing (delayed error positivity component latency) in the central region among binge drinkers, when compared to control. Finally, Maurage et al. (2012) examined 60 young adults aged 19 to 24 years and reported ERP deficits affecting both basic and cognitive control processes, including delayed P100, N100, N2b, P3a and P3b latency, and decreased N100, N170, P100, P2 and N2b amplitude among binge drinkers, when compared with controls. This study also examined extreme-compared to regular-binge drinking participants and found delayed P100, N100, N2b and P3a latency, and decreased N170 and P2 amplitude among extreme binge drinkers.

Neurophysiological studies have also measured ERP amplitude in tasks of inhibition and alcohol cues. Lannoy et al. (2017) reported deficits in electrophysiological correlates of inhibitory control (greater ERN amplitude) in the frontal region during a speeded Go/No-Go Task. Lastly, Petit et al. (2012) reported evidence of early processing enhancement to alcohol cues in binge drinkers aged 19 to 26, indexed by higher P100 amplitudes in the central region and right hemisphere. In this study, longer duration of binge habits and increased number of alcohol doses per week were positively associated with higher P100 amplitude.

Overall, findings from fMRI and neurophysiological studies have provided insight into the functional aberrations associated with binge drinking. In adolescents and young adults, binge drinking was correlated with greater brain activity during working memory, inhibition and attentional tasks, higher brain wave activity during resting state, and aberrations in sensory and cognitive ERP components during attentional control and inhibition.

Meta-Analysis of Neurocognitive Measures

The following section reports on the results of a meta-analysis of neurocognitive deficits associated with binge drinking, utilising cross-sectional data. Of the 58 studies included in this review, 43 reported on neuropsychological data. One study had overlapping samples and data was removed (Crego et al., 2010). Four studies which reported on different tasks using overlapping samples were classified as two studies (Parada et al., 2011; Parada et al., 2012; Carbia, Cadaveira, Caamano-Isorna, et al., 2017; Carbia, Cadaveira, Lopez-Caneda, et al., 2017), and one study which reported on three separate samples, grouped by age, were classified as three studies (Gil-Hernandez et al., 2017). Therefore, 42 studies were found to be eligible for the meta-analysis, with 3,065 participants, including 1,313 binge drinkers and 1,752 comparison participants who did not meet criteria for binge drinking. A total of 186

effect sizes from 42 studies were coded (mean = −0.21; standard error = 0.25; effect size range = −4.34 to 3.25). Binge drinkers in the studies had a mean age of 18.88 (SD = 1.30) years and were 53% male. Comparison participants had a mean age of 18.83 (SD = 1.43) and 48% were male. The studies in this analysis were sampled from schools, universities, and the general population. Figure 2 in the Appendix File displays a funnel plot of neuropsychological effect size estimates against their standard error. Visual inspection of this funnel plot revealed slight asymmetry, and the test of Egger et al. (Egger et al., 1997) for small study effects revealed significant bias ($t = 3.04$; $p = 0.002$; see Table 3 for Egger's test of each domain). The Duval and Tweedie trim and fill method filled an additional five effect sizes and increased the effect size by approximately 23.1% in random-effects analyses (from $g = -0.26$; 95% CI −0.42, −0.10 to $g = -0.32$; 95% CI −0.47, −0.17).

Table 3 displays effect sizes by neurocognitive domain, which ranged from $g = -1.70$ to 0.34. The overall mean neurocognitive effect size was $g = -0.26$, and on average the between-study variance estimate was 0.01 ($p < 0.001$), indicating that variance between studies was significantly more than that explained by sampling error alone. Binge drinking was associated with significant deficits in decision-making ($g = -1.70$) and inhibition ($g = -0.39$), and enhanced processing speed ($g = 0.34$). Deficits in social cognition were observed in one study of emotion recognition and this was significantly associated with binge drinking ($g = -1.05$). Effect sizes were nonsignificant in the domains of mental flexibility ($g = -0.13$), planning ($g = -0.67$), behavioural inhibition ($g = -0.27$), delay discounting ($g = -0.12$), expressive ($g = -0.10$) and receptive language ($g = 0.17$), immediate memory ($g = 0.03$), long-term memory ($g = -0.04$), recent memory ($g = -0.53$), sustained attention ($g = -0.15$), visual perceptual ($g = 0.05$), visuoconstructional ($g = 0.05$), and working memory ($g = -0.15$). Significant heterogeneity was observed for decision-making, inhibition, recent memory, processing speed, and overall neurocognition, while no significant heterogeneity was reported for all other domains. Meta-analysis results based on a small number of studies (i.e., planning, delay discounting, behavioural inhibition, receptive language, recognition of emotions, visual perceptual) should be interpreted with caution due to the small sample size and lack of power. For a summary of the neural and cognitive aberrations that were pre-existing, consequential, and correlational with binge drinking, see Table 4.

Discussion

The purpose of this systematic review was to provide a synthesis of the neuroimaging, neurophysiological and neuropsychological literature investigating binge drinking in young people aged 10 to 24 years. A total of 58 studies met the eligibility criteria for the systematic review (see Fig. 1), including 21 neuroimaging, 16 neurophysiological, and 21 neuropsychological studies. Correlates of binge drinking were summarised from 39 cross-sectional studies and eight longitudinal studies, while the antecedents and consequences of binge drinking were drawn from one interventional pre-post study and 18 prospective longitudinal studies. A meta-analysis was only appropriate for the neuropsychological correlates of binge drinking and 42 studies were included in the analysis. The certainty in outcomes ranged from very low to low (see Table 2), and while methodological issues merit

serious consideration, the following tentative conclusions have been drawn about the relationship between binge drinking, brain development and cognition.

Vulnerability Markers of Binge Drinking

Developmental deviations in the frontal region, which plays a critical role in executive functions, appeared to be a key risk factor for the onset of binge drinking in adolescents and young adults. Specifically, young people who displayed structural (i.e., reduced brain volume and surface area in key frontal regions), functional (i.e., reduced neural activity in the frontoparietal region during executive functioning tasks, delayed ERP latencies indexing decisional processes) and cognitive (i.e., poorer decision-making ability) deviations from the expected developmental trajectory were more likely to initiate binge drinking. These deviations may reflect underdeveloped or abnormal frontal regions where impulse control is still relatively immature, allowing for unmediated reward-seeking behaviours like binge drinking (Casey et al., 2008). These findings are consistent with the broader work in this field examining vulnerability markers of alcohol initiation in adolescence through to alcohol dependence in adulthood (Bernardin, Maheut-Bosser, & Paille, 2014; Silveri, Dager, Cohen-Gilbert, & Sneider, 2016; Squeglia & Cservenka, 2017). This review therefore provides support for the continuum hypothesis of problematic drinking, where binge drinkers display analogous deficits that are quantitatively less marked than alcohol-dependent individuals (Enoch, 2006). This pattern of results may suggest that the deficits linked with binge drinking are likely to contribute to the maintenance of problematic patterns of alcohol use, including alcohol addiction through the inability to suppress maladaptive behaviour despite the adverse consequences (Volkow, Wang, Tomasi, & Baler, 2013).

Targeting these shared vulnerability mechanisms by strengthening executive functions in childhood and adolescence may be a promising prevention avenue to combat the shared risk, for some youth, of alcohol initiation and binge drinking in adolescence, and binge drinking and alcohol dependence in adulthood. Cognitive training treatment strategies have demonstrated success in reducing alcohol use (Bowley et al., 2013), in a range of clinical populations including substance use disorders (Keshavan, Vinogradov, Rumsey, Sherrill, & Wagner, 2014). However, the effectiveness of cognitive training as a prevention initiative has not been thoroughly investigated. There is evidence to suggest that greater inhibitory control skills, and greater integration of emotion regulation and impulse control in childhood are associated with reductions in alcohol use by early adolescence (Pentz, Riggs, & Warren, 2016), providing possible targets for future prevention initiatives, with trials currently underway (Bourque et al., 2016; Mewton, Hodge, Gates, Visontay, & Teesson, 2017; O'leary-Barrett et al., 2017).

Consequences of Binge Drinking

Pre-existing deficits in key frontoparietal regions were further exacerbated as a consequence of binge drinking in adolescence and young adulthood. Young people exhibited accelerated grey matter volume reductions and recruited greater cerebral activity during executive functioning tasks following the uptake of binge drinking. These findings support a frontal dysfunction hypothesis in binge drinking youth, which is similar to conclusions drawn for individuals with alcohol use disorder (Moselhy, Georgiou, & Kahn, 2001; Zorko, Marusic,

Cebasek-Travnik, & Bucik, 2004). Youth also exhibited attenuated white matter development, and accelerated grey matter volume reductions in the neocortex, caudate and across the limbic reward system following binge drinking, which is also consistent with the broader research field on alcohol use and neurofunction (Bernardin et al., 2014; Silveri et al., 2016; Squeglia & Gray, 2016; Zilverstand, Huang, Alia-Klein, & Goldstein, 2018). Accelerated grey matter reductions may reflect nonbeneficial pruning or premature cortical grey matter decline which is similar to patterns observed in adults with alcohol use disorder (Pfefferbaum et al., 1992) and 'normal' aging (Pfefferbaum et al., 2013). Furthermore, alterations in white matter development and cortical thinning disrupts efficient information processing required for cognitive and motor abilities (Squeglia, Jacobus, Sorg, Jernigan, & Tapert, 2013), and likely contributes to the alcohol-related cognitive dysfunctions identified in this review, including deficits in attention, learning, long-term and working memory, and visuoconstructional function.

Impairment to the caudate nucleus, limbic and frontal regions may be integral to the continuation of binge drinking, caused by a disruption in the mediation between reward hypersensitivity, goal selection and impulse control in the decision-making process around whether to drink, and to what extent (Grahn, Parkinson, & Owen, 2008; Spear, 2014). Cognitive substrates of these brain regions also appear to be impacted in binge drinking youth. Deficits in delay discounting were reported following the uptake of binge drinking and this relates to an increased motivation and impulsiveness towards reward and instant gratification in the decision-making process (Da Matta, Goncalves, & Bizarro, 2012). Additionally, cross-sectional neuropsychological evidence obtained from the meta-analysis reported an overall neurocognitive deficit in binge drinking youth, with specific deficits in decision-making and inhibition, and enhanced processing speed which may be indicative of increased impulsivity (Scaife & Duka, 2009). Overall, this review provides evidence of unbalanced interactions between reward-seeking, impulsive and higher order executive function brain regions, and the cognitive substrates, in binge drinking youth.

Components of the Positive Valence System which are related to the early stages of addictive disorders (Koob & Le Moal, 2005) – namely, approach motivations, reward learning and maladaptive habits (Morris & Cuthbert, 2012) – were implicated in binge drinking youth. Cognitive and neurobiological models of addiction propose that maladaptive reinforcement learning occurs following alcohol use, increasing the salience towards substances (Berridge, 2007). This implicit motivation towards alcohol use is linked to poorer executive functioning processes, including decision-making (Day, Kahler, Ahern, & Clark, 2015). Increased approach motivations compounded with poorer executive functioning ability leads to maladaptive habit formation and impaired response inhibition (Hogarth, Balleine, Corbit, & Killcross, 2013; Everitt & Robbins, 2016; Wiers & Gladwin, 2017; Zilverstand et al., 2018). Support for this progression towards addiction was found in this review, where consistent binge drinking over one to two years was associated with aberrant brain wave activity when exposed to alcohol-related cues, and consistent binge drinking over two to six years was associated with maladaptive learning and memory, and poorer executive functioning ability. Furthermore, cross-sectional evidence reported higher neural activity in binge drinkers during decision-making and alcohol cue reactivity tasks in regions including, but not limited to, the amygdala, insula and hippocampus, which are implicated in incentive salience, habit

circuitry, emotion-regulation and reward valuation (Öner, 2018). Overall, these findings suggest that there is a bias in approach motivations and reward appraisal following consistent binge drinking in youth and this may be a gateway for the development of addiction in these youth.

Discontinuation of Binge Drinking

This review also found preliminary, yet promising, evidence that discontinuation of binge drinking may lead to partial neural and cognitive recovery. Alcohol abstinence resulted in normalised BOLD response to alcohol cues and improved some neural (P3 amplitude during inhibition) and cognitive (recent, long-term and working memory) deficits associated with binge drinking, however performance did not match those who had never engaged in binge drinking. The mechanisms by which recovery may occur are not well understood. One suggestion is the young brain is more plastic and may be better at recovering from alcohol-related insults following abstinence (Berlucchi, 2011). On the other hand, improved cognitive performance following discontinuation of use may reflect enhanced neuroadaptation mechanisms (Bernardin et al., 2014). The duration of use may equally influence the rate of recovery, with young people experiencing a greater likelihood or recovery than individuals dependent on alcohol for a longer duration (Schottenbauer, Hommer, & Weingartner, 2007; Pitel et al., 2009). Critically, further evidence is required to determine whether recovery of other neural and cognitive domains – particularly substrates of executive functions – is possible, and whether habits and cognitive motivations can be updated to reorient the relationship between alcohol-related cues and incentives, executive control, and reward in binge drinking youth. There is growing evidence to suggest that retraining approach biases to alcohol cues is effective in both undergraduate and clinical samples (Wiers, Gladwin, Hofmann, Salemink, & Ridderinkhof, 2013; Kakoschke, Kemps, & Tiggemann, 2017). Interventions that target this relationship may be beneficial in improving decision-making processes and updating cognitive motivations in favour of reducing a young binge drinking person’s alcohol use which will hopefully serve to lessen the likelihood of progression from binge drinking in youth to dependence.

Sex Differences

Consistent with existing reviews (Ewing et al., 2014; Silveri et al., 2016; Carbia et al., 2018), sex differences were imbedded within a small number of neuroimaging and neuropsychological studies. Binge drinking females exhibited increased cortical thickness in the frontal lobe, less brain activation during a spatial working memory task in frontal, temporal and cerebellar regions, and displayed poorer visuoconstructional function, when compared to non-binge drinking females. Alternatively, binge drinking males exhibited less intracranial volume in the striatum, more brain activation during a spatial working memory task and poorer sustained attention, when compared to non-binge drinking males. These results parallel findings among adolescents with alcohol use disorder (Caldwell et al., 2005; Medina et al., 2008). The different manifestations of cognitive and neural decrements could relate to divergent neurodevelopmental trajectories, physiological responses to alcohol, and social factors influencing drinking onset (Squeglia et al., 2011). Neural activation differences across frontocortical regions could have a greater influence on cognitive performance. In the study by Squeglia et al. (2011), hypoactivation in the frontal region of

female binge drinkers correlated with poorer attention and working memory performance, and in contrast, male binge drinkers exhibited equal or greater activation in frontal areas which was associated with better cognitive performance on spatial tasks. The reduced activation among young female binge drinkers during executive functioning processes could have important implications, as diminished working memory may contribute to further substance use involvement (Casey et al., 2008). Further research which is sufficiently powered to examine sex differences is required to provide insight into the nuanced effects on cognition, brain structure and function in males and females, however at this time, it appears that males may be less adversely influenced by binge drinking, a similar conclusion to that drawn by Ewing et al. (2014) and Silveri et al. (2016).

Methodological Considerations

Although there have been considerable advancements in this field of research, definitive conclusions about the relationship between binge drinking, cognition, brain structure and function cannot be drawn at this time. Clear comparisons of findings are a challenge as many studies in this field lack statistical power from limited sample sizes, with wide age ranges which reduces precision of results (Button et al., 2013). There was serious concern of imprecision for the cognitive domains of behavioural inhibition, delay discounting, expressive language, planning, receptive language, visual perceptual, visuoconstructional, and recognition of emotions due to the small number of studies($n = \leq 4$)with small sample sizes, where the number of participants included in the review was smaller than the required number generated from a sample size calculator for a single adequately powered trial. The preliminary DTI, MRS, resting-state EEG and MEG findings should also be interpreted with caution due to small sample sizes and lack of power.

Inconsistencies were observed in the measures used to assess neural and cognitive outcomes, and in the measures used to quantify alcohol use. These factors likely contributed to the considerable heterogeneity in results for the cognitive domains of decision-making, inhibition, processing speed, and recent memory. While we used standardised criteria to assess binge drinking status, there was large variation in the frequency and quantity of alcohol being consumed by the participants. In the majority of studies, binge drinking was at relatively modest levels (e.g., one to two binges in the past three months as part of inclusion criteria), while other studies captured young people drinking at levels largely above these lower-cut offs (i.e., extreme binge drinking). Importantly, the tentative findings identified in the review reflect patterns of drinking behaviour that are consonant with a large proportion of adolescents and young people (White & Williams, 2016; Kraus et al., 2016; Johnston et al., 2019; Substance Abuse and Mental Health Services Administration, 2017; Australian Institute of Health and Welfare, 2017; Office for National Statistics, 2018). However, caution should be taken when extrapolating results found in this review to youth with much heavier binge patterns, such as weekly binges, as there is not enough data available to delineate the effects of infrequent from frequent binges, and from extreme binges at this time. Further to this point, included studies mostly relied on self-reports of binge drinking. Incorporation of real time measures, such as smart phone technology, and biological markers of alcohol use (e.g., Phosphatidylethanol, Ethyl glucuronide, Carbohydrate-deficient transferrin) would

greatly improve the accuracy of reporting and would elucidate the more nuanced effects of drinking on neurofunction and cognition.

While it was beyond the scope of this review to examine comorbidities, we found throughout the study screening process that in the broader field, there was a lack of explicit consideration of psychiatric comorbidities and other substance use. Other mental health conditions are known to affect neurofunction, for example, depression has been shown to have a negative impact on neural (Bora, Fornito, Pantelis, & Yücel, 2012) and cognitive function (Lee, Hermens, Porter, & Redoblado-Hodge, 2012). Further, the exclusion of papers exploring co-occurring substance use may have minimised the effects observed in this review, as those engaging in extreme binge drinking are likely to be misusing other substances. Understanding the relationships between co-occurring psychological disorders and the differential effects of other substances on the developing brain is an important next step, however much larger samples are needed to parse these factors. Of note, studies in this review were not excluded if participants were tobacco users. A long history of smoking is associated with neural atrophy and accelerated cognitive decline in adults (Swan & Lessov-Schlaggar, 2007). For the majority of cases, the number of participants using tobacco were low and the patterns of use were infrequent. Again, much larger studies are needed to determine the differential effects of tobacco from alcohol on neural and cognitive development in youth.

A limitation of the meta-analysis was overarching cognitive constructs, such as executive functions or fluid reasoning, were not calculated due to inconsistencies in categorisation of cognitive domains across theoretical frameworks. A further limitation was the exclusion of longitudinal studies from the meta-analysis because reliable estimates were indeterminate from the small number of published studies. More prospective longitudinal data that begins examining youth prior to alcohol uptake is critically needed to address concomitant factors of alcohol use and determine whether i) neural and cognitive vulnerabilities to alcohol vary at different points of neurodevelopment during adolescence and young adulthood (Sullivan et al., 2011), ii) what the exposure thresholds are for negative impacts on neural and cognitive development, iii) how alcohol-related harms such as alcohol-induced blackouts impact neurodevelopment, iv) whether extended alcohol use during youth differentially impacts neurodevelopment, and v) the degree to which neural and cognitive recovery can occur. Large multi-site studies such as the Adolescent Brain Cognitive Development Study (Volkow et al., 2018), NCANDA project (e.g. (Sullivan et al., 2016) and IMAGEN Study (Schumann et al., 2010) are underway and will help answer the existing gaps in the literature. Finally, the majority of published studies have originated from a small number of research teams and have included predominantly Caucasian youth from upper middle-class families. Thus, replication of design and findings across more diverse samples in research laboratories from other countries is encouraged in order to improve both the comparability and robustness of these findings (Open Science Collaboration, 2015; Munafò et al., 2017). Together, this will allow for future quantitative analyses of neuroimaging and neurophysiological studies to draw more conclusive evidence on the relationship between binge drinking and neurodevelopment.

Conclusion

Overall, recent research has substantially advanced our understanding of the complicated relationship between adolescent brain development and binge drinking, with prospective, longitudinal designs parsing pre-existing vulnerabilities from alcohol-related consequences. Although studies in young binge drinkers have identified deficits, the existing research on the impact of binge drinking on brain and cognitive development has yet to yield consistent, replicated findings. Tentatively, abnormal or delayed development of key frontal executive-control regions may predispose youth to binge drink. Following the uptake of binge drinking, there is some evidence that neurotoxic effects are apparent in the reward-seeking, incentive salience and executive control regions, indexed by cognitive deficits and maladaptive alcohol associations. These deficits may further increase the propensity for young people to engage in risky and sensation-seeking activities, including alcohol and drug use, abuse, and addiction. Further research in this area has the potential to significantly impact global health by informing the development of targeted prevention and intervention strategies to address the vulnerabilities and consequences of binge drinking in youth.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

American Psychiatric Association. (2013). Diagnostic and statistical manual of mental disorders (5th ed.). Arlington, VA: American Psychiatric Publishing.

Ames SL, Wong SW, Bechara A, Cappelli C, Dust M, Grenard JL, & Stacy AW (2014). Neural correlates of a go/NoGo task with alcohol stimuli in light and heavy young drinkers. Behavioural Brain Research, 274, 382–389. [PubMed: 25172182]

Australian Institute Of Health And Welfare. (2017). National drug strategy household survey 2016: Detailed findings. Canberra: AIHW.

Banca P, Lange I, Worbe Y, Howell NA, Irvine M, Harrison NA, … Voon V. (2016). Reflection impulsivity in binge drinking: behavioural and volumetric correlates. Addict Biol, 21(2), 504–515. [PubMed: 25678093]

Berlucchi G. (2011). Brain plasticity and cognitive neurorehabilitation. Neuropsychology Rehabilitation, 21(5), 560–578.

Bernardin F, Maheut-Bosser A, & Paille F. (2014). Cognitive impairments in alcohol-dependent subjects. Frontiers in Psychiatry, 5, 78. [PubMed: 25076914]

Berridge KC (2007). The debate over dopamine's role in reward: The case for incentive salience. Psychopharmacology, 191(3), 391–431. [PubMed: 17072591]

Bora E, Fornito A, Pantelis C, & Yücel M. (2012). Gray matter abnormalities in major depressive disorder: A meta-analysis of voxel based morphometry studies. Journal of Affective Disorders, 138(1–2), 9–18. [PubMed: 21511342]

Borenstein M, Hedges L, Higgins J, & Rothstein HR (2014). Comprehensive meta-analysis version 3. Biostat: Engelwood.

Bourque J, Baker TE, Dagher A, Evans AC, Garavan H, Leyton M, … Conrod PJ (2016). Effects of delaying binge drinking on adolescent brain development: A longitudinal neuroimaging study. BMC Psychiatry, 16(1), 445. [PubMed: 27955636]

Bowley C, Faricy C, Hegarty B, Johnstone SJ, Smith JL, Kelly PJ, & Rushby JA (2013). The effects of inhibitory control training on alcohol consumption, implicit alcohol-related cognitions and brain electrical activity. International Journal of Psychophysiology, 89(3), 342–348. [PubMed: 23623953]

Bräker A-B, Göbel K, Scheithauer H, & Soellner R. (2015). Adolescent alcohol use patterns from 25 European countries. Journal of Drug Issues, 45(4), 336–350.

Brozek JL, Akl EA, Alonso-Coello P, Lang D, Jaeschke R, Williams JW, … Schunemann HJ (2009). Grading quality of evidence and strength of recommendations in clinical practice guidelines. Part 1 of 3. An overview of the GRADE approach and grading quality of evidence about interventions. Allergy, 64(5), 669–677. [PubMed: 19210357]

Brumback T, Squeglia LM, Jacobus J, Pulido C, Tapert SF, & Brown SA (2015). Adolescent heavy drinkers' amplified brain responses to alcohol cues decrease over one month of abstinence. Addictive Behaviors, 46, 45–52. [PubMed: 25796007]

Brumback TY, Worley M, Nguyen-Louie TT, Squeglia LM, Jacobus J, & Tapert SF (2016). Neural predictors of alcohol use and psychopathology symptoms in adolescents. Development and Psychopathology, 28(4pt1), 1209–1216. [PubMed: 27739397]

Button KS, Ioannidis JPA, Mokrysz C, Nosek BA, Flint J, Robinson ESJ, & Munafò MR (2013). Power failure: Why small sample size undermines the reliability of neuroscience. Nature Reviews Neuroscience, 14(5), 365–376. [PubMed: 23571845]

Caldwell LC, Schweinsburg AD, Nagel BJ, Barlett VC, Brown SA, & Tapert SF (2005). Gender and adolescent alcohol use disorders on BOLD (blood oxygen level dependent) response to spatial working memory. Alcohol and Alcoholism, 40(3), 194–200. [PubMed: 15668210]

Campanella S, Peigneux P, Petit G, Lallemand F, Saeremans M, Noel X, … Verbanck P. (2013). Increased cortical activity in binge drinkers during working memory task: A preliminary assessment through a functional magnetic resonance imaging study. PLoS One, 8(4), e62260. [PubMed: 23638017]

Carbia C, Cadaveira F, Caamano-Isorna F, Rodriguez-Holguin S, & Corral M. (2017). Binge drinking during adolescence and young adulthood is associated with deficits in verbal episodic memory. PLoS One, 12(2), e0171393. [PubMed: 28152062]

Carbia C, Cadaveira F, Lopez-Caneda E, Caamano-Isorna F, Rodriguez Holguin S, & Corral M. (2017). Working memory over a six-year period in young binge drinkers. Alcohol, 61, 17–23. [PubMed: 28599713]

Carbia C, López-Caneda E, Corral M, & Cadaveira F. (2018). A systematic review of neuropsychological studies involving young binge drinkers. Neuroscience & Biobehavioral Reviews, 90, 332–349. [PubMed: 29678643]

Casey BJ, Jones RM, & Hare TA (2008). The adolescent brain. Annals of the New York Academy of Sciences, 1124(1), 111–126. [PubMed: 18400927]

Cohen J. (1988). Statistical power analysis for the behavioral sciences. Hillsdale: Lawrence Erlbaum.

Correas A, Rodriguez Holguin S, Cuesta P, Lopez-Caneda E, Garcia-Moreno LM, Cadaveira F, & Maestu F. (2015). Exploratory analysis of power spectrum and functional connectivity during resting state in young binge drinkers: A MEG study. International Journal of Neural Systems, 25(03), 1550008. [PubMed: 25753601]

Courtney KE, & Polich J. (2010). Binge drinking effects on EEG in young adult humans. International Journal of Environmental Research and Public Health, 7(5), 2325–2336. [PubMed: 20623027]

Crego A, Holguin SR, Parada M, Mota N, Corral M, & Cadaveira F. (2009). Binge drinking affects attentional and visual working memory processing in young university students. Alcoholism, Clinical and Experimental Research, 33(11), 1870–1879.

Crego A, Rodriguez-Holguin S, Parada M, Mota N, Corral M, & Cadaveira F. (2010). Reduced anterior prefrontal cortex activation in young binge drinkers during a visual working memory task. Drug and Alcohol Dependence, 109(1–3), 45–56. [PubMed: 20079980]

Crego A, Cadaveira F, Parada M, Corral M, Caamano-Isorna F, & Rodriguez Holguin S. (2012). Increased amplitude of P3 event-related potential in young binge drinkers. Alcohol, 46(5), 415–425. [PubMed: 22459872]

Crews F, He J, & Hodge C. (2007). Adolescent cortical development: A critical period of vulnerability for addiction. Pharmacology, Biochemistry and Behaviour, 86(2), 189–199.

Cservenka A, & Brumback T. (2017). The burden of binge and heavy drinking on the brain: Effects on adolescent and young adult neural structure and function. Frontiers in Psychology, 8, 1111. [PubMed: 28713313]

Cuthbert BN, & Kozak MJ (2013). Constructing constructs for psychopathology: The NIMH research domain criteria. Journal of Abnormal Psychology, 122(3), 928–937. [PubMed: 24016027]

Da Matta A, Goncalves FL, & Bizarro L. (2012). Delay discounting: Concepts and measures. Psychology & Neuroscience, 5(2), 135–146.

Day AM, Kahler CW, Ahern DC, & Clark US (2015). Executive functioning in alcohol use studies: A brief review of findings and challenges in assessment. Current Drug Abuse Reviews, 8(1), 26–40. [PubMed: 25877524]

Duval S, & Tweedie R. (2000). Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. Biometrics, 56(2), 455–463. [PubMed: 10877304]

Dwyer-Lindgren L, Bertozzi-Villa A, Stubbs RW & et al. 2018 Trends and patterns of geographic variation in mortality from substance use disorders and intentional injuries among us counties, 1980–2014. JAMA, 319, 1013–1023, 10. [PubMed: 29536097]

Egger M, Smith GD, Schneider M, & Minder C. (1997). Bias in meta-analysis detected by a simple, graphical test. BMJ, 315 (7109), 629–634. [PubMed: 9310563]

Eickhoff SB, Nichols TE, Laird AR, Hoffstaedter F, Amunts K, Fox PT, … Eickhoff CR (2016). Behavior, sensitivity, and power of activation likelihood estimation characterized by massive empirical simulation. NeuroImage, 137, 70–85. [PubMed: 27179606]

Enoch MA (2006). Genetic and environmental influences on the development of alcoholism: Resilience vs. risk. Annals of the New York Academy of Sciences, 1094(1), 193–201. [PubMed: 17347351]

Everitt BJ, & Robbins TW (2016). Drug addiction: Updating actions to habits to compulsions ten years on. Annual Review of Psychology, 67(1), 23–50.

Ewing SW, Sakhardande A, & Blakemore S-J (2014). The effect of alcohol consumption on the adolescent brain: A systematic review of MRI and fMRI studies of alcohol-using youth. NeuroImage: Clinical, 5, 420–437. [PubMed: 26958467]

Faul F, Erdfelder E, Lang AG, & Buchner A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175–191. [PubMed: 17695343]

Folgueira-Ares R, Cadaveira F, Rodríguez Holguín S, López-Caneda E, Crego A, & Pazo-Álvarez P. (2017). Electrophysiological anomalies in face–name memory encoding in young binge drinkers. Frontiers in Psychiatry, 8, 216. [PubMed: 29163235]

Gil-Hernandez S, Mateos P, Porras C, Garcia-Gomez R, Navarro E, & Garcia-Moreno LM (2017). Alcohol binge drinking and executive functioning during adolescent brain development. Frontiers in Psychology, 8, 1638. [PubMed: 29046650]

Grahn JA, Parkinson JA, & Owen AM (2008). The cognitive functions of the caudate nucleus. Progress in Neurobiology, 86(3), 141–155. [PubMed: 18824075]

Hartley DE, Elsabagh S, & File SE (2004). Binge drinking and sex: effects on mood and cognitive function in healthy young volunteers. Pharmacol Biochem Behav, 78(3), 611–619. [PubMed: 15251270]

Hedges LV, & Olkin I. (1985). Statistical methods for meta-analysis. San Diego, CA: Academic Press.

Heffernan T, Clark R, Bartholomew J, Ling J, & Stephens R. (2010). Does binge drinking in teenagers affect their everyday prospective memory? Drug Alcohol Depend, 109(1–3), 73–78. [PubMed: 20071106]

Henges AL, & Marczinski CA (2012). Impulsivity and alcohol consumption in young social drinkers. Addict Behav, 37(2), 217–220. [PubMed: 21981824]

Hermens DF, & Lagopoulos J. (2018). Binge drinking and the young brain: A mini review of the neurobiological underpinnings of alcohol-induced blackout. Frontiers in Psychology, 9, 12. [PubMed: 29403418]

Hogarth L, Balleine BW, Corbit LH, & Killcross S. (2013). Associative learning mechanisms underpinning the transition from recreational drug use to addiction. Annals of the New York Academy of Sciences, 1282(1), 12–24. [PubMed: 23126270]

Johnson CA, Xiao L, Palmer P, Sun P, Wang Q, Wei Y, … Bechara A. (2008). Affective decision-making deficits, linked to a dysfunctional ventromedial prefrontal cortex, revealed in 10th grade Chinese adolescent binge drinkers. Neuropsychologia, 46(2), 714–726. [PubMed: 17996909]

Johnston LD, Miech RA, O'Malley PM, Bachman JG, Schulenberg JE, & Patrick ME (2019). Monitoring the future national survey results on drug use, 1975–2018: Overview, key findings on adolescent drug use. Ann Arbor: Institute for Social Research, The University of Michigan.

Jones SA, Steele JS, & Nagel BJ (2017). Binge drinking and family history of alcoholism are associated with an altered developmental trajectory of impulsive choice across adolescence. Addiction, 112(7), 1184–1192. [PubMed: 28317212]

Kakoschke N, Kemps E, & Tiggemann M. (2017). Approach bias modification training and consumption: A review of the literature. Addictive Behaviors, 64, 21–28. [PubMed: 27538198]

Keshavan MS, Vinogradov S, Rumsey J, Sherrill J, & Wagner A. (2014). Cognitive training in mental disorders: Update and future directions. American Journal of Psychiatry, 171(5), 510–522. [PubMed: 24700194]

Koob GF, & Le Moal M. (2005). Plasticity of reward neurocircuitry and the 'dark side' of drug addiction. Nature Neuroscience, 8(11), 1442–1444. [PubMed: 16251985]

Kraus L, Guttormsson U, Leifman H, Arpa S, Molinaro S, Monshouwer K, … Hibell B. (2016). ESPAD report 2015: Results from the European school survey project on alcohol and other drugs. Luxembourg: European Monitroing Centre for Drugs and Drug Addiction.

Kvamme TL, Schmidt C, Strelchuk D, Chang-Webb YC, Baek K, & Voon V. (2016). Sexually dimorphic brain volume interaction in college-aged binge drinkers. NeuroImage: Clinical, 10, 310–317. [PubMed: 26900571]

Labhart F, Livingston M, Engels R & Kuntsche E 2018 After how many drinks does someone experience acute consequences—determining thresholds for binge drinking based on two event-level studies. Addiction, 0.

Lannoy S, D'hondt F, Dormal V, Billieux J, & Maurage P. (2017). Electrophysiological correlates of performance monitoring in binge drinking: Impaired error-related but preserved feedback processing. Clinical Neurophysiology, 128, 2110–2121. [PubMed: 28926739]

Lee RSC, Hermens DF, Porter MA, & Redoblado-Hodge MA (2012). A meta-analysis of cognitive deficits in first-episode major depressive disorder. Journal of Affective Disorders, 140(2), 113–124. [PubMed: 22088608]

Lees B, Mewton L, Stapinski L, Squeglia LM, Rae C, & Teesson M. (2018). Binge drinking in young people: Protocol for a systematic review of neuropsychological, neurophysiological and neuroimaging studies. BMJ Open, 8(7), e023629.

Lezak MD, Howieson DB, Bigler ED, & Tranel D. (2012). Neuropsychological Assessment (5th ed.). New York: Oxford University Press.

Lisdahl KM, Gilbart ER, Wright NE, & Shollenbarger S. (2013). Dare to delay? The impacts of adolescent alcohol and marijuana use onset on cognition, brain structure and function. Frontiers in Psychiatry, 4, 53. [PubMed: 23847550]

López-Caneda E, Cadaveira F, Correas A, Crego A, Maestú F, & Rodríguez Holguín S. (2017). The brain of binge drinkers at rest: Alterations in theta and beta oscillations in first-year college students with a binge drinking pattern. Frontiers in Behavioral Neuroscience, 11, 168. [PubMed: 28959193]

Lopez-Caneda E, Cadaveira F, Crego A, Doallo S, Corral M, Gomez-Suarez A, & Rodriguez Holguin S. (2013). Effects of a persistent binge drinking pattern of alcohol consumption in young people: A

follow-up study using event-related potentials. Alcohol and Alcoholism, 48(4), 464–471. [PubMed: 23695975]

Lopez-Caneda E, Cadaveira F, Crego A, Gomez-Suarez A, Corral M, Parada M, … Rodriguez Holguin S. (2012). Hyperactivation of right inferior frontal cortex in young binge drinkers during response inhibition: A follow-up study. Addiction, 107(10), 1796–1808. [PubMed: 22487028]

Lopez-Caneda E, Holguin SR, Corral M, Doallo S, & Cadaveira F. (2014). Evolution of the binge drinking pattern in college students: Neurophysiological correlates. Alcohol, 48(5), 407–418. [PubMed: 24835220]

Macpherson L, Magidson Jessica F, Reynolds Elizabeth K, Kahler Christopher W, & Lejuez CW (2010). Changes in sensation seeking and risk-taking propensity predict increases in alcohol use among early adolescents. Alcoholism: Clinical and Experimental Research, 34, 1400–1408.

Mashhoon Y, Czerkawski C, Crowley DJ, Cohen-Gilbert JE, Sneider JT, & Silveri MM (2014). Binge alcohol consumption in emerging adults: Anterior cingulate cortical “thinness” is associated with alcohol use patterns. Alcoholism, Clinical and Experimental Research, 38(7), 1955–1964.

Maurage P, Bestelmeyer PEG, Rouger J, Charest I, & Belin P. (2013). Binge drinking influences the cerebral processing of vocal affective bursts in young adults. Neuroimage: Clinical, 3, 218–225. [PubMed: 24179866]

Maurage P, Joassin F, Speth A, Modave J, Philippot P, & Campanella S. (2012). Cerebral effects of binge drinking: Respective influences of global alcohol intake and consumption pattern. Clinical Neurophysiology, 123(5), 892–901. [PubMed: 22055841]

Maurage P, Pesenti M, Philippot P, Joassin F, & Campanella S. (2009). Latent deleterious effects of binge drinking over a short period of time revealed only by electrophysiological measures. Journal of Psychiatry and Neuroscience, 34, 111–118. [PubMed: 19270761]

Mcqueeny T, Schweinsburg BC, Schweinsburg AD, Jacobus J, Bava S, Frank LR, & Tapert SF (2009). Altered white matter integrity in adolescent binge drinkers. Alcoholism, Clinical and Experimental Research, 33(7), 1278–1285.

Medina KL, Mcqueeny T, Nagel BJ, Hanson KL, Schweinsburg AD, & Tapert SF (2008). Prefrontal cortex volumes in adolescents with alcohol use disorders: Unique gender effects. Alcoholism, Clinical and Experimental Research, 32(3), 386–394.

Mewton L, Hodge A, Gates N, Visontay R, & Teesson M. (2017). The brain games study: Protocol for a randomised controlled trial of computerised cognitive training for preventing mental illness in adolescents with high-risk personality styles. BMJ Open, 7(9), e017721.

Moreno M, Estevez AF, Zaldivar F, Montes JM, Gutierrez-Ferre VE, Esteban L, … Flores P. (2012). Impulsivity differences in recreational cannabis users and binge drinkers in a university population. Drug Alcohol Depend, 124(3), 355–362. [PubMed: 22425410]

Morris SE, & Cuthbert BN (2012). Research domain criteria: Cognitive systems, neural circuits, and dimensions of behavior. Dialogues in Clinical Neuroscience, 14(1), 29–37. [PubMed: 22577302]

Moselhy HF, Georgiou G, & Kahn A. (2001). Frontal lobe changes in alcoholism: A review of the literature. Alcohol and Alcoholism, 36(5), 357–368. [PubMed: 11524299]

Mota N, Parada M, Crego A, Doallo S, Caamaño-Isorna F, Holguin SR, … Corral M. (2013). Binge drinking trajectory and neuropsychological functioning among university students: A longitudinal study. Drug and Alcohol Dependence, 133(1), 108–114. [PubMed: 23791027]

Muller VI, Cieslik EC, Laird AR, Fox PT, Radua J, Mataix-Cols D, … Eickhoff SB (2018). Ten simple rules for neuroimaging meta-analysis. Neuroscience and Biobehavioural Reviews, 84, 151–161.

Munafò MR, Nosek BA, Bishop DVM, Button KS, Chambers CD, Percie Du Sert N, … Ioannidis JPA (2017). A manifesto for reproducible science. Nature Human Behaviour, 1(1), 0021.

National Institute On Alcohol Abuse And Alcoholism 2018 Drinking levels defined. Retrieved from: https://www.niaaa.nih.gov/alcohol-health/overview-alcohol-consumption/moderate-binge-drinking. Accessed 12 April 2018

Office For National Statistics. 2018 Adult drinking habits in Great Britain: 2017. Retrieved from: https://www.ons.gov.uk/releases/adultdrinkinghabitsingreatbritain2017. Accessed 12 April 2018

O’leary-Barrett M, Masse B, Pihl RO, Stewart SH, Se’guin JR, & Conrod PJ (2017). A cluster-randomised controlled trial evaluating the effects of delaying onset of adolescent substance abuse

on cognitive development and addiction following a selective, personality-targeted intervention programme: The co-venture trial. Addiction, 112, 1871–1881. [PubMed: 28544009]

Öner S. (2018). Neural substrates of cognitive emotion regulation: A brief review. Psychiatry and Clinical Psychopharmacology, 28(1), 91–96.

Oosterhoff B, Kaplow JB, & Layne CM (2016). Trajectories of binge drinking differentially mediate associations between adolescent violence exposure and subsequent adjustment in young adulthood. Translational Issues in Psychological Science, 2(4), 371–381.

Open Science Collaboration. (2015). Estimating the reproducibility of psychological science. Science, 349(6251), aac4716. [PubMed: 26315443]

Parada M, Corral M, Caamano-Isorna F, Mota N, Crego A, Holguin SR, & Cadaveira F. (2011). Binge drinking and declarative memory in university students. Alcoholism: Clinical and Experimental Research, 35, 1475–1484.

Parada M, Corral M, Mota N, Crego A, Holgunn SR, & Cadaveira F. (2012). Executive functioning and alcohol binge drinking in university students. Addictive Behaviors, 37(2), 167–172. [PubMed: 21996093]

Pentz MA, Riggs NR, & Warren CM (2016). Improving substance use prevention efforts with executive function training. Drug and Alcohol Dependence, 163, S54–S59. [PubMed: 27306732]

Petit G, Kornreich C, Dan B, Verbanck P, & Campanella S. (2014). Electrophysiological correlates of alcohol- and non-alcohol-related stimuli processing in binge drinkers: A follow-up study. Journal of Psychopharmacology, 28(11), 1041–1052. [PubMed: 25122045]

Petit G, Kornreich C, Maurage P, Noel X, Letesson C, Verbanck P, & Campanella S. (2012). Early attentional modulation by alcohol-related cues in young binge drinkers: An event-related potentials study. Clinical Neurophysiology, 123(5), 925–936. [PubMed: 22119177]

Petit G, Maurage P, Kornreich C, Verbanck P, & Campanella S. (2014). Binge drinking in adolescents: A review of neurophysiological and neuroimaging research. Alcohol and Alcoholism, 49(2), 198–206. [PubMed: 24302160]

Pfefferbaum A, Kwon D, Brumback T, Thompson WK, Cummins K, Tapert SF, … Sullivan EV (2018). Altered brain developmental trajectories in adolescents after initiating drinking. American Journal of Psychiatry, 175(4), 370–380. [PubMed: 29084454]

Pfefferbaum A, Lim KO, Zipursky RB, Mathalon DH, Rosenbloom MJ, Lane B, … Sullivan EV (1992). Brain gray and white matter volume loss accelerates with aging in chronic alcoholics: A quantitative MRI study. Alcoholism, Clinical and Experimental Research, 16(6), 1078–1089.

Pfefferbaum A, Rohlfing T, Rosenbloom MJ, Chu W, Colrain IM, & Sullivan EV (2013). Variation in longitudinal trajectories of regional brain volumes of healthy men and women (ages 10 to 85 years) measured with atlas-based parcellation of MRI. Neuroimage, 65, 176–193. [PubMed: 23063452]

Pfefferbaum A, Rohlfing T, Pohl KM, Lane B, Chu W, Kwon D, … Sullivan EV (2016). Adolescent Development of Cortical and White Matter Structure in the NCANDA Sample: Role of Sex, Ethnicity, Puberty, and Alcohol Drinking. Cereb Cortex, 26(10), 4101–4121. 10.1093/cercor/bhv205 [PubMed: 26408800]

Pitel AL, Rivier J, Beaunieux H, Vabret F, Desgranges B, & Eustache F. (2009). Changes in the episodic memory and executive functions of abstinent and relapsed alcoholics over a 6-month period. Alcoholism, Clinical and Experimental Research, 33(3), 490–498.

Pompili M, Serafini G, Innamorati M, Dominici G, Ferracuti S, Kotzalidis GD, … Lester D. (2010). Suicidal behavior and alcohol abuse. International Journal of Environmental Research and Public Health, 7(4), 1392–1431. [PubMed: 20617037]

Rehm J, & Shield KD (2014). Alcohol and mortality: Global alcohol-attributable deaths from cancer, liver cirrhosis, and injury in 2010. Alcohol Research: Current Reviews, 35, 174–183.

Ryan R & Hill S 2016 How to GRADE the quality of the evidence. Cochrane consumers and communication group. Retrieved from: http://cccrg.cochrane.org/author-resources.

Sanhueza C, Garcia-Moreno LM, & Exposito J. (2011). Weekend alcoholism in youth and neurocognitive aging. Psicothema, 23(2), 209–214. [PubMed: 21504671]

Scaife JC, & Duka T. (2009). Behavioural measures of frontal lobe function in a population of young social drinkers with binge drinking pattern. Pharmacology, Biochemistry, and Behavior, 93(3), 354–362.

Schneider WJ & McGrew KS 2018 The Cattell-horn-Carroll theory of cognitive abilities Contemporary intellectual assessment: Theories, tests, and issues, (4th ed). New York: The Guilford Press.

Schottenbauer MA, Hommer D, & Weingartner H. (2007). Memory deficits among alcoholics: Performance on a selective reminding task. Neuropsychology, Development, and Cognition, 14(5), 505–516.

Schumann G, Loth E, Banaschewski T, Barbot A, Barker G, Buchel C, … Struve M. (2010). The IMAGEN study: Reinforcement-related behaviour in normal brain function and psychopathology. Molecular Psychiatry, 15(12), 1128–1139. [PubMed: 21102431]

Schünemann H, Brożek J, Guyatt G & Oxman A 2013 Handbook for grading the quality of evidence and the strength of recommendations using the GRADE approach. Updated October, 2013 The GRADE Working Group, 2013. Retrieved from: guidelinedevelopment.org/handbook.

Scott J, Slomiak ST, Jones JD, Rosen AG, Moore TM & Gur RC 2018 Association of cannabis with cognitive functioning in adolescents and young adults: A systematic review and meta-analysis. JAMA Psychiatry.

Shulman EP, Smith AR, Silva K, Icenogle G, Duell N, Chein J, & Steinberg L. (2016). The dual systems model: Review, reappraisal, and reaffirmation. Developmental Cognitive Neuroscience, 17, 103–117. [PubMed: 26774291]

Silveri MM, Cohen-Gilbert J, Crowley DJ, Rosso IM, Jensen JE, & Sneider JT (2014). Altered anterior cingulate neurochemistry in emerging adult binge drinkers with a history of alcohol-induced blackouts. Alcoholism, Clinical and Experimental Research, 38(4), 969–979.

Silveri MM, Dager AD, Cohen-Gilbert JE, & Sneider JT (2016). Neurobiological signatures associated with alcohol and drug use in the human adolescent brain. Neuroscience and Biobehavioural Reviews, 70, 244–259.

Spear LP (2013). Adolescent neurodevelopment. Journal of Adolescent Health, 52(2), S7–S13. [PubMed: 23332574]

Spear LP (2014). Adolescents and alcohol: Acute sensitivities, enhanced intake, and later consequences. Neurotoxicology and Teratology, 41, 51–59. [PubMed: 24291291]

Spear LP 2018 Effects of adolescent alcohol consumption on the brain and behaviour. Nature Reviews Neuroscience.

Squeglia LM, Ball TM, Jacobus J, Brumback T, Mckenna BS, Nguyen-Louie TT, … Tapert SF (2017). Neural predictors of initiating alcohol use during adolescence. American Journal of Psychiatry, 174(2), 172–185. [PubMed: 27539487]

Squeglia LM, & Cservenka A. (2017). Adolescence and drug use vulnerability: Findings from neuroimaging. Current Opinion in Behavioral Sciences, 13, 164–170. [PubMed: 28111629]

Squeglia LM, & Gray KM (2016). Alcohol and drug use and the developing brain. Current Psychiatry Reports, 18(5), 46. [PubMed: 26984684]

Squeglia LM, Jacobus J, Sorg SF, Jernigan TL, & Tapert SF (2013). Early adolescent cortical thinning is related to better neuropsychological performance. Journal of the International Neuropsychological Society, 19(9), 962–970. [PubMed: 23947395]

Squeglia LM, Pulido C, Wetherill RR, Jacobus J, Brown GG, & Tapert SF (2012). Brain response to working memory over three years of adolescence: Influence of initiating heavy drinking. Journal of Studies on Alcohol and Drugs, 73(5), 749–760. [PubMed: 22846239]

Squeglia LM, Rinker DA, Bartsch H, Castro N, Chung Y, Dale AM, … Tapert SF (2014). Brain volume reductions in adolescent heavy drinkers. Developmental Cognitive Neuroscience, 9, 117–125. [PubMed: 24632141]

Squeglia LM, Schweinsburg AD, Pulido C, & Tapert SF (2011). Adolescent binge drinking linked to abnormal spatial working memory brain activation: Differential gender effects. Alcoholism, Clinical and Experimental Research, 35(10), 1831–1841.

Squeglia LM, Sorg SF, Schweinsburg AD, Wetherill RR, Pulido C, & Tapert SF (2012). Binge drinking differentially affects adolescent male and female brain morphometry. Psychopharmacology, 220(3), 529–539. [PubMed: 21952669]

Squeglia LM, Spadoni AD, Infante MA, Myers MG, & Tapert SF (2009). Initiating moderate to heavy alcohol use predicts changes in neuropsychological functioning for adolescent girls and boys. Psychology of Addictive Behaviors, 23(4), 715–722. [PubMed: 20025379]

Squeglia LM, Tapert SF, Sullivan EV, Jacobus J, Meloy MJ, Rohlfing T, & Pfefferbaum A. (2015). Brain development in heavy-drinking adolescents. American Journal of Psychiatry, 172(6), 531–542. [PubMed: 25982660]

Steinberg L. (2010). A dual systems model of adolescent risk-taking. Developmental Psychobiology, 52(3), 216–224. [PubMed: 20213754]

Sterne JAC, Egger M, & Smith GD (2001). Investigating and dealing with publication and other biases in meta-analysis. BMJ, 323(7304), 101–105. [PubMed: 11451790]

Strauss E, Sherman EM & Spreen O 2006 A compendium of neuropsychologial tests: Adminstration, norms, and commentary (3rd Ed.), American Chemical Society.

Substance Abuse And Mental Health Services Administration. 2016 Binge Drinking: Terminology and Patterns of Use. Retrieved from: https://www.samhsa.gov/capt/tools-learning-resources/binge-drinking-terminology-patterns. 12 April 2018

Substance Abuse And Mental Health Services Administration. 2017 Key substance use and mental health indicators in the United States: Results from the 2016 National Survey on Drug Use and Health HHS Publication No. SMA 17–5044, NSDUH Series H-52. Rockville, MD: Center for Behavioral Health Statistics and Quality, Substance Abuse and Mental Health Services Administration.

Sullivan EV, Brumback T, Tapert SF, Fama R, Prouty D, Brown SA, … Pfefferbaum A. (2016). Cognitive, emotion control, and motor performance of adolescents in the NCANDA study: Contributions from alcohol consumption, age, sex, ethnicity, and family history of addiction. Neuropsychology, 30(4), 449–473. [PubMed: 26752122]

Sullivan EV, Pfefferbaum A, Rohlfing T, Baker FC, Padilla ML, & Colrain IM (2011). Developmental change in regional brain structure over 7 months in early adolescence: Comparison of approaches for longitudinal atlas-based parcellation. Neuroimage, 57(1), 214–224. [PubMed: 21511039]

Swan GE, & Lessov-Schlaggar CN (2007). The effects of tobacco smoke and nicotine on cognition and the brain. Neuropsychology Review, 17(3), 259–273. [PubMed: 17690985]

Teesson M, Hall W, Slade T, Mills K, Grove R, Mewton L, … Haber P. (2010). Prevalence and correlates of DSM-IV alcohol abuse and dependence in Australia: Findings of the 2007 National Survey of mental health and wellbeing. Addiction, 105(12), 2085–2094. [PubMed: 20707771]

Townshend JM, & Duka T. (2005). Binge drinking, cognitive performance and mood in a population of young social drinkers. Alcohol Clin Exp Res, 29(3), 317–325. [PubMed: 15770105]

Townshend JM, Kambouropoulos N, Griffin A, Hunt FJ, & Milani RM (2014). Binge drinking, reflection impulsivity, and unplanned sexual behavior: Impaired decision-making in young social drinkers. Alcoholism: Clinical and Experimental Research, 38(4), 1143–1150.

Vinader-Caerols C, Duque A, Montañés A, & Monleón S. (2017). Blood Alcohol Concentration-Related Lower Performance in Immediate Visual Memory and Working Memory in Adolescent Binge Drinkers. Frontiers in psychology, 8, 1720. [PubMed: 29046656]

Volkow ND, Koob GF, Croyle RT, Bianchi DW, Gordon JA, Koroshetz WJ, … Weiss SRB (2018). The conception of the ABCD study: From substance use to a broad NIH collaboration. Developmental Cognitive Neuroscience, 32, 4–7. [PubMed: 29051027]

Volkow ND, Wang GJ, Tomasi D, & Baler RD (2013). Unbalanced neuronal circuits in addiction. Current Opinion in Neurobiology, 23(4), 639–648. [PubMed: 23434063]

Welsh JW, Knight JR, Hou SS, Malowney M, Schram P, Sherritt L, & Boyd JW (2017). Association between substance use diagnoses and psychiatric disorders in an adolescent and young adult clinic-based population. Journal of Adolescent Health, 60(6), 648–652. [PubMed: 28202303]

Wetherill RR, Squeglia LM, Yang TT, & Tapert SF (2013). A longitudinal examination of adolescent response inhibition: Neural differences before and after the initiation of heavy drinking. Psychopharmacology, 230(4), 663–671. [PubMed: 23832422]

White V & Williams T 2016 Australian secondary school students' use of tobacco, alcohol, and over-the-counter and illicit substances in 2014. Cancer Council Victoria.

Wiers RW & Gladwin TE 2017 Reflective and impulsive processes in addiction and the role of motivation In: Deutsch R, Gawronski B & Hofmann W (eds.) Reflective and impulsive determinants of human behavior. Psychology Press.

Wiers RW, Gladwin TE, Hofmann W, Salemink E, & Ridderinkhof KR (2013). Cognitive bias modification and cognitive control training in addiction and related psychopathology: Mechanisms, clinical perspectives, and ways forward. Clinical Psychological Science, 1(2), 192–212.

Xiao L, Bechara A, Gong Q, Huang X, Li X, Xue G, … Johnson CA (2013). Abnormal affective decision making revealed in adolescent binge drinkers using a functional magnetic resonance imaging study. Psychology of Addictive Behaviors, 27(2), 443–454. [PubMed: 22486330]

Xiao L, Bechara A, Grenard JL, Stacy AW, Palmer P, Wei Y, … Johnson CA (2009). Affective decision-making predictive of Chinese adolescent drinking behaviors. Journal of the International Neuropsychological Society, 15(4), 547–557. [PubMed: 19573273]

Yoo J-Y, & Kim M-S (2016). Deficits in decision-making and reverse learning in college students who participate in binge drinking. Neuropsychiatry, 6(6), 321–330.

Zilverstand A, Huang AS, Alia-Klein N, & Goldstein RZ (2018). Neuroimaging impaired response inhibition and salience attribution in human drug addiction: A systematic review. Neuron, 98(5), 886–903. [PubMed: 29879391]

Zorko M, Marusic A, Cebasek-Travnik Z, & Bucik V. (2004). The frontal lobe hypothesis: Impairment of executive cognitive functions in chronic alcohol in-patients. Psychiatria Danubina, 16(1–2), 21–28. [PubMed: 19114938]

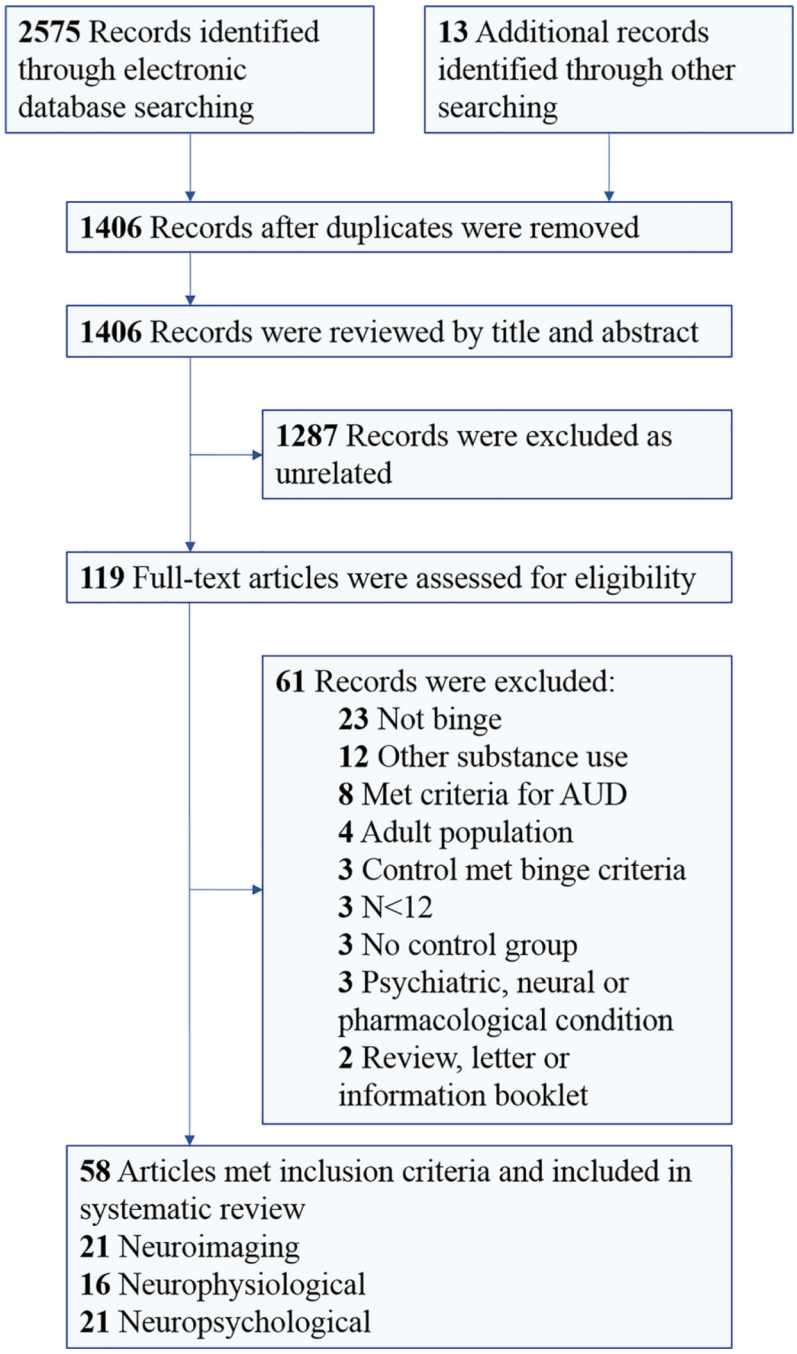

Fig. 1.
PRISMA diagram: flowchart of searches for studies included in systematic review

Table 1

Overview of study characteristics[1] ($n = 58$)

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
Neuroimaging: MRI										
Brumback et al., 2016 [L2] (USA)	SU, prenatal SU, premature birth, NI, DSM4A1, MI, LD, psychotropic medication	–	–	127	13.6	138	13.6	T1: < 10 days in life or ≤ 2 days in week T2: 1 + BD occasion, past yr	24:0 BD occasions,past yr	N/R
Kvamme et al., 2016 (UK)	SU, PD, NI, HI	–	–	18:12	21.3	23:23	21.3	BD occasion weekly for >6mths	N/R	24 h
Lisdahl, Gilbart, Wright, & Shollenbarger, 2013 (USA)	DSM4 A1, NI, HI, prenatal SU, NC sensory, premature birth, psychotropic medication, MI, SU, LH	–	–	31:15	18.0	35:25	17.7	1 + BD occasion, past 3mths	2.5:0 PDr	26.7:211.7
Mashhoon et al.,2014 (USA)	DSM4 A1, NI, PD, SU, HI,MI, SU dependence, psychotropic medication, pregnancy	–	–	12:11	22.0	16:15	21.5	3 + BD occasions per mth	11.2:1.7 UPW	6.1:12.1
Pfefferbaum et al. 2016 (USA)	BA	–	–	113	12.0–21.9	674	12.0–21.9	1 + BD occasion, past yr.	1–137:0 BD occasions, past yr	N/R
Pfefferbaum et al.,2018 [L1] (USA)	SU	–	–	61:66	15.5	180:176	15.5	T1: ≤3 drinks per occasion (F, M 12–13.9 yrs), ≤4 drinks per occasion (M 14–19.9 yrs), ≤5 drinks per occasion (M 20 yrs.+)	9.6:0 BD occasions	N/R
Squeglia et al., 2012 (USA)	DSM4 A1, NI, MI, LH, SU, prenatal PD, prenatal SU, premature birth, psychotropic medication	Complex figure, Digits (forward, backward), Colour word interference, Towers, Reading score	Immediate memory, inhibition, LT memory, mental flexibility, receptive language, visuoconstructional, WM	15:14	18.2	15:15	18.0	2 + BD occasions, past 3mths	9.3:0.4 PDr	21.0:N/A
Squeglia et al., 2014 [L3] (USA)	T1: SU, DSM4 A1, prenatal SU, NI, MI, psychotropic medication	Letter-number switch, Colour word interference, Towers	Inhibition, mental flexibility	12:8	18.0	13:7	17.2	T1: < 10 days in life or ≤ 2days in week	4.7:0.3	37.1:119.3
Squeglia et al., 2015[L8] (USA)	DSM4 A1, NI, MI, psychotropic medication, prematurebirth, prenatal	–	–	45:30	19.6	31:28	17.3	T1: 0 T2: 1 + BD occasion	9.8:0.2 PDr	N/R

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
	SU, illicit SU, NC sensory, BA, poorEnglish									
Neuroimaging: DTI										
Mcqueeny et al., 2009 (USA)	NI, PD, AUD, SUD, prenatal SU, psychotropic medication	–	–	12:2	18.1	12:2	18.0	1 + BD occasion, past 3mths	8.2:0.1 PDr	20.3:513.3
Neuroimaging: MRS										
Silveri et al., 2014 (USA)	HI, BA, psychotropic medication, SU	Trail making, Go no-go, Block design, Mental rotation	Inhibition, mental flexibility, processing speed, sustained attention, visual perception, visuo constructional	10:11	21.9	14:13	21.6	1 + BD occasion	5.0:1.7	5.9:13.1
Neuroimaging: fMRI										
Ames et al., 2014 (USA)	PD, NI, psychotropic medication	Operation span	WM	9:8	20.2	5:14	20.8	8+ (F), 15+ (M) drinks per week, with 2+ BD occasions per week	6.2:3.0	Test day
Ames et al., 2014 (USA)	PD, NI, psychotropic medication	Alcohol go no-go	Inhibition, processing speed, sustained attention	10:11	20.2	7:13	20.8	8+ (F), 15+ (M) drinks per week, with 2+ BD occasions per week	6.1:3.0	N/R
Banca et al. 2016 (UK)	PD, NI, HI, SUD, MI	Beads task, Delay discounting	Delay discounting, DM	17:13	22.2	17:13	21.9	1+ BD occasion, past 3mths	13.2:4.8 UPW	24 h
Brumback et al., 2015[L4wk] (USA)	PD, SU, HI, DSM4 A1, NI, MI, prenatal SU, NC sensory, psychoactive medication	–	–	10:12	17.9	9:7	17.4	3+ BD occasions past mth, >100 life time drinking occasions	5.7:2.5	N/R
Campanella et al.,2013 (Belgium)	MI, CNS condition, NC sensory, SU, alcohol abstinence	Digits (forward, backward), N-back	Immediate memory, processing speed, sustained attention, WM	7:9	20.9	7:9	21.6	2+ BD occasions per week	6.6:2.6	24 h
Maurage, Bestelmeyer, Rouger, Charest, & Belin, 2013 (UK)	AUD history, SU, psychoactive medication, nicotine dependence, MI, CNS condition, NC sensory, high	2-alternative forced choice	Recognition of emotion	7:5	24.2	7:5	23.4	3 BD occasions per week,with >2 drinks perhr	7.5:1.4	3 days
Squeglia, Schweinsburg, Pulido, & Tapert, 2011 (USA)	DSM A1 history, prenatal SU, premature birth, NI, MI, psychotropic medication, DSM4 A1, NC sensory, SU	Complex figure, Block design, Digits (forward, backward), Digit vigilance, Digit symbol, Reading score	Immediate memory, LT memory, processing speed, receptive attention, visuoconstructional, WM	27:13	18.0	31:24	17.9	1+ BD occasion, past 3mths	2.7:0	27.6:226.1

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
Squeglia et al., 2012 E1 (USA)	Prenatal SU, MI, NI, DSM4 A1, PD history, psychotropic medication, poor English, NC sensory, LH	Visual WM	WM	20	17.6	20	17.6	1+ BD occasion	N/R	N/R
Squeglia, Sorg, et al. 2012 E2 [L3]	T1: SU, prenatal SU, MI, NI, DSM4 A1, PD history, psychotropic medication, poor English, NC sensory, LH	Visual WM	WM	14:7	18.5	14:7	17.7	T1: 0 T2: 1+ BD occasion	6.1:0.3	N/R
Wetherill, Squeglia, Yang, & Tapert, 2013 [L3] (USA)	PD history, prenatal SU, premature birth, LH, MI, NI, DSM4 A1, psychotropic medication, SU, NC sensory, poor English	Go no-go	Inhibition	11:9	18.5	11:9	17.6	1+ BD occasion	4.2:0.2	N/R
Xiao et al., 2013 (China)	NC sensory, NI, PD	Iowa Gambling	DM	8:6	17.3	5:11	17.1	1+ BD occasion, past mth	N/R	N/R
Correas et al., 2015 (Spain)	MI, NI history, DSM4 A1, DSM A1 history, SUD history, SU, NC sensory, AUDIT >20	–	–	17:18	18.0	21:17	18.0	1+ 0.8% + BAC occasion, past mth	N/R	24 h
Neurophysiological: EEG										
Courtney et al. 2010 (USA)	AUD history, NI, PD, SU, alcohol abstinence, psychotropic medication, MI	–	–	32:32	20.4	16:16	21.1	Low BD: 1+ BD occasion, past 6mths High BD: 1+ occasion of ≤ 10 drinks with in 2 h, past 6 mths	5.7:3.0	N/R
López-Caneda et al., 2017 (Spain)	NC sensory, HI, NI, DSM4 AUDIT >20, SU	–	–	20:20	18.1	21:19	18.1	1+ 0.8% + BAC occasion, past mth	4.9:0.7	24 h
Neurophysiological: ERP										
Crego et al., 2009, Crego et al., 2010 (Spain)[5]	AUDIT >20, SU, NC sensory, NI, DSM A1 history, >90 GSI, 2+ symptoms on SCL-90-R, AUD, alcohol abstinence	Continuous performance	Behavioural inhibition, processing speed, sustained attention	21:21	18.9	27:26	18.7	1+ BD occasion per mth, with >3 drinks per hr	3.6:0.7	12 h
Crego et al. 2012 (Spain)	NC sensory, NI, DSM A1 A2, DSM A1 history, SUD history, SU, AUD, LH, AUDIT >20	Visual oddball	Processing speed, sustained attention	17:15	18.8	28:25	18.5	1+ BD occasion per mth, with >3 drinks per hr	3.6:0.7	12 h
Folgueira-Ares et al., 2017 [L2] (Spain)	NC sensory, NI, DSM4 A1 A2, DSM4 A1	Visual face-name association	Recent memory	14:11	20.8	13:12	20.5	1+ BD occasion per mth, with >3 drinks per hr	3.6:1.4	12 h

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
	history, SU besides cannabis, AUDIT >20									
Lannoy, D'hondt, Dormal, Billieux, & Maurage, 2017 (Belgium)	AUD, AUD history, NI, PD, medication, MI, NC sensory, SU	Speeded Go no-go, Balloon analogue risk	DM, inhibition, processing speed, sustained attention	8:12	20.3	7:13	21.2	16+ BD score (drinks per hr.; times drunk last 6 mths; %of being drunk when drinking)	5.1:3.2	3 days
Lopez-Caneda et al., 2012 [L2] (Spain)	AUD history, SUD, PD history, SU except cannabis, NI, NC sensory, AUDIT>20	Go no-go	Inhibition, processing	13:10	18.8	11:14	18.6	1+ BD occasion per mth, with >3 drinks per hr., maintain 2 yrs	9.4:1.7 UPW	24 h
Lopez-Caneda et al., 2013 [L2] (Spain)	NC sensory, NI, DSM4 A1 A2, SU except cannabis, PD history, SUD history, AUDIT >20	Visual oddball	Processing speed, sustained attention	15:11	18.8	15:16	18.5	1+ BD occasion per mth, with >3 drinks per hr., maintain 2 yrs	4.0:1.2	24 h
Lopez-Caneda, Holguin, Corral, Doallo, & Cadaveira, 2014 [L2] (Spain)	NC sensory, NI, DSM4 A1 A2, SU except cannabis, PD history, SU, AUDIT >20	Go no-go	Inhibition, processing	11:11	18–19	11:14	18–19	1+ BD occasion per mth, with >3 drinks per hr., maintain 2 yrs	14.0:1.0 UPW	24 h
López-Caneda et al., 2017 (Spain)	NC sensory, NI, DSM4 A1 A2 history, PD history, SUD history, psychotropic medication, >20 AUDIT, SU except cannabis	Go no-go	Inhibition, processing speed, sustained attention	17:19	18.1	20:16	18.1	1+ 0.8% + BAC occasion, past mth	0.17:0.01 BAC	24 h
Maurage, Pesenti, Philippot, Joassin, & Campanella, 2009[L9mth] (Belgium)	AUD history, SU, psychotropic medication, high alcohol consumption, BD prior to university, MI, NI, NC sensory, high depression-anxiety score, PD	–	–	7:11	18.2	7:11	18.2	T1: No BD T2: 20 units per week	8.9:0	3 days
Maurage et al., 2012 (Belgium)	AUD history, SU, psychotropic medication, high alcohol consumption, BD prior to university, MI, NI, NC sensory, high depression-anxiety score	Visual oddball	Visual perception	22:18	21.1	11:9	21.6	Low BD: 2+ BD occasions per week, 15–29 units per week High BD: 3+ occasions of ≤ 10 drinks	8.2:0.79	5 days
Petit et al., 2012 (Belgium)	MI, NI, NC sensory, SU, AUD history, high alcohol consumption, BD prior to university, drinking pattern shift during university, psychotropic medication	–	–	12:6	21.3	8:10	21.9	1+ BD occasion	21.7:1.1 UPW	N/R

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
Petit, Kornreich, Dan, Verbanck, & Campanella, 2014 [L1] (Belgium)	MI, NI, SU (other than cannabis, tobacco, alcohol), alcohol abstinence	–	–	11:4	22.0	4:11	22.0	Maximum of 3–4 BD occasions per week	7.6:2.4	24 h
Neuropsychological										
Carbia, Cadaveira, Caamano-Isorna, Rodriguez-Holguin, & Corral, 2017, Carbia et al., 2017[L6] (Spain)	SU except cannabis, tobacco, AUD, NC sensory, NC motor, MI history, AUD history, DSM4 history, >90/2+ symptoms GSI SCL-90-R	Logical memory, self-ordered pointing, RAVLT	Immediate memory, long term memory, mental flexibility, recent memory, WM	40:39	18.9	36:40	18.6	1+ 0.8% + BAC occasion, per mth	3.4:1.0	N/R
Gil-Hernandez et al., 2017 (Spain)[3]	SU, NI, AUD, AUD history, PD	Digits (forward, backward), Spatial span (forward, backward), Letter-number, Verbal fluency (phonemic, semantic), Trail making, Stroop	Expressive language, immediate memory, inhibition, mental flexibility, processing speed, WM	78:80	13.8 17.1 19.8	89:75	13.7 16.8 19.7	1+ BD occasion per mth for 6 mths	N/R	24 h
Goldstein et al. 2016 E1 (Canada)	NC sensory, PD	Concentration memory	WM	12:19	18.5	9:11	18.5	1+ BD occasion	N/R	N/R
Hartley et al. 2004 (UK)	N/R	Delayed word recall, Delayed	LT memory, mental	9:5	21.5	6:7	20.9	24+ BD score (drinks per hr.; times drunk last 6mths; % of being drunk when drinking)	18.8:0 UPW	During study
Heffernan et al. 2010 (UK)	SU	Prospective remembering video procedure	LT memory	7:14	18.7	5:24	18.6	2+ BD occasions per week	26.4:4.1 UPW	3.7:6.6
Henges et al. 2012 (USA)	NI, NC sensory	Stop signal reaction	Inhibition, sustained	20:20	19.5	26:4	19.6	1+ 0.8% + BAC occasion	10.3:4.5 PDr	N/R
Johnston et al., 2019 (China)	N/R	Iowa Gambling, Self-ordered pointing	DM, WM	13:9	16.0	90:95	16.2	1+ BD occasion	3–5:0 drinking days	N/R
Jones, Steele, & Nagel, 2017[L1] (USA)	PD, no family history information, MI, PD history, prenatal SU, SU	Delay discounting	Delay discounting	19:14	14.5	43:40	14.0	3+ BD occasions, past 3mths	N/R	N/R
Moreno et al. 2012 (Spain)	NC sensory, PD, NI, SU	2-choice, Iowa Gambling, Go no-go, Stop	DM, inhibition	10:12	19.5	11:15	20.1	1+ BD occasion per mth	4.4:0	3 days

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
Morris & Cuthbert, 2012 (UK)	PD, SUD, MI, psychotropic medication	4-choice serial reaction time, Stopsignal	Behavioural inhibition, inhibition	18:14	22.1	36:28	23.1	1+ BD occasion per week, past 3mths	15.8:4.1 UPW	N/R
Mota et al., 2013[L2] (Spain)	NI, PD, SU except cannabis, tobacco, AUD, NC sensory, NC motor, PD history, AUD history, AUDIT >20	RAVLT, Logical memory, Family pictures, Digits backward, Spatial location backward, Self-ordered pointing, Zoomap, Key search	Immediate memory, LTM memory, recent memory, WM	22:27	18.8	19:21	18.5	1+ BD occasion per week	N/R	Test day
Parada et al., 2011 (Spain)[4]	>90/2+ symptoms GSI SCL-90-R, NI, SU, PD, PD history, AUD, AUD history	RAVLT, Logical memory, Family pictures	Immediate memory, LTM memory, mental flexibility, recent memory, WM	32:30	18.9	31:29	18.7	1+ BD occasion per mth	N/R	24 h
Parada et al., 2012 (Spain)[4]	>90/2+ symptoms GSI SCL-90-R, NI, SU, PD, PD history, AUD, AUD history	Digits backward, Spatial span backward, Self-ordered pointing, Phonetic fluency, Zoomap, Key search, WCST	Expressive language, mental flexibility, WM	32:30	18.9	31:29	18.7	1+ BD occasion per mth	N/R	24 h
Sanhueza et al. 2011 (Spain)	SU, PD, NI	TAVEC, Digits forward, Corsiblocks, Stroop, Towerof Hanoi, BVRT	Immediate memory, inhibition, LT memory, mental flexibility, processing speed, recent memory, WM	8:13	19.0	17:25	18.9	6+ (F) or 8+ (M) drinks per occasion	6.9:0.9	N/R
Scaife & Duka, 2009 (UK)	MI, NI, AUD, SUD CANTAB (Spatial WM, Simple reaction time, IDED)	Paired associates learning, processing speed, recent memory, WM	Mental flexibility, processing speed, recent memory, WM	18:12	20.7	13:17	22.3	24+ BD score (drinks per hr.; times drunk last 6mths; % of being drunk when drinking)	N/R	12 h
Squeglia, Spadoni, Infante, Myers, & Tapert, 2009[L1–5] (USA)	Prenatal SU, MI, DSM4 A1, PD history, NC sensory, LH, SU	CVLT, Colour word interference, Towers, Letter-number, Complex figure copy, Digit vigilance, Block design, Digits (forward, backward), Digit symbol coding	Immediate memory, inhibition, LT memory, mental flexibility, processing speed, sustained attention, visuoconstructional, WM	36:13	13.8	24:16	13.5	T1: 0 T2: 1+ BD occasion	8.0:0.3 UPM	N/R
Townshend et al., 2014 (UK)	MI, NI, AUD, SUD	CANTAB (Matching to sample, Spatial WM), Vigilance	Inhibition, selective attention, WM	23:15	20.9	13:21	20.9	24+ BD score (drinks per hr.; times drunk last 6mths; % of being	33.3:20.5 UPM	12 h

Source (country of origin)	Exclusion criteria	Cognitive paradigm	Cognitive domain	Binge		Comparison		Alcohol use criteria for BD group	Use BD:C UPO	Abstinent BD:C[2]
				n M:F	Age	n M:F	Age			
								drunk when drinking)		
Vinader-Caerols et al. 2017 (Spain)	Medication, PD, irregular sleep, SU, SUD, AUD history	Immediate visual memory, WM	Recent memory, WM	18:24	18–19	18:24	18–19	3+ BD occasions per mth, past yr	4.6:0	Test day
Xiao et al., 2009[L1] (China)	N/R	Iowa Gambling, Self-ordered pointing	DM, WM	10:2	16.4	71:78	16.2	1+ BD occasion, past mth	1.4:0.6 2.7:0.7	N/R
Yoo et al. 2016 (Korea)	PD, MI, NI, AUD, AUD history	Iowa Gambling, Reversal learning	DM, mental flexibility	12:18	21.8	12:19	21.7	1+ BD occasion, past 2 weeks, 12–26 AUDIT score	N/R	24 h

AUD: alcohol use disorder; AUDIT: Alcohol Use Disorders Identification Test; BA: brain abnormalities; BAC: blood alcohol concentration; BD: binge drink; BVRT: Benton Visual Retention Test; C: control participants; CNS: central nervous system; DM: decision-making; DSM4 A1/A2: clinically diagnosed with any DSM4 Axis 1/Axis 2 condition; E1: experiment 1; E2: experiment 2; F: female; GSI SCL-90-R: Global Severity Index Symptom Check List-90-Revised; HI: head injury; IDED: CANTAB Intradimensional Extradimensional Shift Task; L: longitudinal (years); LD: learning disability; LH: left-handed; M: male; MI: chronic medical illness; MTH: month; N/A: not applicable NC: non-corrected; NI: neurological illness; N/R: not reported; PD: psychiatric disorder; PDr: peak drinks; RAVLT: Rey Auditory Verbal Learning Task; SU: substance use; SUD: substance use disorder; T1: baseline assessment; T2: follow-up assessment; UPM: units per month; UPO: units per occasion; UPW: units per week; WCST: Wisconsin Card Sorting Task; WK: weeks; WM: working memory. TAVEC = Spanish version of California Verbal Learning Test

[1] Study characteristics presented for first time point where binge drinkers are compared to control (i.e., in longitudinal studies this may be at baseline or follow-up)

[2] Where alcohol abstinence is reported as X:X, this refers to the number of days for binge drinkers: controls

[3] Gil-Hernandez et al., 2017 reported on neurocognitive performance in three age groups (13–15 yrs., 18 yrs., 22 yrs). This study was classified as three studies in the meta-analysis

[4] Parada et al., 2011, 2012 report on the same participant sample, and is therefore classified as one study in the meta-analysis

[5] Crego et al., 2009, 2010 report the same cognitive data, the duplicate data was removed from the meta-analysis

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Table 2

Grading of Recommendations, Assessment, Development and Evaluation (GRADE) Evidence Profile for neuroimaging, neurophysiological and neuropsychological studies

	Certainty assessment							Certainty
Outcome	**No. of studies**	**Study design**	**Risk of bias**	**Inconsistency**	**Indirectness**	**Imprecision**	**Other considerations**	
Behavioural inhibition only	2	observational	unclear [b]	not serious	not serious	serious [d]	none	VERY LOW
Brain electrical activity[3]	13	observational	not serious	not serious	not serious	not serious	none	LOW
Decision-making	7	observational	serious [a]	serious [c]	not serious	not serious	none	VERY LOW
Delay discounting	2	observational	unclear [b]	not serious	not serious	serious [d]	none	VERY LOW
Expressive language	4	observational	not serious	not serious	not serious	serious [d]	none	VERY LOW
Functional neural activity[1]	10	observational	not serious	not serious	not serious	not serious	none	LOW
Immediate memory	11	observational	not serious	not serious	not serious	not serious	none	LOW
Inhibition	18	observational	serious [a]	serious [c]	not serious	not serious	none	VERY LOW
Long term memory	9	observational	not serious	not serious	not serious	not serious	none	LOW
Mental flexibility	12	observational	not serious	not serious	not serious	not serious	none	LOW
Neural structure, connectivity[2]	13	observational	not serious	not serious	not serious	not serious	none	LOW
Planning	1	observational	unclear [b]	not serious	not serious	serious [d]	none	VERY LOW
Processing speed	18	observational	serious [a]	serious [c]	not serious	not serious	none	VERY LOW
Recent memory	7	observational	not serious	serious [c]	not serious	not serious	none	VERY LOW
Receptive language	2	observational	unclear [b]	not serious	not serious	serious [d]	none	VERY LOW
Recognition of emotions	1	observational	unclear [b]	not serious	not serious	serious [d]	strong association	VERY LOW
Sustained attention	13	observational	not serious	not serious	not serious	not serious	none	LOW
Visual perceptual	3	observational	not serious	not serious	not serious	serious [d]	none	VERY LOW
Visuoconstructional	4	observational	not serious	not serious	not serious	serious [d]	none	VERY LOW
Working memory	20	observational	not serious	not serious	not serious	not serious	none	LOW

[1] BOLD; fMRI

[2] Structural MRI studies (volume, surface area, cortical thickness), structural DTI studies (FA), structural MRS

[3] EEG, MEG, ERP

[a] Egger's test $p < 0.05$

[b] A minimum of three studies are needed to calculate risk of publication bias using Egger's linear regression method

[c] Unexplained heterogeneity of results was assessed through examination of variance in point estimates across studies, and the Q, I^2, tau and tau^2 statistics in the meta-analysis, in addition to examination of large differences in effect size

[d] The number of participants included in the review was smaller than the required number of participants generated from a sample size calculator for a single adequately powered trial

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Table 3

Meta-Analysis findings

	Meta-analysis					Heterogeneity						Publication bias (Egger's)	
Domain	**k**	**n (BD:C)**	**Hedges' *g***	***p***	**95% CI**	***Q***	***df***	***p***	***T***	T^2	I^2	***t-test***	***p***
Behavioural inhibition only	2	74:117	−0.27	0.08	−0.58, 0.03	1.09	1	0.300	0.06	0.00	8%	–	–
Decision-making	7	149:453	−1.70	0.002	−2.77, −0.63	115.64	6	<0.001	1.39	1.94	95%	2.57	0.025
Delay discounting	2	62:102	−0.12	0.475	−0.44, 0.20	0.35	1	0.553	0.00	0.00	0%	–	–
Expressive language	4	220:224	−0.10	0.313	−0.30, 0.10	3.37	3	0.338	0.07	0.01	11%	0.21	0.426
Immediate memory	11	490:523	0.03	0.731	−0.13, 0.19	16.62	10	0.083	0.17	0.03	40%	0.10	0.461
Inhibition	18	569:660	−0.39	0.026	−0.74, −0.05	144.94	17	<0.001	0.70	0.49	83%	2.50	0.012
Long term memory	9	344:384	−0.04	0.702	−0.27, 0.18	17.67	8	0.024	0.25	0.06	55%	1.58	0.079
Mental flexibility	12	421:455	−0.13	0.289	−0.37, 0.11	33.27	11	<0.001	0.34	0.12	67%	1.17	0.135
Planning	1	14:13	−0.67	0.100	−1.47, 0.13	0.00	0	1.000	0.00	0.00	0%	–	–
Processing speed	18	592:671	0.34	0.040	0.02, 0.67	135.93	17	<0.001	0.66	0.44	87%	2.27	0.019
Recent memory	7	316:317	−0.53	0.076	−1.11, 0.06	74.12	6	<0.001	0.75	0.56	92%	2.19	0.040
Receptive language	2	69:85	0.17	0.296	−0.15, 0.48	0.03	1	0.852	0.00	0.00	0%	–	–
Recognition of emotions	1	12:12	−1.05	0.013	−1.88, −0.22	0.00	0	1.000	0.00	0.00	0%	–	–
Sustained attention	13	385:467	−0.15	0.237	−0.41, 0.10	40.01	12	<0.001	0.38	0.15	70%	1.18	0.131
Visual perceptual	3	78:50	0.05	0.778	−0.30, 0.40	1.79	2	0.409	0.00	0.00	0%	0.67	0.312
Visuoconstructional	4	119:139	0.05	0.753	−0.24, 0.33	4.05	3	0.256	0.15	0.02	26%	0.78	0.258
Working memory	20	724:1035	−0.15	0.082	−0.32, 0.02	48.50	19	<0.001	0.29	0.09	61%	0.72	0.241
Neurocognition	42	1313:1752	−0.26	0.001	−0.42, −0.10	163.72	41	0.00	0.44	0.19	75%	3.04	0.002

k: number of studies; n: pooled sample size; CI: confidence interval; heterogeneity (Q-value, degrees of freedom [df], significance test [*p* value], standard deviation of true effects [tau; T], variance of true effects [tau^2; T^2], true/total variance [I^2]); BD: binge drinkers; C: comparators

Note. Where there were ≤ 2 studies, Egger's test of publication bias could not be calculated

Table 4

Overview of findings: Structural and functional correlates of binge drinking in young people

	Brain structure	Brain function	Neurophysiological	Cognitive
Pre-existing features, identified from longitudinal studies Consequences of binge drinking, identified from longitudinal studies	↓ Cortical volume (ACC, frontal, cingulate) ↓ Surface area (DLPFC) ↓ White matter volume (cerebellar) ↓ Grey matter volume (neocortex, frontal, temporal, diencephalon, caudate, brainstem, PCC) ↓ White matter growth (pons, corpus callosum)	↓ Brain activation during tasks of working memory (parietal, frontal), inhibition (frontal, parietal, putamen, cerebellar) ↑ Brain activation during tasks of inhibition (frontal, parietal, cerebellar) Aberrant brain activation during tasks of working memory (frontal, parietal)	Delayed P1, N2, P3b latencies during emotional valence task ↑Amplitude during tasks of inhibition (P3), attention (P3b), associative memory (VPP, DM), alcohol related cues (P3) ↑ PFC, insula activation during task of inhibition ↓ Amplitude during non-alcohol related cues (P1, P3)	↓ Decision-making ↓ Recent memory ↑ Amplitude during tasks of inhibition ↓ Long-term memory ↓ Sustained attention (males) ↓Visuoconstructional function (females) ↓ Working memory (improvement with time) ↑ Impulsivity (delay discounting)
Cross-sectional correlates with binge drinking	↓ Cortical thickness (frontal, parietal, ACC, PCC) ↓ GABA (ACC) ↓ Grey matter volume (L hemisphere) ↓ Grey matter voxel content (ACC) ↓ NAA/cr (ACC) ↓ White matter integrity (corona radiata, corpus callosum, longitudinal fasciculus, internal & external capsule, fornix, cerebellar peduncle) ↓ White matter volume (L, R hemisphere) ↑ White matter voxel content (ACC) Abnormal cortical volume (↓ males, ↑ females; PFC, temporal, motor, somatosensory, striatal) Abnormal cortical thickness (↓ males, ↑ females; frontal)	↓ Brain activation during tasks of emotion recognition (temporal) ↑ Brain activation during tasks of decision-making (amygdala, insula), inhibition (frontal, ACC, insula), working memory (frontal, parietal, supplementary motor, PFC, cerebellar, thalamus, insula), alcohol cue reactivity (ACC, dorsal striatum, globus pallidus, cerebellar, parahippocampal), emotion recognition (frontal) Aberrant brain activation during spatial working memory (↓ females, ↑ males; frontal, ACC, temporal, cerebellar)	↓ Alpha connectivity (frontal-temporal) ↓ Alpha power (temporal, occipital) ↓ Amplitude during tasks of attention (N100, N170, P100, P2, N2b, LPC) ↓ PFC activation ↑ Amplitude during tasks of attention (N2), inhibition (ERN), alcohol cue reactivity (P100) ↑ Beta (frontal-temporal), delta (frontal-temporal), theta (frontal-parietal) connectivity ↑ Beta (parahippocampal, fusiform), theta (cuneus, lingual) density ↑ Delta, theta, mean spectral power Delayed P100, N100, N2b, P3a, P3b, Pe latency during tasks of attention	↓ Decision-making ↓ Inhibition ↓ Executive functioning ↓ Emotion recognition ↑ Processing speed
Effect of discontinuation of binge drinking, identified from longitudinal studies	–	Normalised brain activation during alcohol related cues	↓ P3 amplitude during task of inhibition *	↑ Long-term memory * ↑ Recent memory ↑ Working memory *

* Results of ex-binge drinkers reflect an intermediate position between continuous binge and non-binge drinking participants

ACC: anterior cingulate cortex; DLPFC: dorsolateral prefrontal cortex; DM: difference due to memory effect; ERN: error-related negativity; L: left; LPC: late potential component; Pe: error positivity component; PCC: posterior cingulate cortex; PFC: prefrontal cortex; R: right; VPP: vertex positive potential

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