IMPACT OF ALCOHOL USE ON INHIBITORY CONTROL (AND VICE VERSA) DURING ADOLESCENCE AND YOUNG ADULTHOOD

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ABSTRACT

Aims: Adolescence is usually the time when individuals first drink alcohol and this has been associated with relatively weak or immature inhibitory control. This review examines the changes on brain development and inhibitory function that take place during adolescence and youth as well as the relationship between inhibitory control and alcohol use at this early age. **Methods:** Narrative review of the chief studies related to (a) the development of inhibitory control during adolescence, (b) the deficits in the inhibitory ability in alcohol use disorders and (c) the effects of acute alcohol intake and binge drinking on inhibitory control in adolescents and young adults. **Results:** Inhibitory control processes are developing during adolescence and youth. Poor inhibitory functions may predispose the individual to alcohol misuse. Likewise, acute and binge alcohol drinking may impair the inhibitory control and compromise the ability to prevent or stop behaviour related to alcohol use. **Conclusion:** Poor inhibitory control can be both the cause and the consequence of excessive alcohol use. Adolescence and young adulthood may be a particularly vulnerable period due to (a) the weak or immature inhibitory functioning typical of this stage may contribute to the inability of the individual to control alcohol use and (b) alcohol consumption per se may alter or interrupt the proper development of inhibitory control leading to a reduced ability to regulate alcohol intake. Further longitudinal research is needed to evaluate the interaction between inhibitory control dysfunction and alcohol use in both situations.

INTRODUCTION

Adolescence is a stage of life characterized by drug experimentation and engagement in health-risky behaviours (Spear, 2000; Dahl, 2004). In Western countries, alcohol is one of the most available and used drugs at this age (Anderson and

Baumberg, 2006; Johnston *et al.*, 2009), and it currently constitutes a major public health concern (Eurobarometer, 2010; SHAMSA, 2011).

While several decades of research in adults have shown that chronic alcohol abuse is associated with major brain and cognitive impairments (e.g., Oscar-Berman and Marinkovic, 2007; Harper, 2009), the relationship between alcohol consumption and neurocognitive damage during adolescence and youth is still poorly investigated. Understanding the neurocognitive consequences of alcohol on the adolescent brain is crucial, since adolescence is a period of critical brain development and the time in which alcohol use is typically initiated.

Within the various cognitive processes affected by alcohol, the inhibitory control deserves a particular consideration. Indeed, the ability to inhibit a response or action may prevent alcohol misuse, but deficits in such ability might in turn promote excessive alcohol consumption. Recent research indicates that acute alcohol intake, as well as heavy or binge drinking during adolescence and youth, may induce anomalies in behaviour (poor decision making, altered impulse control, etc.) and brain functioning related to inhibition (Field *et al.*, 2007; Loeber and Duka, 2009; López-Caneda *et al.*, 2012). Likewise, an alteration in the inhibitory control may constitute a vulnerability factor for subsequent alcohol misuse and lead to an escalation or disordered regulation of alcohol intake (Norman *et al.*, 2011; Wetherill *et al.*, 2013).

This review will focus on he definition of inhibitory control and the main experimental paradigms used to measure it, on the core brain circuitry involved in response inhibition and its development across adolescence and early adulthood. Finally, the role of inhibitory processes as both a determinant and a consequence of excessive alcohol use will be discussed. This review ends with some additional considerations about the relation of inhibitory control with impulsivity, as well as with

other cognitive processes affected by alcohol, and with a brief discussion of the application of current knowledge to the prevention of alcohol abuse in youths.

INHIBITORY CONTROL

Inhibitory control is a core component of human behaviour. The importance of this executive function is highlighted by the broad range of psychiatric problems associated with inhibitory deficits, such as attention deficit hyperactivity disorder (Nigg, 2001), bipolar disorder (Frangou *et al*., 2005), obsessive-compulsive disorder (OCD) (Penades *et al*., 2007) and substance use disorder (Verdejo-García *et al*., 2008). Although it is generally defined as the ability to withhold or suppress actions or thoughts that are inappropriate, inhibitory control is a heterogeneous construct which lacks of a simple operational definition, probably due to the multiple kinds of inhibitory processes underlying this executive function as well as the wide range of tasks used to measure it.

From an overall view, two different inhibitory functions can be distinguished: involuntary or *automatic inhibition* and voluntary or *effortful inhibition* (Nigg, 2000). The first one refers to the involuntary inhibition of attention that takes place to recently inspected locations or objects, which is traditionally known as inhibition of return (Klein, 2000). The effortful inhibition is frequently divided in *behavioural inhibition* and *interference control* (see Diamond, 2013, for a recent review).

Behavioural inhibition is the ability to suppress or stop responses that are ready to be emitted (prepotent responses) and it would comprise the motor inhibition measured by the Go/NoGo (GNG) and the stop-signal (SS) tasks (Logan, 1994). Interference control includes two other subtypes of inhibition. The first one, *cognitive inhibition*, involves (a) the inhibition of thoughts and memories, i.e., the ability to

suppress unwanted mental representations (Anderson and Levy, 2009) –usually measured by the Think/No-Think paradigm (Anderson and Green, 2001) –, and (b) the inhibition of the tendency to choose smaller, immediate rewards in favour of delayed but larger rewards, also known as delayed gratification (Mischel *et al*., 1989), which is frequently assessed by the delay discounting task (Bickel and Marsch, 2001). The second subtype of interference control refers to the inhibition of the processing of nonpertinent or irrelevant stimuli, which can be measured, for instance, by the Stroop or the Flanker tasks (Eriksen and Eriksen, 1974; MacLeod, 1991).

For the purpose of the present review, we will focus on behavioural inhibition, which has been the type of inhibitory control more investigated in studies on the relationship between alcohol and inhibitory processes. Throughout this article, when we refer to inhibitory control, we essentially refer to behavioural or response inhibition.

Given that response inhibition is typically measured by the GNG and SS paradigms, these tasks have been widely used to examine the effects of alcohol on inhibitory processes as well as the influence of inhibitory control ability on the regulation of alcohol intake. Both tasks involve rapid, repeated responses to targets, while also demanding suppression of those prepotent responses when faced with a Stop or No-Go stimulus. The main difference between them is that while the GNG task requires that individuals respond to one type of stimuli (Go) and withhold the response to the other (No-Go), the SS task demands that individuals inhibit a response that has been already initiated when a SS is presented (Fig. 1). The commission errors or false alarms (inappropriate responses to the No-Go stimulus), for the GNG task, and the time required to stop a response once it has been initiated, for the SS task, provide the behavioural index of inhibitory control.

Figure 1

Using functional magnetic resonance imaging (fMRI), the neural substrates underlying these tasks, and therefore the inhibitory control processes, have begun to be identified. Studies in healthy population have consistently revealed a frontostriatal network involved in the inhibition of prepotent responses (Aron *et al*., 2007; Chambers *et al*., 2009). Within this network, the prefrontal cortex (PFC) and, particularly, the inferior frontal cortex (IFC), seem to be a critical region for successful inhibition (Konishi *et al*., 1999; Aron *et al*., 2004; Chikazoe *et al*., 2009). This is also supported by neuropsychological studies, which have reported impairments in inhibitory control in subjects with IFC damage (Aron *et al*., 2003).

Briefly, the IFC would be responsible for generating the NoGo signal which, passing through the subthalamic nucleus and the globus pallidus, would lead to the inhibition of the thalamus and, consequently, to the inhibition of motor responses in the primary motor cortex (Fig. 2) (Nambu *et al*., 2002; Aron and Poldrack, 2006). This is clearly a very simplified model as there are other less direct inhibitory pathways (Duann *et al*., 2009; Aron, 2011), as well as other regions such as anterior cingulate or parietal cortex (Durston *et al*., 2002; Watanabe *et al*., 2002) that are involved in response inhibition.

Figure 2

On the other hand, neuroimaging studies have found abnormal IFC functioning linked to substance use (for reviews see Volkow and Fowler, 2000; Dom *et al*., 2005; Feil *et al*., 2010), including alcohol (Pfefferbaum *et al*., 2001; Noël *et al*., 2001; Li *et al*., 2009). Adolescence also appears to be associated with a particular IFC functioning

which has been related to the maturational changes that take place during this period (see section below).

INHIBITORY CONTROL DEVELOPMENT DURING ADOLESCENCE

Basic cognitive processes are already well established in childhood. However, more complex cognitive functions, such as inhibitory control, undergo a substantial refinement during adolescence. Thus, although the ability to inhibit a response is already present in infancy and childhood (Diamond and Goldman-Rakic, 1989; Jones *et al*., 2003), it is during adolescence when this ability becomes more efficient (Tamm *et al*., 2002; Marsh *et al*., 2006; Luna, 2009). A number of studies show that inhibitory control improves with age, as demonstrated by the higher speed (reduction in reaction times) (Williams *et al*., 1999; Band *et al*., 2000), and better performance (lower commission error rates) (Casey and Trainor, 1997; Jonkman, 2006) in response inhibition across development.

This more efficient inhibitory control appears to be related to the anatomical and functional changes that take place in the PFC throughout adolescence and youth (Luna *et al*., 2004). Important brain maturational changes such as myelination or synaptic pruning/reorganization continue well into late adolescence and early adulthood, being the PFC the last region to reach maturity (Giedd *et al*., 1999; Gogtay *et al*., 2004; Lenroot and Giedd, 2006). Both myelination and synaptic reorganization have been associated with an improvement in neural networks functioning as well as with increased neuronal and behavioural efficiency (Casey *et al*., 2005; Spear, 2010).

Similarly, fMRI studies have shown that inhibitory function develops in association with changes in PFC activity. Although the relationship between behavioural performance in inhibitory tasks and greater or lesser fMRI activation is still

controversial (Bunge and Wright, 2007; Luna *et al*., 2010), several studies have reported greater IFC activity during inhibition in children compared with adolescents, and in adolescents compared to adults. This progressive reduction in prefrontal activation has been associated with better inhibitory control performance (Casey *et al*., 1997; Somerville *et al*., 2011). These findings support the notion that an immature brain (such as the adolescent brain) displays greater and less efficient prefrontal activation as well as poorer performance related to inhibition than a mature (and, therefore, adult) brain.

The adolescent brain, and particularly the PFC, appears to be especially sensitive to the harmful effects of alcohol as compared to the adult brain (Crews *et al*., 2000; Spear, 2013), probably due to these maturational changes (Giedd *et al*., 1999; Lebel and Beaulieu, 2011). This special sensitivity along with the relative developmental delay in inhibitory control could involve, on one hand, a greater propensity to excessive alcohol consumption (due to the reduced ability to prevent or stop behaviours related to alcohol use) and, on the other, a greater vulnerability of inhibitory mechanisms to the harmful effects of alcohol (due to the alteration or interruption in the normal development of inhibitory function).

POOR INHIBITORY CONTROL AND PROPENSITY TO ALCOHOL INTAKE DURING ADOLESCENCE

The immaturity of brain functioning underlying inhibitory control during adolescence appears to be linked to the peak onset of substance abuse observed through this period (Steinberg, 2008). Adolescence constitutes a stage of special risk for drug use initiation and the development of substance dependence (Rohde *et al*., 2001; Hardin and Ernst,

2009), as well as for the emergence of psychiatric disorders related to disinhibitory behaviours such as conduct disorders or OCD (Zoccolillo, 1993; Pauls *et al*., 1995).

Ineffective response inhibition may render individuals more vulnerable to develop addictive behaviours (Perry and Carrol, 2008). In this sense, Goldstein and Volkow (2002) proposed that drug addiction is a "syndrome of impaired response inhibition", in which deficits in inhibitory control, along with an increased salience of drug related stimuli (e.g., alcoholic drinks), would contribute to the inability to control the drugs use (Goldstein and Volkow, 2002; see also Jentsch and Taylor, 1999; Robinson and Berridge, 2003; Wiers *et al*., 2007).

Consistent with this hypothesis, several studies have reported a weak inhibitory control with alcohol use during adolescence and youth. For example, Henges and Marczinski (2012) observed that failures to inhibit a response, as measured by the cued GNG task (Miller *et al*., 1991), predicted the binge use of alcohol in young social drinkers. Other authors have reported that poor inhibitory control, as measured with the SS task, is associated with alcohol use-related problems as well as with risk of alcohol dependence in adolescents (Nigg *et al*., 2006; Rubio *et al*., 2008).

Studies of offsprings of alcoholics have shown a lower response in the inhibition performance in subjects with family history of alcohol use disorders (Nigg *et al*., 2004; Schweinsburg et *al*., 2004). Consistent with this, children and adolescents with a positive family history for alcohol use disorders also show anomalies in the anatomical and functional structure of some regions involved in inhibitory control (Schweinsburg *et al*., 2004; Hill *et al*., 2009; Heitzeg *et al*., 2010). These anomalies might predispose the children to develop alcohol misuse during adolescence (Norman *et al*., 2011). Accordingly, a recent longitudinal study conducted by Wetherill and Colleagues. showed that adolescents who later became heavy drinkers displayed less activation of

inhibitory circuitry during a GNG task than age-matched controls, which was indicative of neural vulnerabilities *prior* to the onset of alcohol use. After becaming heavy drinkers, adolescents showed more activation during response inhibition than controls, indicating that heavy drinking *per se* may lead to additional alterations in brain functioning related to inhibitory control (Wetherill et al., in press).

Finally, weak inhibitory control has also been proposed as a general vulnerability factor for addictive behaviours, including alcohol use disorder (Goldstein and Volkow, 2002, 2011; Brewer and Potenza, 2008).

Although reduced inhibitory ability may play a major causal role in development of alcohol misuse or heavy drinking, conversely an impairment of the inhibitory control can be directly caused by heavy alcohol consumption. As described below, alcohol might compromise brain regions responsible for successful inhibition, thus reducing the ability to withhold a response. Therefore, not only a weak response inhibition may increase or encourage alcohol consumption, but also alcohol drinking may produce a weakening of inhibitory control, leading to a lower ability to stop alcohol consumption.

CONSEQUENCES OF ALCOHOL INTAKE ON INHIBITORY CONTROL

There are two main lines of research in the study of alcohol effects on inhibitory control: (a) the study of the acute effects of alcohol on response inhibition, where subjects execute different cognitive tasks or neuropsychological testing under the influence of certain doses of alcohol; and (b) the study of the consequences of heavy or binge alcohol drinking on the inhibitory ability.

Acute effects of alcohol

Studies of the acute effects of alcohol support the hypothesis that alcohol disrupts (reduces) inhibitory control ability (Reynolds *et al*., 2006; Ostling and Fillmore, 2010). Specifically, adolescents and youths exposed to different doses of alcohol exhibit poor performance in a variety of response inhibition tasks. For instance, using SS and GNG tasks, several studies have demonstrated that moderate to high doses of alcohol (leading to blood alcohol contents ~0.06-0.09%) impairs inhibitory control in young healthy subjects (Fillmore and Vogel-Sprott, 1999; Easdon and Vogel-Sprott, 2000; Marczinski and Fillmore, 2003; Rose and Duka, 2007, 2008; Loeber and Duka, 2009). Interestingly, it has been found that although moderate doses of alcohol impair the ability to suppress a response, they do not affect the ability to execute a response, which appears to be indicative of a specific disruption of the inhibitory mechanisms (Field *et al*., 2010). Accordingly, the alcohol-seeking behaviour might remain intact whereas the ability to inhibit this impulse and to control alcohol use might be compromised (Leeman *et al*., 2012).

Another particularly relevant study showed that impairments in inhibitory control after a moderate dose of alcohol are most pronounced in binge drinkers than in non-binge drinker subjects (Marczinski *et al*., 2007). This study indicates that individuals who binge drink alcohol can be particularly sensitive to the acute alcohol effects on response inhibition, such that when they become intoxicated they are less able to refrain from the impulse or desire to consume more alcohol, leading to further binge drinking (BD). This finding is consistent with a study conducted by Weafer and Fillmore (2008), who reported that greater impairment of inhibitory control from alcohol predicted increased *ad libitum* drinking in young social drinkers.

Research examining the neural correlates of acute effects of alcohol also suggests that moderate-to-high doses of alcohol induce abnormalities on brain

functioning involved in inhibitory control in adults (Ridderinkhof *et al*., 2002; Easdon *et al*., 2005). However, to our knowledge, only one study has assessed the electrophysiological patterns of response inhibition during alcohol intoxication in young people (Euser and Franken, 2012). In this study, moderate doses of alcohol not only decreased performance in an emotional GNG task, but also altered the components of the event-related potentials (ERPs) related to inhibitory control (N2-NoGo and P3-NoGo) (see, e.g., Falkenstein *et al*., 1999; Kok *et al*., 2004; for information about these components). These results were interpreted as indicating that youths under the effects of alcohol need to effortfully activate more cognitive resources during the inhibition process (Euser and Franken, 2012).

Despite the well-established view that alcohol impairs inhibitory control, to date only one fMRI study has assessed the effect of acute alcohol ingestion in young people during response inhibition (Schuckit et al., 2012). In line with other studies that considered jointly young and adult participants (Anderson et al., 2011; Nikolau et al., 2013), alcohol decreased activity of regions involved in inhibitory control (such as prefrontal and cingulate regions) during a SS task in young people, specifically in those with a low-response to alcohol and, therefore, with higher risk of problem drinking (Schuckit et al., 2012). However, additional research in this field is needed to clarify the impact of acute alcohol consumption on brain functioning related to response inhibition at this young age.

Effects of heavy/binge alcohol drinking

BD or *heavy episodic drinking*, i.e., the consumption of large amounts of alcohol in a short time followed by periods of abstinence (NIAAA, 2004; Courtney and Polich, 2009), has been related to neurocognitive impairments in adolescents and young people

(e.g., Heffernan *et al*., 2010; Squeglia *et al*., 2012; López-Caneda *et al*., 2013; Mota *et al*., 2013; see also Hermens *et al*., 2013; Jacobus and Tapert, 2013, for recent reviews). Studies about inhibitory control, although still rare, have reported that BD is associated with abnormalities in brain function and behavioural performance related to response inhibition. In this sense, neuropsychological studies have shown poor performance in several tasks assessing inhibitory processes in youths with a BD pattern (Townshend and Duka, 2005; Nederkoorn *et al*., 2009; Scaife and Duka, 2009). For instance, Townshend and Duka (2005) observed that young BD women had more difficulties to inhibit their response to alerting stimuli in a vigilance task than controls, which was interpreted as a sign of a deficit in the frontal inhibitory control. More recently, Nederkoorn *et al*. (2009) reported an increased SS reaction time also in young BD women, indicating again a poor response inhibition in this population. Although these data are suggestive of a greater vulnerability in females to the neurotoxic effects of alcohol on inhibitory control, which is consistent with the stronger structural and functional impairments observed in women with an alcohol use disorder (Caldwell *et al*., 2005; Medina *et al*., 2008), additional research is required to test this hypothesis.

The three electrophysiological studies that to date have examined the effects of alcohol on inhibitory processes in young binge or heavy drinkers have shown anomalies both in the latency (Petit *et al*., 2012) and the amplitude (López-Caneda *et al*., 2012; Smith and Mattick, 2013) of the NoGo-P3 component of the ERPs. In the study by Petit *et al*. (2012), heavy social drinkers showed delayed latencies of NoGo-P3 in an alcohol related-context, which was considered as an index of prioritizing processing related to alcohol that leads to poorer inhibitory performance. In a recent follow-up study by our research group (López-Caneda *et al*., 2012), a greater NoGo-P3 was observed in young binge drinkers, which was associated with a hyperactivation in the right IFC. These

results were interpreted as indicative of the activation of additional neural resources to compensate emerging functional alterations in the regions engaged in response inhibition, which would allow binge drinkers to perform an efficient inhibitory control. Finally, the study conducted by Smith and Mattick (2013) showed longer stop-signal reaction time in young female heavy drinkers than in female controls as well as larger P3 increase for successful compared with failed inhibition trials in female heavy drinkers. Following the authors, these results were indicative that females who regularly drink heavily needed longer time and greater cognitive effort to inhibit the response correctly.

On the other hand, to our knowledge, the only neuroimaging study examining the response inhibition in adolescent binge drinkers is the one conducted by Wetherill et al. (2013), which reported anomalies in the functioning of inhibitory circuitry before and after the onset of heavy alcohol use (see previous section). Another study in adolescents binge drinkers assessed the neural correlates of the Iowa Gambling Task (IGT), a decision-making task that can be considered a measure of cognitive inhibition (Verdejo-García *et al*., 2008). In this study, Xiao *et al*. (2013) reported that adolescents with a BD pattern displayed a poor decision-making as well as a higher activity in the neural circuitry involved in emotional and incentive-related behaviours (the amygdala and the insula). According to the authors, the hyperreactivity of this neural system could entail difficulties to inhibit the desire to consume alcohol.

Taken together, research on the effects of acute and binge alcohol drinking suggests that alcohol consumption might lead to a 'snowball effect' by which the acute effects of alcohol on inhibitory control would promote a continuous auto-administration of the substance which, in turn, would contribute to the deterioration of the inhibitory control system.

ADDITIONAL CONSIDERATIONS

Inhibitory control and impulsivity

Impulsivity is a psychological construct closely linked to inhibitory control. This term includes those behaviours that are risky, poorly planned, and that entail undesirable or negative consequences (e.g., Evenden, 1999; Mitchell, 2004). Within neuropsychology and cognitive neuroscience, impulsivity is often associated with *disinhibition*, and it is thought to arise from an impairment of inhibitory control (Enticott *et al*., 2006; Lawrence *et al*., 2009). Impulsivity, similar to inhibitory control, plays a major role in alcohol-related disorders, as is demonstrated by the fact that (a) it predicts early onset drinking age and development of heavy drinking and alcohol dependence in young adults (Ernst *et al*., 2006); (b) different impulsivity dimensions are positively correlated with increased alcohol use and with alcohol related-problems (Dom *et al*., 2006; Hittner and Swickert, 2006; Cyders *et al*., 2008); and (c) alcohol-dependent subjects display high scores on impulsivity measures (Whiteside and Lynam, 2003; Mitchell *et al*., 2005; Fox *et al*., 2008). In the same way, several studies have suggested that excessive alcohol consumption in adolescents and youths is linked to the increased impulsivity during this period (Carlson *et al*., 2010; Moreno *et al*., 2012). A decline in this trait that usually takes place over the 18-25 age range has been related to decrease in alcohol use (Littlefield *et al*., 2010).

Although impulsivity and inhibitory control are related, they can make unique contributions to alcohol use (Leeman *et al*., 2012) and both constructs should be taken into account in studies examining the individual's ability to control alcohol use.

Alcohol also affects other related cognitive processes

Although this review is focused on the inhibitory control impairment induced by alcohol use, it is important to note that alcohol may also indirectly affect the inhibitory system. Other cognitive processes that interact with inhibitory control, such as working memory, are also affected by alcohol consumption. For instance, a study conducted by Finn *et al*. (1999) showed that young subjects with low working memory capacity were more susceptible to the effects of alcohol on impulsive behaviour, suggesting that alcohol reduced the ability of working memory to modulate response inhibition. Alcohol might thus affect inhibitory control via (a) weakening the inhibitory system, or (b) decreasing working memory capacity (Vogel-Sprott *et al*., 2001).

Alcohol, inhibition and gender

Another important moderator of the relationship between alcohol and inhibitory control is the gender. In this sense, it has been observed that while men display greater disruption of inhibitory control when receiving acute doses of alcohol than women (Fillmore and Weafer, 2004), the effects of frequent or binge alcohol drinking on response inhibition appear to be greater in females compared to males (Townshend and Duka, 2005; Nederkoorn *et al*., 2009). However, the neurocognitive results relating to gender and alcohol consumption in non clinical populations are still scarce and inconsistent, so further research is therefore needed.

Potential clinical implications

Given that alcohol misuse is associated with deterioration of inhibitory control skills, response inhibition training could theoretically improve inhibitory control and, consequently, lead to a decrease of alcohol intake (Houben *et al*., 2011; Jones *et al*., 2011). Houben *et al*. (2011) demonstrated, in a recent study, that young heavy drinkers

trained to withhold a response to alcohol-related stimuli during a GNG task, consumed significantly less alcohol in the week following the training. This finding, although needs to be replicated and validated for longer periods, suggests that the strengthening of response inhibition may be a useful intervention strategy for reducing alcohol use. It also underlines the importance of inhibitory control mechanisms on alcohol drinking behaviour as well as the usefulness of the early detection of response inhibition problems in alcohol use disorders prevention programmes.

CONCLUSIONS

Adolescence is a stage of life frequently associated with an early onset of alcohol use. It is also characterized by a weak inhibitory control due to the immaturity of the brain circuitry supporting this executive function. These reduced inhibitory skills consequently affect the ability to control the alcohol intake. Inhibitory control processes, in particular the behavioural inhibition, may equally be the cause and the consequence of excessive alcohol use. In fact, not only a weak response inhibition may lead to alcohol consumption, but drinking alcohol, in turn, may entail a weakening of the inhibitory control, leading to a lower ability to stop alcohol consumption. In this review, we have highlighted the main studies examining the relationship between inhibitory control and alcohol use in adolescents and young adults. Nevertheless, much further research is required to clarify how the excessive alcohol consumption may induce deficits in inhibitory control or how inhibitory control disruptions may constitute a vulnerability factor for alcohol misuse. The cross-sectional nature of most of the studies exploring neurocognitive functioning in young and adolescent binge drinkers makes it difficult to establish this relationship, so longitudinal studies are needed to evaluate the extent of the interaction between the inhibitory control dysfunction and

alcohol use in both directions, as a vulnerability factor and as an effect of excessive drinking. Another major challenge would be to design prevention and treatment programmes that systematically integrate this growing body of knowledge.

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FIGURE LEGENDS

Figure 1. Schematic of the Go/NoGo (GNG) and the stop-signal (SS) tasks. *a)* In the GNG task, subjects are required to respond when a *go* stimulus (e.g., a blue square) is presented, and to inhibit or withhold their response when a *nogo* stimulus (e.g., a green square) is presented. *b)* In the SS task, subjects have to respond as quickly as possible to the *go* stimuli (e.g., the X letter). During the stop condition, a stop signal (e.g., an auditory stimulus) is presented at a certain delay after the onset of the go stimulus and subjects must stop the already initiated motor response. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

Figure 2. Schematic representation of the neural circuitry involved in response execution and inhibition, according to Aron (2011). (a) When a motor action is initiated (e.g. moving the hand to press a button), the premotor cortex (PMC) activates the putamen (PUT), which in turn inhibits the internal segment of the globus pallidus (GP). This inhibitory projection leads to a disinhibition of the thalamus (THA), which leads to an increase in the impulses to the primary motor cortex (M1), thus resulting in response execution. (b) The inferior frontal cortex (IFC) sends a 'Stop' command through the subthalamic nucleus (SubTHA). This nucleus sends excitatory output to the GP, which results in the inhibition of large thalamic areas and hence in the inhibition of thalamocortical projections involved in hand movements, resulting in response inhibition. NC, nucleus caudatus.

Figure 1

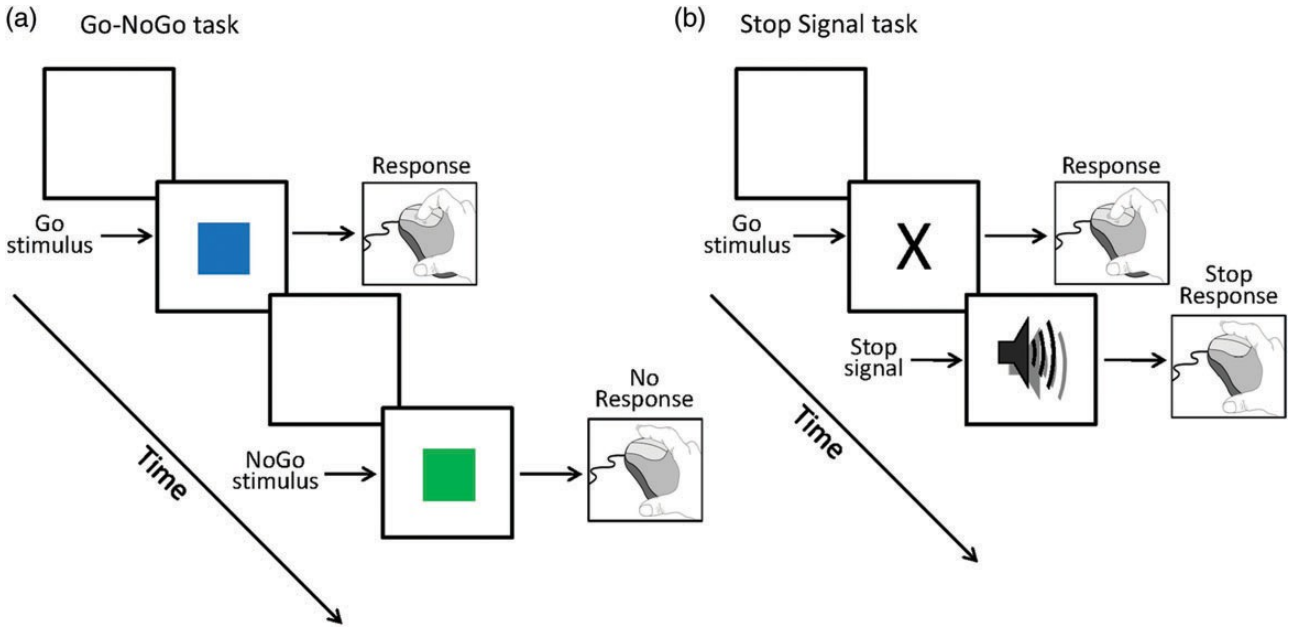

Figure 2