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Multisensory stop signals can reduce the disinhibiting effects of alcohol in adults

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Abstract

Background: Alcohol impairs drinkers' abilities to inhibit inappropriate responses. Certain stimulus conditions have been shown to facilitate behavioral control. Under conditions where individuals are presented with multiple inhibitory signals, the speed and consistency with which they are able to inhibit a response is improved. Recent research has shown that multisensory signals might protect against the disruptive effects of alcohol on mechanisms of behavioral control. The present study examined whether multisensory stop-signals can be used to improve inhibitory control, possibly by speeding attentional shifts towards inhibitory "stop" signals in the environment.

Method: Twenty adult social drinkers performed a modified cued go/no-go task that measured the ability to inhibit prepotent responses following 0.64 g/kg alcohol and placebo. Response targets were presented as unimodal (visual) and as multisensory (visual+aural) stimuli.

Results: Results showed that during unimodal response target trials, participants made more inhibitory failures under 0.64 g/kg alcohol compared to placebo. During multisensory trials, however, there was no significant effect of alcohol on inhibitory control.

Conclusions: These findings identify multisensory inhibitory signals as a potentially important environmental factor that can reduce the degree to which alcohol disinhibits behavior possibly by intersensory co-activation between the visual and auditory pathways.

Keywords

Inhibitory control; acute alcohol effects; cued go/no-go task; redundant signal effect; multisensory processing

Introduction

A well-known acute effect of alcohol is disruption of cognitive processes that results in slowed reaction time (RT) and an impaired ability to inhibit inappropriate action (Hendershot et al., 2015; Fillmore, 2012). Blood alcohol concentrations (BACs) in the moderate range (i.e., 50-80 mg/100 ml) can produce considerable impairment in these areas.

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Alcohol exerts this effect by slowing the speed at which information is centrally processed (Bartholow et al., 2003; Moskowitz and Depry, 1968). As the transmission of information in the CNS is slowed, drinkers show outward signs of intoxication, such as impulsive action and delayed responses to external stimuli. Laboratory studies find that alcohol reliably increases failures to inhibit responses to stop-signals in a dose-dependent manner (Fillmore, 2003; Marczinski and Fillmore, 2003). Cognitive-process models and analyses of event-related potentials suggest that alcohol impairs inhibitory control by slowing information processing to disrupt late stages of stimulus-response selection (Bartholow et al., 2003; Fillmore and Van Selst, 2002; Lukas et al., 1990; Moskowitz and Depry, 1968). Characteristics of the stimuli being processed can influence the degree to which alcohol impairs cognitive processing. It is well known that alcohol impairment intensifies as a function of task complexity. As greater processing is required to complete a task, drinkers tend to be more impaired, even at doses where no impairment is present for simpler tasks (Maylor et al., 1992).

Other characteristics of stimuli may facilitate processing and improve performance. For example, people tend to respond more quickly to environmental signals that are delivered redundantly to more than one sensory modality (Diederich and Colonius, 2004; Forster et al., 2002; Gondan et al., 2010). This phenomenon has been recognized for some time (Todd, 1912) and is referred to as the “redundant signal effect” (RSE). Studies of the RSE typically require participants to perform a choice response task with three conditions: one in which participants respond to a visual cue (e.g., an X or O), another where they respond to an auditory cue (e.g., a high or low tone), and one condition where both stimuli are presented simultaneously (Sinnott et al., 2008). Performance in the simultaneous, redundant signal condition is superior to performance in both unimodal conditions, both in terms of the speed and accuracy of responses.

This facilitative effect of redundant signals could be used to reduce acute alcohol impairment of inhibition. Physiologically, brain regions implicated in inhibitory control include the anterior cingulate, dorsolateral prefrontal cortex, insula, and parietal regions (Botvinick et al., 2004; Seeley et al., 2007). Neuroimaging studies indicate that alcohol decreases activity in these regions (Anderson, 2011; Marinkovic, 2012), which may explain why the drug reduces inhibitory control. Although the neural processes underlying the RSE are not fully understood, there is evidence that specialized multisensory neurons distributed in key brain regions become active in the presence of multimodal stimuli. Chen and colleagues (2015) reported evidence for multisensory activation in many of the brain regions involved in inhibitory control, including the right anterior insula, dorsal anterior cingulate, and posterior parietal cortices, suggesting that multisensory signals may facilitate improved response inhibition. Indeed, there is some evidence that multisensory inhibitory signals can enhance inhibitory control in the sober state (Cavina-Pratesi et al., 2001; Gondan et al., 2010; Gondan et al., 2005). The finding that redundant environmental signals may boost neural activity in inhibitory control centers impaired by alcohol suggests its potential utility for ameliorating the drug’s impairing effects on inhibitory control.

Despite this strong rationale that multisensory signals can ameliorate the impairing effects of alcohol on inhibitory control, the possibility remains uncertain. Inhibitory control appears

especially vulnerable to the disruptive effects of alcohol (Fillmore and Weafer, 2012). A recent study by our group failed to demonstrate that multisensory inhibitory signals could reduce the disinhibiting effects of alcohol (Miller and Fillmore, 2013). In that study, inhibitory control was assessed by a go/no-go task which included unimodal (visual) and multisensory (visual + aural) inhibitory signals. Results showed that 0.65 g/kg alcohol reduced response inhibition to a similar degree regardless of whether inhibitory signals were delivered bimodally or unimodally.

Although there might be several reasons for the failure to observe an advantage of multisensory signals over the unimodal signals in the study, task simplicity may have played key role. The unimodal stop signal was presented in the center of the visual field as a distinct color, requiring minimal attention and stimulus discrimination to achieve highly accurate responding. Such highly accurate responding to this unimodal stimulus limits the ability to observe further gains by the addition of an auditory stimulus. However, when visual stop signals require more processing, such as the orienting of attention and greater feature discrimination, accompanying auditory signals might facilitate inhibitory control by increasing the speed with which people orient and detect inhibitory cues in the environment. For example, an auditory signal that accompanies a visual stop cue could alert and hasten orientation to the visual signal faster than would occur to the visual stimulus alone. Such speeding of attention to stop signals should improve inhibitory control and possibly reduce the disinhibiting effects of alcohol.

The purpose of the present study was to test whether multisensory inhibitory signals can reduce the disinhibiting effects of alcohol in healthy adults by facilitating the focus of attention to inhibitory cues. A group of healthy adults received 0.64 g/kg alcohol and placebo and completed a modified cued go/no-go task. This task utilized an RSE paradigm to assess how multisensory signals affect participants' ability to respond quickly as well as inhibit those responses. Unlike in our previous work (Miller and Fillmore, 2013), the task used in this study required spatial target detection in addition to the inhibition of responses. Participants' eye movements were measured to determine how multisensory signals affected the speed of their orientation to target stimuli. We hypothesized that orientation to visual targets would be faster when those targets were accompanied by aural stimuli (i.e., multisensory facilitation) and that this facilitative multisensory effect would reduce the degree to which alcohol impairs response inhibition.

Methods

Participants

Twenty adult drinkers (10 men and 10 women) participated in this study. Recruiting took place through fliers and online advertising. Volunteers were screened via telephone to ensure they were at least 21 years old, had normal or corrected vision and hearing, and consumed alcohol at least once per week. Volunteers who reported past or current severe psychiatric diagnoses (e.g., bipolar disorder, schizophrenia) did not participate in this study. Those who reported symptoms of severe alcohol use disorder, as determined by a score of 5 or higher on the Short Michigan Alcoholism Screening Test (Selzer et al., 1975), did not participate. Following initial screening, volunteers who met these criteria were contacted via telephone

and invited to participate in the study. Urine samples were tested for the presence of metabolites of amphetamine, methamphetamine, barbiturates, benzodiazepines, cocaine, opiates, methadone, phencyclidine, tricyclic antidepressants, and tetrahydrocannabinol (THC) (ICUP Drugscreen, Instant Technologies, Norfolk, VA). Positive urine analysis for any substance other than THC resulted in discontinuation from the study. Participants who reported use of marijuana during the 24 hours preceding the session were discontinued. Urine samples were also tested for pregnancy in female participants (Icon25 Hcg Urine Test, Beckman Coulter, Pasadena, CA). No female volunteers who were pregnant or breast-feeding participated in the research.

Materials and measures

Multisensory Go No-go Task.—This task examined the ability of participants to inhibit prepotent responses to no-go signals that were presented either as a visual stimulus or as a multisensory stimulus, comprised of a visual and auditory signal. The task required individuals to locate the go or no-go target, which appeared in a different location than where the cue was presented. Figure 1 illustrates a trial sequence on the task. Participants were presented with a cue in the middle of the screen, which is followed by the presentation of a target in one of eight possible locations. Participants were instructed to respond to these targets by either pressing a button (forward slash key) in response to a go target (the word “go”) or inhibit a response when presented with a no-go target (the word “no”). Each trial consisted of the following events: (1) presentation of a fixation point for 800 ms; (2) a prereponse cue that was displayed for one of six stimulus onset asynchronies preceding the target (SOAs = 100, 200, 300, 400, 500 and 600 ms); (3) a go or no-go target visible at one of eight locations around the center of the screen which remained visible until either a response is made or 1 second elapsed; and (4) a 700 ms intertrial interval.

The prereponse cue was either green or blue and signaled the probability that a go or no-go target would be displayed. Green squares preceded the go target on 80% of the trials and preceded the no-go target on 20% of the trials. Blue squares preceded the no-go target on 80% of the trials and preceded the go target on 20% of the trials. Green and blue squares functioned as go and no-go cues, respectively. Presentation of the go cue increases response preparation, making it more difficult to inhibit a response when the no-go target unexpectedly appears. The disinhibiting effects of alcohol are most evident in this cue condition (Marczinski and Fillmore, 2003). The random SOAs (100, 200, 300, 400, 500, and 600 ms) between the cues prevented participants from anticipating the exact onset of the targets.

During half of the trials, targets were presented as multisensory signals by presenting an auditory tone in conjunction with the visual “go” and “no” target stimuli. During multisensory target trials, tones were presented concurrently with the go or no-go targets. Go targets were presented with a 1000 Hz (high) tone and no-go targets were presented with a 125 Hz (low) tone. Participants were told that some trials may include tones but they were not given specific instruction about the purpose of the tones. Participants were told to locate the visual target before making the appropriate response.

A test consisted of 200 trials that presented all possible cue-target combinations for both visual and multisensory trials and required 15 minutes to complete. Half of the trials presented visual targets and on the other half of the trials multisensory signals were presented. The target was presented in each possible radial position at least one time for each cue-target combination for both visual and multisensory trials. SOAs were distributed evenly across the different cue-target conditions in both visual and multisensory trials. The trial order was pseudo-random in order to avoid clustering of visual or multisensory trials. To encourage quick and accurate responding, feedback was presented to the participant during the intertrial interval by displaying the words *correct* or *incorrect* and their response time in milliseconds.

The task was operated by using E-prime software on a PC (Schneider et al., 2002). Participants' eye movements during each trial were measured to assess the speed with which they oriented their attention to the visual target when it was presented. A Tobii T120 Eye Tracking Monitor (Tobii Technology, Stockholm, Sweden) equipped with dual embedded cameras was used to track eye movements. Participants were seated with their heads approximately 60 cm in front of the computer with a free range of head and neck motion. Gaze locations were sampled at 120 Hz and fixations were defined as gazes with standard deviations less than 0.5 degrees of visual angle for durations of 90 ms or longer. All sampled eye locations during a fixation were averaged to determine the location of that fixation. By tracking eye movements we were able to quantify how quickly participants attended to response targets once they were presented.

Timeline Follow-Back.—Participants drinking habits were assessed using the timeline follow-back procedure (Sobell and Sobell, 1992), which assessed daily drinking patterns over the past 3 months. Four measures of drinking habits were obtained: (1) total number of drinking days (*drinking days*), (2) total number of drinks consumed (*total drinks*), (3) total number of days characterized by subjective drunkenness (*drunk days*), and (4) total number of days in which binge drinking occurred (*binge days*). Binge drinking days were determined by estimating participants BACs on each day according to the reported number of drinks they consumed as well as the amount of time they spent drinking using anthropometric-based BAC estimation formulae that assume an average clearance rate of 15 mg/100 ml per hour (Watson et al., 1981).

Procedure

Volunteers responding to advertisements for this study underwent an intake screening by telephone. They were told that the purpose of the study was to examine the effects of alcohol on performance on cognitive tasks. They then made appointments to come to the laboratory for three sessions, including one familiarization and two dose-challenge sessions. Participants were instructed to fast for 4 hours prior to each dose-challenge session. They were also instructed to abstain from consuming alcohol or using other psychoactive drugs during the 24 hours preceding each session.

Familiarization session.—All participants completed a familiarization session during which they became acquainted with laboratory procedures, completed questionnaires,

provided informed consent for participation, and completed a training version of the multisensory go no-go task. Volunteers who did not meet criteria for participation in the study were paid \$10 and discontinued.

Dose-challenge sessions.—Participants were tested under 0.64 g/kg alcohol and placebo. Participants were blinded to dose and dose order was counterbalanced across the two test sessions. Sessions were separated by no less than one day and no more than one week. Alcohol doses were calculated on the basis of body weight and administered as absolute alcohol mixed with three parts carbonated soda. A peak BAC of 80 mg/100 ml is produced by the 0.64 g/kg dose approximately 65 minutes post-administration (Fillmore et al., 2005; Roberts et al., 2013). The placebo dose consisted of an equal volume of carbonated soda mix matching the total volume of the 0.64 g/kg alcohol dose. A small amount (3 mL) of alcohol was floated on the surface of the beverage and it was sprayed with an alcohol mist that resembled condensation and provided a strong alcoholic scent as the beverage was consumed. All drinks were consumed within 6 minutes.

Participants performed the multisensory go/no-go task 30 minutes after dose administration. BAC levels were recorded throughout the session at 28, 45, 52, 65, and 72 min following dose administration for both the 0.0 and 0.64 g/kg dose. BACs were determined from expired air samples measured by an Intoxilyzer Model 400 (CMI, Inc., Owensboro, KY). Following testing, participants remained in a lounge area until their BACs reached 20 mg/100 mL or below. Participants received a meal and were allowed to watch movies and relax. Transportation home was provided. Participants were paid \$85 and debriefed upon completion of the final session.

Criterion variables and data analyses

The multisensory go/no-go task measured inhibitory control and response speed to visual and multisensory stimuli. Response inhibition was measured as participants' failures to inhibit responses to no-go targets (i.e., failures of response inhibition). Failure of response inhibition was measured as the proportion (p) of no-go targets in the go cue condition in which a participant failed to inhibit a response (i.e., p -inhibition failures). Manual reaction time (manual RT) was defined as the mean time taken to make a response during go target trials. Shorter RTs indicated greater facilitation of response execution. Responses with RTs less than 100 ms and greater than 1000 ms were excluded. These outliers were infrequent, occurring on average less than 0.25% of the trials for which a response was observed (i.e., less than one trial per test). RTs and p -inhibition failures were calculated separately for visual and multisensory trials.

Visual fixations were used to determine saccadic reaction time (saccadic RT). Saccadic RT was defined as the number of milliseconds that elapsed between the presentation of the target and the beginning of the first visual fixation at the location of the target. This measured the time required to execute a saccade from the central fixation point on the screen to the location of the target once it was presented.

Criterion variables from the multisensory go/no-go task (i.e., p -inhibition failures, manual RT, saccadic RT) were each analyzed by 2 (dose: placebo vs. 0.64 g/kg alcohol) x 2 (target

condition: unimodal vs. multisensory) repeated measures analyses of variance (ANOVAs). Significant interactions were probed using two sets of *a priori* one tailed *t* tests. The first set examined the dose effects by comparing performance between the dose conditions within each target condition. The second set examined effects of target condition by comparing performance between the target conditions within each dose.

We conducted all analyses to include gender as a between-subjects variable. These analyses found no significant effect of sex and did not change the significance level of other main effects or interactions. As such, reported analyses of task performance are collapsed across gender.

Results

Drinking and demographic information

Participants' drinking habits and demographic information are presented in Table 1. In addition to moderate alcohol use, some participants reported past month use of nicotine ($n = 9$), marijuana ($n = 7$), and sedatives ($n = 1$). Six participants had tetrahydrocannabinol positive urine screens during one or more dose-challenge session. All of these participants verbally confirmed abstinence during the 24 hours preceding each session. No other drug urine screens were positive.

BACs

No detectable BACs were observed in the placebo condition. Sex differences in BAC in the active dose condition were analyzed by a 2 (sex) $\times$ 5 (time: 28, 45, 52, 65, and 78 minutes past dose) mixed-design ANOVA. There was a main effect of time, $F(4, 68) = 14.9$, $p < .001$, owing to the increase in BAC during the ascending limb of the BAC curve. There was no significant main effect of sex, $F(1, 17) = 0.1$, $p = .826$, or sex $\times$ time interaction, $F(4, 68) = 0.1$, $p = .995$. The mean BACs (mg/ 100 mL) at 28, 45, 52, 65, and 78 minutes were 58.4 ($SD = 16.6$), 80.1 ($SD = 14.6$), 80.9 ($SD = 10.9$), 70.2 ($SD = 11.5$), and 65.6 ($SD = 11.7$), respectively.

Disinhibition

Figure 2 plots *p*-inhibition failures separated by dose and target condition. There was a significant main effect of dose, $F(1, 19) = 5.4$, $p = .032$, confirming the expected increase in inhibitory failures following alcohol versus placebo. There was a significant dose $\times$ target condition interaction effect, $F(1, 19) = 4.7$, $p = .044$. As seen in Figure 2, this interaction occurred because participants made fewer inhibitory failures in the multisensory versus unimodal condition under alcohol, but there was no such difference under placebo. The first set of *a priori* *t* tests indicated that alcohol increased inhibitory failures compared with placebo in the unimodal target condition, $t(19) = 3.0$, $p = .008$, $d_z = 0.67$, but not in the multisensory target condition, $t = 0.1$, $p = .886$, $d_z = 0.02$. The second set of *a priori* *t* tests found that following placebo, there was no significant effect of target condition on *p*-inhibition fails, $t(19) = 0.2$, $p = .415$, $d_z = 0.04$. However, under 0.64 g/kg alcohol, participants made significantly fewer inhibitory failures during multisensory target trials compared to the unimodal trials, $t(19) = 2.6$, $p = .009$, $d_z = 0.58$.

Reaction Time

Manual.—Figure 3 plots manual RT separated by dose and signal condition. There was a significant main effect of dose, $F(1, 19) = 8.8$, $p = .008$. As expected, RT was slower following 0.64 g/kg alcohol compared to placebo. There also was a main effect of target condition, $F(1, 19) = 31.4$, $p < .001$. Participants responded to targets more quickly on multisensory trials compared to unimodal trials. No significant dose X target condition interaction effect was observed, $F(1, 19) = 1.4$, $p = .257$.

Saccadic.—Figure 4 plots saccadic RT separated by dose and signal condition. There was a significant main effect of dose, $F(1, 19) = 27.1$, $p < .001$, due to slower saccadic RT under 0.64 g/kg alcohol compared to placebo. The dose X target condition interaction was significant, $F(1, 19) = 7.9$, $p = .011$. As seen in Figure 4, this interaction indicates that, under alcohol, multisensory targets speeded saccades compared with unimodal targets, but following placebo, there was little difference in saccadic RT between the two target conditions. The first set of *a priori* *t* tests examined dose effects and indicated that alcohol significantly slowed saccadic RT compared with placebo in both unimodal, $t = 4.6$, $p < .001$, $d_z = 1.03$, and multisensory target conditions, $t = 4.3$, $p < .001$, $d_z = 0.96$. The second set of *a priori* *t* tests examined the effects of target condition and showed that following alcohol, saccadic RT was faster to multisensory versus unimodal targets, $t(19) = 2.0$, $p = .028$, $d_z = 0.45$, but no significant difference between target conditions was observed following placebo, $t(19) = 1.1$, $p = .862$, $d_z = 0.25$.

Discussion

This study examined how multisensory stop signals influence the disruptive effects of alcohol on drinkers' inhibitory control. Results were consistent with prior work that has shown that multisensory stop signals can improve inhibition (Gondan et al., 2005). Inhibition was improved following multisensory targets compared to unimodal targets. In the multisensory target condition, participants had a similar rate of inhibitory failures following alcohol compared to following placebo, suggesting that alcohol did not impair inhibitory control in the multisensory response target condition. Participants were faster to respond to multisensory targets and alcohol slowed RT to the same extent in both conditions. We also examined how attentional processing may differ following multisensory stimuli and whether this difference may explain how multisensory information protects against alcohol impairment. Participants were slower in executing saccades to the response targets following alcohol compared with placebo (Abroms et al., 2006). This alcohol-induced slowing of saccadic RT is important because it may explain why intoxicated drinkers have difficulty responding in situations where information must be sought out, processed, and responded to quickly. However, the present study showed that such slowing effects of alcohol can be reduced by the multisensory signals. Multisensory signals might offer some protection from the disruptive effects of alcohol by facilitating the speed with which drinkers gather relevant information from the environment to guide their behavior.

The results of this study are especially noteworthy with respect to the lack of alcohol impairment of inhibitory control following multimodal response targets. The disruptive

effect of alcohol on inhibitory control is a robust phenomenon. Alcohol reliably reduces impulse control (de Wit et al., 2000; Feola et al., 2000; Fillmore and Van Selst, 2002; Mulvihill et al., 1997), an effect that directly contributes to the abuse potential of the drug. Humans and other animals that are highly susceptible to this effect tend to drink more when given free access to alcohol (Poulos et al., 1998; Weafer and Fillmore, 2008). This effect of the drug is thought to contribute to negative outcomes associated with alcohol intoxication (e.g., interpersonal violence, personal injury). Prior research has shown that the disinhibiting effects of alcohol can be minimized using behavioral contingencies (i.e., rewarding successful inhibitions) and stimulant drug treatment (Fillmore and Vogel-Sprott, 1999); however, to our knowledge this study is the first to show that multisensory characteristics of the inhibitory signal itself can reduce the disinhibiting effect of the drug.

These findings differ from our previous research study that used a different paradigm to examine how multisensory signals affected alcohol impairment of inhibitory control (Miller and Fillmore, 2013). In that study, participants completed an RSE task under 0.64 g/kg alcohol and placebo. The RSE task was similar to the task used in the current study except all of the stimulus information was presented centrally. That task did not require visual searching for the response target once it was presented because it was always in the same location as the prereponse cue. Participants in that study showed the expected increase in inhibitory failures under the active dose of alcohol; however, the use of multimodal stop signals did not reduce this impairment. In fact, following alcohol, participants made *more* inhibitory failures in the multimodal target conditions compared to unimodal targets, although this difference was not significant. As such, those findings contrast with the current study in which multisensory inhibitory signals reduced inhibitory failures under alcohol.

The differences in the findings between the two studies are most likely related to characteristics of the tasks used to model the RSE on inhibitory control. The most substantial difference is that the unimodal visual targets in the current study were not readily detectable by participants but required radial search and orienting before they could be identified. Although we initially made this change in order to assess the role of attention in the RSE, requiring participants to search for the response target likely increased the difficulty level of the task. Differences in study design preclude statistical comparison; however, an informal comparison of task performance in the current study with those reported by Miller and Fillmore (2013) shows that participants in the current study responded more slowly and with less accuracy. It is well known that people are more impaired by alcohol when performing more complex tasks (Maylor and Rabbitt, 1993; Maylor et al., 1992). As such, a certain level of task difficulty might be needed to observe the facilitation from multisensory signals needed reduce the behavioral disruption from alcohol that might otherwise be unobservable under less demanding circumstances. Support for this suggestion also comes from stimulus degradation studies of RSE that find that the neural activation and performance enhancement of bimodal over unimodal stimuli is most evident when the individual stimuli are degraded in some manner, making them more difficult to identify unimodal targets (e.g., Werner and Noppeney, 2010). It is also possible that by adding a spatial orientation requirement to task, rather than the increase in difficulty, may explain our findings. Given the presence of multisensory neurons in brain regions associated with spatial attention (e.g., superior parietal lobe; Molholm et al., 2006), the

spatial demands of our task may have facilitated the activation of additional multisensory neurons to make the RSE gain more apparent.

Although it is not entirely clear why multisensory response targets protected against alcohol-induced disinhibition, one possible explanation for this finding concerns alcohol-induced slowing of information processing speed. Evidence suggests that alcohol impairs behavior by slowing the speed with which drinkers are able to process information (Bartholow et al., 2003; Fillmore and Van Selst, 2002). Presenting multisensory response targets may facilitate the recruitment of additional processing resources, perhaps via activation of multisensory neurons in the superior colliculus. Given the role of the superior colliculus in saccadic eye movement (Lee et al., 1988), results from the current study concerning participants' saccadic RT appear to support this interpretation. Specifically, although alcohol slowed saccadic RT in both target conditions, the magnitude of this effect was smaller in the multisensory condition compared to the unimodal condition. The close relation between gaze location and attention (Godijn and Theeuwes, 2003) suggests that one way that multisensory stimuli might protect against alcohol impairment is by increasing the speed with which drinkers can attend to and process these stimuli. It is important to recognize, however, that the hastening of saccadic RT following multisensory response targets cannot fully explain the lack of alcohol-induced disinhibition in this condition. In terms of behavioral output, multisensory stop signals entirely blocked the effect of alcohol on inhibitory failures. Its actual speeding effect on saccadic RT was more modest—participants continued to show appreciable alcohol impairment even in the multisensory response target condition. As such, it is most likely that other factors in addition to speeded saccadic RT contributed to amelioration of alcohol-induced disinhibition.

The ability of multisensory signals to reduce the disinhibiting effect of alcohol could also involve brain regions involved in decision-making and conflict monitoring, such as the anterior cingulate and dorsolateral prefrontal cortex. Functional imaging studies show that alcohol reduces activation in these brain regions during performance of behavioral tasks requiring response inhibition (Anderson, 2011; Marinkovic, 2012). Imaging studies of multisensory stimuli show that these same brain regions receive an integrated multisensory signal from visual and auditory stimuli as part of a frontal-cingulate-parietal attentional network that responds specifically to multisensory stimuli (Chen et al., 2015).

The findings also should be considered in light of some limitations. First, participants were tested under a single active dose of alcohol. Although this dose was selected for its ability to produce considerable behavioral impairment in adults drinkers (Holloway, 1995), it would be informative to examine how multimodal signals affect alcohol impairment under a range of doses. Second, we did not test participants' performance in an auditory only condition. It is possible that the presence of auditory response target, rather than the multisensory combination of both visual and aural targets, may account for the differences between target conditions. However, prior research using similar paradigms to study the RSE on response activation shows similar RTs to visual and auditory unimodal targets (Fillmore, 2010). Further, these studies find that multisensory response targets engender comparable improvement in RT over both unimodal conditions.

In conclusion, these results are important because they indicate that multisensory stimuli can serve as a protective factor against the disruptive effects of alcohol. Laboratory models of inhibitory control in studies of addiction or externalizing disorders, such as ADHD, have been based entirely on measuring response inhibition to a solitary, unimodal inhibitory-signal. By examining multisensory, the current study represents a novel departure aimed at providing a more ecologically-based account of how individuals exercise impulse control in their everyday environments, where information is delivered to multiple sensory channels. A logical continuation of this technique is to use multisensory signals to strengthen inhibitory control in individuals before drinking begins when pre-drinking alcohol-related cues capture their attention and disinhibit their behavior. Such protection afforded by multisensory signals would be especially beneficial for drinkers with deficient inhibitory control and attentional dysfunction, such as those with ADHD (Roberts et al., 2013).

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Figure 1.

Schematic of a go cue trial in the multisensory go/no-go task. Following the fixation point (panel A), a go cue is presented (panel B). A green square serves as a go cue, signally that a go target is likely to appear. In this example, a no-go target is then presented (panels C1 and C2). In panel C1, the no-go target is visual only (unimodal) and is displayed in the central left region. In panel C2, the no-go target is presented in the upper right and paired with the no-go (i.e., 125 Hz) tone (multisensory).

Figure 2. Effects of alcohol dose and target condition on proportion of inhibition failures. Capped vertical lines show SEMs.

Figure 3. Effects of alcohol dose and target condition on manual reaction time. Capped vertical lines show SEMs.

Figure 4. Effects of alcohol and target condition on saccadic reaction time. Capped vertical lines show SEMs.

Table 1.

Participants' Demographic Characteristics and Drinking Habits by Gender

	Men		Women	
	Mean	SD	Mean	SD
Demographic				
Age	24.2	3.9	26.5	4.6
Weight (kg)	81.0	10.6	66.4	10.0
Drinking habits				
TLFB				
Total Days	35.4	23.8	28.5	17.4
Total Drinks	142.7	81.7	78.8	48.8
Binge Days	18.0	5.5	5.4	5.7
Drunk Days	14.5	9.8	5.5	4.5

Note. TLFB is the Timeline Follow-Back reporting alcohol use over the past 90 days. AUDIT is the Alcohol Use Disorders Identification Test.