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RESEARCH ARTICLE

Assessing real-time positive subjective effects of alcohol using high-resolution ecological momentary assessment in risky versus light drinkers

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Abstract

Background: High-resolution ecological momentary assessment (HR-EMA) can assess acute alcohol responses during naturalistic heavy drinking episodes. The goal of this study was to use HR-EMA to examine drinking behavior and subjective responses to alcohol in risky drinkers (moderate–severe alcohol use disorder [MS-AUD], heavy social drinkers [HD]) and light drinkers (LD). We expected that risky drinkers would endorse greater alcohol stimulation and reward, with lower sedation, than LD, even when controlling for amount of alcohol consumed.

Methods: Participants ($N=112$; 54% male, M ± SD age = 27.2 ± 4.2 years) completed smartphone-based HR-EMA during one typical alcohol drinking occasion and one nonalcohol-drinking occasion in their natural environment. Participants were prompted to complete next-day surveys that assessed drinking-related outcomes, study acceptability, and safety.

Results: HR-EMA prompt completion rates were excellent (92% and 89% for the alcohol and nonalcohol episodes, respectively). The MS-AUD group consumed the most alcohol with the highest estimated blood alcohol concentration (eBAC) by the end of the alcohol drinking episode (0.14 g/dL) versus LD (0.02 g/dL), with HD intermediate (0.10 g/dL). Relative to LD, MS-AUD and HD endorsed greater positive effects of alcohol (stimulation, liking, and wanting).

Conclusions: This study is the first to use HR-EMA to measure and compare real-world acute alcohol responses across diverse drinker subgroups, including persons with MS-AUD. Results demonstrate that risky drinkers experience heightened pleasurable effects measured in real-time during natural-environment alcohol responses. Rather than drinking excessively to eventually achieve desirable subjective effects, risky drinkers show sensitivity to positive alcohol effects throughout a heavy drinking episode.

KEYWORDS
alcohol use disorder, heavy drinking, high-resolution ecological momentary assessment, stimulation, subjective responses

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INTRODUCTION

Excessive alcohol use is a leading cause of disability and preventable death in the United States (Esser et al., 2020; Griswold et al., 2018; Spillane et al., 2020; Stahre et al., 2014). Binge drinking, defined as consuming ≥5 standard alcoholic drinks for men or ≥4 for women in an occasion (NIAAA, 2022), is associated with alcohol-related injury and death, and frequent binge drinking (risky drinking) increases the likelihood of having alcohol use disorder (AUD; Holahan et al., 2022; White & Hingson, 2013). In the USA, approximately one-third of young adults aged 21–35 engage in binge drinking at least monthly, which is the highest incidence for any age group (SAMHSA, 2022). Individual differences in subjective responses to alcohol's stimulating, sedating, and rewarding effects are an important risk factor for excessive alcohol consumption and AUD (King et al., 2011, 2021; Quinn & Fromme, 2011; Schuckit, 1994). Specifically, human laboratory-based alcohol challenge studies in young adults have shown that those at risk for alcohol-related problems show heightened sensitivity to alcohol's stimulant and rewarding effects but lower sensitivity to its sedative properties (King, 2023; Schuckit, 1994), with heightened alcohol stimulating and rewarding effects emerging as the strongest predictors of the development and maintenance of AUD. However, those data were from fixed-dose, placebo-controlled laboratory alcohol challenge paradigms, and it is unclear whether heightened stimulation and rewarding effects of alcohol are evident in excessive drinkers in their natural environment.

Ecological momentary assessment (EMA) is a method to capture real-time natural environment behaviors and has demonstrated reliability, feasibility, and acceptability for assessing drinking behaviors and alcohol effects (Piasecki, 2019). EMA can be implemented in multiple ways depending upon the research question (including random prompt or daily diary-type implementations). High-resolution ecological momentary assessment (HR-EMA; Piasecki, 2019) allows researchers to capture a large amount of information targeting a specific behavior of interest, such as binge drinking. Prior work using this method showed positive associations among self-reported alcohol consumption and subjective stimulation and sedation during naturalistic drinking events in adult light-to-moderate drinkers, with stimulation more strongly associated than sedation with estimated blood alcohol concentration (eBAC) during the episodes (Carpenter et al., 2017; Piasecki et al., 2012). Notably, these prior studies sought to capture any alcohol consumption over an extended period (21 days) and so tended to assess mainly lighter-drinking events (~2–3 standard drinks).

Our group developed a HR-EMA method specifically targeting binge drinking episodes in young heavy social drinkers (Fridberg et al., 2021). Results showed positive associations between two natural environment binge episodes on reported stimulation, sedation, and reward. Moreover, these subjective alcohol responses were positively correlated with the same responses in a laboratory fixed-dose alcohol challenge (0.8 g/kg). However, to our knowledge, HR-EMA has not been used previously to assess real-world alcohol responses in participants with moderate to severe AUD (MS-AUD). Importantly, no prior study has compared those responses to the same responses during a non-alcohol-drinking episode to determine whether participant reports of real-world stimulation, sedation, and reward are specific to alcohol consumption versus a nonspecific response bias.

Thus, the present study had two goals: (1) to determine the feasibility of natural-environment HR-EMA in drinkers from across the alcohol-use spectrum and (2) to compare subjective responses during typical real-world alcohol drinking episodes with those recorded during typical non-alcohol-drinking episodes. During typical drinking episodes, we predicted that persons with MS-AUD would consume more alcohol than light or heavy social drinkers and that after controlling for estimated blood alcohol concentration (eBAC), persons with MS-AUD would show the highest positive-like effects, that is, increased stimulation, liking, and wanting more, and lowest sedation. We also predicted that these group differences would be specific to the alcohol drinking episodes and not to a response bias observed during non-alcohol-drinking episodes.

MATERIALS AND METHODS

Design

Participation in this mixed between- and within-subject study took place over approximately 1 week. Participants were enrolled from October 2020 to September 2021, and all study procedures were approved by the University of Chicago Institutional Review Board. The study included smartphone-based HR-EMA in drinkers' natural environments of one each of a typical alcohol drinking and non-alcohol-drinking episode. Participants also completed next-day surveys the morning after each episode to report any further alcohol drinking after the HR-EMA episodes, alcohol consequences, and study acceptability.

Participants

Candidates were recruited from online advertisements, flyers, and word-of-mouth referrals. Eligible candidates were 21–35 years old, current drinkers (i.e., drinking alcohol at least once per week for the past 2 years), generally healthy, completed at least 9 years of education, could understand English, and owned a smartphone running iOS or Android. Candidates meeting these basic eligibility criteria from an online survey were contacted for a phone screen to assess physical and mental health status, alcohol use patterns, and use of any other substances. Those who were deemed eligible and interested in participating were invited to a 1-h online screening conducted via secure video conference that consisted of informed consent, an online Timeline Follow-back (OTLFB) calendar for the past month (Rueger et al., 2012; Sobell & Sobell, 1995), health and demographic surveys, a first-degree biological relatives family

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history tree for AUD, and the AUD module from the Structured Clinical Interview for the DSM-5 (SCID-5; First et al., 2015). Exclusion criteria included variable or moderate drinking patterns (i.e., not fitting into a drinking subgroup listed below), major psychiatric disorders including current or past schizophrenia, bipolar disorder, OCD, panic disorder, eating disorder or suicidal ideation within the past 6 months, significant substance use patterns that could affect participation (i.e., cannabis use >3 times/week, other illicit drug use >2 times past month, or smoking >5 cigarettes per day), receiving substance use treatment in the past 6 months, or a current desire to stop drinking alcohol.

Candidates were enrolled if they met criteria for one of three subgroups on the AUD risk continuum: (a) light drinkers (LD; 1–9 [1–7 for women] drinks per week, rare binge drinking of ≤1 occasion per month, and no past year AUD), (b) heavy drinkers with no-to-mild AUD (HD; 10–27 [8–20 for women] drinks per week, 1–4 binge drinking episodes/week, and 0–3 criteria met for past year AUD), or (c) drinkers with moderate–severe AUD (MS-AUD; ≥28 drinks [≥21 for women] per week, ≥10 binge drinking episodes monthly, and meeting ≥4 criteria for past year AUD). The latter two groups are considered risky drinkers (McKnight-Eily et al., 2017). These subgroup criteria are similar to those of prior studies (Bujarski et al., 2017; Fridberg et al., 2021; King et al., 2011, 2022) and combining drinking behavior and AUD symptom criteria ensured no overlap across subgroups.

There were 198 study candidates scheduled for screening, and attendance at the screening session varied by drinking group, with 92% (47/51) of LD candidates attending versus 87% (52/60) and 67% (53/79) of HD and MS-AUD candidates attending, respectively. Of those who attended screening, 45 (28%) were deemed ineligible by virtue of reporting inconsistent drinking patterns, falling between drinking groups, or meeting criteria for major psychiatric disorders. Of the 115 enrolled participants, three were excluded from analyses as they did not complete study measures or had comprehension difficulties with study procedures. Thus, the final sample was $N = 112$ participants (39 LD, 41 HD, and 32 MS-AUD).

Study orientation

Enrolled participants completed a 30-min virtual orientation session where study staff helped them download and configure the HR-EMA app (MetricWire®, Toronto, ON, Canada) on their smartphone and trained them on proper use of the app and study procedures. They were instructed to enable notifications on their device to avoid missing any study prompts. The research assistant used the participant's past month OTLFB as a reference to determine their typical heaviest alcohol drinking days during the week, as well as typical non-alcohol-drinking days for their nonalcohol episode. After discussing the typical time of day when the participant would consume alcohol, the research assistant encouraged the participant to "match" their alcohol and non-alcohol-drinking episodes such that they both started at approximately the same time of day. The participant was encouraged to target those day(s) when they completed the HR-EMA assessments the following week and to avoid special occasions or times when they felt unusually excited, stressed, worried, happy, etc. For safety and ethical reasons, participants were neither instructed nor required to consume a specific amount of alcohol during the alcohol drinking episode. Participants were told to complete all issued episode surveys for the duration of the 3-h HR-EMA period and asked to refrain from using nicotine or recreational drugs the day of and during both episodes and to refrain from drinking alcohol during the non-alcohol-drinking episode or prior to the start of their alcohol drinking episode. Last, they were reminded that they would be prompted to complete next-day surveys the morning following each episode. After completing all study procedures, participants were debriefed and compensated with an electronic gift card worth $140 (approximately $15/h for time spent in the study).

Measures

Episode surveys

The HR-EMA survey measures and procedures were identical for alcohol and non-alcohol-drinking episodes, except for follow-up questions assessing beverage type. Participants self-initiated their alcohol drinking and non-alcohol-drinking episodes by completing a brief (~1 min) baseline survey 3 h to 30 min before consuming their first beverage. The baseline survey assessed the type of episode to be recorded (i.e., alcohol drinking or nonalcohol drinking), current location, social context, recent consumption of food, caffeine, or nicotine, and current mood, stimulation, and sedation. The survey also assessed whether participants reported consuming any alcohol prior to completing the baseline survey. To encourage truthful reporting of alcohol use prior to the HR-EMA episodes, participants were aware that they would not be penalized and still eligible for full payment if they endorsed alcohol use at the baseline survey. If participants endorsed alcohol use prior to the baseline survey, the survey was discontinued, participants were reminded to abstain from alcohol for at least 24 h before re-initiating the baseline survey, and the survey was made unavailable for 24 h. Three participants (3%) reported consuming alcohol prior to completing a baseline survey and were permitted to complete the episode 24 h later without penalty. After submitting the baseline survey and prior to consuming their first beverage, participants were required to submit a photo of their first drink through the HR-EMA app for visual confirmation of serving size and beverage type and to advance to the next survey (post first drink). Participants were asked to submit only one photo per episode to minimize burden and disruption of their typical drinking behavior. The photo survey was implemented approximately one-third of the way into data collection, and all participants (75/75; 100%) who were asked to submit photos did so for both episodes.

Immediately after consuming their first beverage, participants self-initiated a post-first-drink survey. Participants then received automatic notifications to complete drinking episode surveys at 15, 30,

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60, 90, 120, 150, and 180 min after they finished their first drink. Like the baseline surveys, all episode surveys were brief (~1 min). The duration of the HR-EMA monitoring was limited to 3 h to minimize participant burden while capturing drinking behavior and subjective experiences during rising-to-peak BAC, when stimulating and rewarding effects predominate in at-risk drinkers (King et al., 2011). During the post-first-drink survey and all 7 subsequent episode surveys, participants recorded how many beverages they had finished since the last survey, the type(s) of beverage(s) (i.e., beer, wine, liquor or nonalcoholic), and the serving size(s) of each beverage consumed. They then completed the six-item Brief Biphasic Alcohol Effects Scale (B-BAES; Rueger et al., 2009), with stimulation (sum of the items energized, excited, and up) and sedation (sum of the items sedated, slow thoughts, and sluggish) subscales derived from their responses. Next, they completed the Drug Effects Questionnaire (DEQ; Morean et al., 2013) in which they used separate visual analog scales (0–100) to rate the statements "I FEEL the effects of the drink," "I LIKE the effects I am feeling," and "I WANT MORE of what I consumed." This was followed by questions regarding whether any other substances were consumed since the last survey (choices were: food, tobacco/nicotine, drugs/substances, other, or none/I have not consumed anything else), and the amount and type consumed, if endorsed.

After participants completed each survey, the data were uploaded automatically by the HR-EMA software to a secure server for analysis. For the alcohol drinking episode, eBAC was calculated as: $eBAC = [(c/2) \times (CG/w)] - (\beta_{60} \times t)$, where c is the total standard drinks consumed to that point since drinking started, GC is a gender constant (7.5 for men and 9.0 for women), w is the participant's weight in pounds, β_{60} is a constant representing the mean population alcohol metabolism rate (0.017 g/dL/h), and t is the time in hours since drinking started (Matthews & Miller, 1979).

Next-day surveys

The morning after completing each episode, participants received a notification at 11:00 A.M. local time to fill out a 3-min next-day survey assessing their behavior and experiences during the prior HR-EMA period; participants received additional reminder prompts to complete the survey 2 and 4 h later if needed. The next-day survey assessed behaviors and activities that happened after the 3-h HR-EMA assessment concluded. Participants reported on the specific types of alcohol consumed during the episode (if applicable), activities during the assessment period (e.g., sitting, socializing, playing games, etc.; data not presented here), and drinking-related consequences (e.g., arguments, accidents, hangover) via the modified Brief Young Adult Alcohol Consequences Questionnaire (BYAACQ; Fridberg et al., 2019; Kahler et al., 2005). Acceptability items asked participants to rate ease of use of the mobile app, intrusiveness and length of the surveys, likelihood of recommending the study to other participants, and overall satisfaction with participation (each item rated 1 = "strongly disagree" to 5 = "strongly agree"; Fridberg et al., 2019).

Statistical analyses

Generalized Estimating Equations (GEE; Liang & Zeger, 1986) models were conducted for the primary dependent variables, that is, "feel," subjective stimulation, sedation, like and want more, and included episode (alcohol or nonalcohol), time (treated as a continuous variable), group (light drinker, heavy, alcohol use disorder), and their interaction. Of note, eBAC was ≥0.30 g/dL for a small number of survey responses ($n = 6$) during the alcohol drinking episodes. As this level of intoxication is associated with loss of consciousness or death, we assumed that those time points reflected errors in reporting and opted to treat alcohol consumption and subjective response data for those responses as missing prior to entry into the models, as in our prior work (Fridberg et al., 2019, 2021). The secondary outcome of blood alcohol level was fit using GEE with group and time (treated as a continuous variable) and their interaction. We used the Bonferroni method to correct Type-I error for the primary outcomes. Significant main effects and interactions from GEE were further examined with postestimation comparisons (marginal linear contrasts) and are reported in the text; detailed results from the GEE analyses are provided in Supplementary Table S1. All analyses controlled for sex, family history of alcohol-related problems in first-degree relatives, and drinking context (i.e., whether the individual with others or alone, and current location [bar/restaurant versus all other locations]; Fischer et al., 2023). In addition, all subjective response outcomes included eBAC, time, and their interaction to account for the effect of intoxication and different drinking behaviors across groups.

RESULTS

Participant characteristics

Table 1 shows the major demographic and drinking background variables across groups. The groups did not differ on age, sex, or race, but MS-AUD and HD had fewer years of education than LD. A larger proportion of MS-AUD endorsed a family history of problem drinking, versus HD or LD (Table 1). All drinking variables differed across groups, with any drinking and binge drinking frequency, mean drinks per drinking day, AUDIT scores, and AUD symptom counts highest among MS-AUD (MS-AUD > HD > LD, $ps < 0.001$).

For HR-EMA episodes, participants showed high response rates to the seven system-issued survey prompts after the participant-initiated baseline and post-first-drink surveys, with 92% (719/784) of prompts completed during the alcohol drinking episodes versus 89% (699/784) for the non-alcohol-drinking episodes. A higher proportion of alcohol drinking episodes (61%) than non-alcohol-drinking episodes (27%) were completed on weekends (Friday–Sunday), $\chi^2(1) = 27.53$, $p < 0.001$. Alcohol drinking episodes completed on weekends did not differ significantly from

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TABLE 1 Demographic, drinking, and other substance use characteristics across groups.

	Light drinkers (LD; $n=39$)	Heavy drinkers (HD; $n=41$)	Moderate–severe AUD drinkers (MS-AUD; $n=32$)	Significance testing
Demographics				
Age (years)	27.7 (3.7)	27.2 (4.2)	26.9 (5.0)	$p=0.72$
Sex (% female)	22 (56%)	18 (44%)	12 (36%)	$p=0.22$
Race				
White	27 (69%)	30 (73%)	27 (84%)	$p=0.51$
More than one race	6 (15%)	5 (12%)	1 (3%)	
Other[a]	6 (15%)	6 (15%)	4 (13%)	
Ethnicity				
Hispanic/Latino	7 (18%)	4 (10%)	3 (9%)	$p=0.44$
Not Hispanic/Latino	32 (82%)	37 (90%)	29 (91%)	
Education (years)	17.1 (1.7)	16.0 (1.8)	15.3 (1.8)	$p<0.001$, LD > HD = MS-AUD
Alcohol use and related variables				
% Drinking days (past month)	37% (17.7)	54% (17.6)	69% (17.4)	$p<0.001$, LD < HD < MS-AUD
% Heavy drinking days[b] (past month)	1% (2.5)	24% (10.8)	54% (17.6)	$p<0.001$, LD < HD < MS-AUD
Drinks per drinking day (past month)	1.8 (0.6)	4.5 (2.0)	8.0 (2.5)	$p<0.001$, LD < HD < MS-AUD
Drinks per heavy drinking day (past month)[c]	-	6.5 (1.7)	9.4 (2.7)	$p<0.001$, HD < MS-AUD
AUDIT[d] (total score, range 0–40)	4.8 (2.3)	10.5 (3.9)	16.9 (4.6)	$p<0.001$, LD < HD < MS-AUD
DSM-5 AUD[e] symptoms (range 0–11)	0.2 (0.4)	1.7 (1.1)	5.3 (1.3)	$p<0.001$, LD < HD < MS-AUD
Family history of alcohol use disorder in primary relatives	5 (13%)	9 (22%)	18 (55%)	$p<0.001$, LD = HD < MS-AUD
Past year substance use (%)				
Any cigarette use	1 (3%)	12 (29%)	12 (36%)	$p=0.001$, LD < HD = MS-AUD
Any cannabis use	12 (31%)	31 (76%)	21 (64%)	$p<0.001$, LD < HD = MS-AUD
Any other substance use	3 (8%)	10 (24%)	12 (36%)	$p=0.01$, LD < HD = MS-AUD

Note: Values are Mean (SD) or N (%), as indicated. Groups were compared by one-way ANOVA or chi-squared tests, as appropriate. Significance testing indicates the main effect of group with post hoc between-group comparisons to determine the source of the group main effect.

[a] Other Race includes Black, Asian, Native American, or Native Hawaiian/Pacific Islander.

[b] Heavy drinking days defined as number of days consuming 5 or more alcoholic drinks for men (4 or more for women) in an occasion.

[c] LD were not included in this comparison as binge drinking was very infrequent in that group (~1% of past-month drinking days).

[d] AUDIT = Alcohol Use Disorders Identification Test.

[e] AUD = alcohol use disorder; family history of alcohol use disorder based on participant report of primary (parents, siblings) biological relatives with probable AUD (percentage value is the percentage of each group with a family history of AUD).

those completed on weekdays in terms of total alcohol consumed during the HR-EMA period ($M \pm SD = 6.6 \pm 4.0$ standard drinks consumed on weekends versus 5.3 ± 4.1 on weekdays, $t(87.9) = -1.62$, $p = 0.11$). Most (78%) of the HR-EMA episodes were initiated in the evening hours (between 5:00 PM and midnight) or afternoon (18%; between noon and 4:59 PM), and time of day for initiating the episodes did not vary between the alcohol drinking and non-alcohol-drinking events ($\chi^2[3] = 5.59$, $p = 0.11$). Group × episode type ANOVA revealed a difference across groups on prompts completed [group: $F(2, 218) = 4.79$, $p < 0.01$] with MS-AUD completing slightly fewer system-initiated prompts (85%) than did HD (91%) or LD (94%), $ps < 0.05$.

Estimated blood alcohol concentration (eBAC) and "feel"

Mean eBAC and subjective "feel" across groups and episode type are depicted in Figure 1. As expected, MS-AUD consumed more alcohol ($M \pm SD = 9.3 \pm 4.3$ standard drinks) during the alcohol

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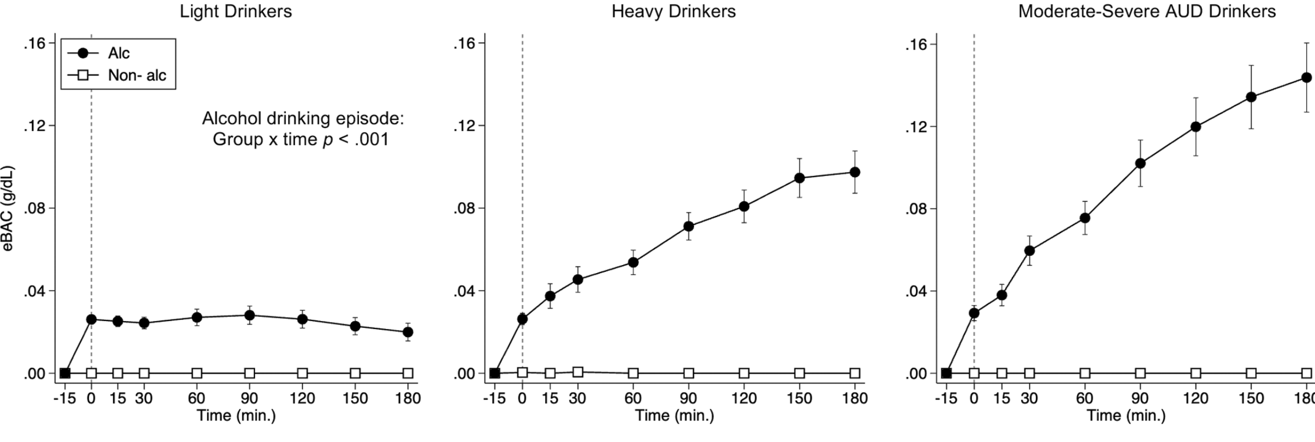
drinking episodes than HD (6.8 ± 3.3 standard drinks), who in turn consumed more alcohol than LD (2.7 ± 1.3; *ps* ≤0.001). Notably, these consumption levels resembled typical alcohol use on a heavy drinking day reported in the risky drinker subgroups (see Table 1). Accordingly, eBAC was highest during the alcohol episode in MS-AUD (mean final eBAC = 0.14 g/dL) and lowest among LD (0.02 g/dL), with HD intermediate (0.10 g/dL; group × time $\chi^2[2] = 113.32$, $p < 0.001$, Figure 1A, see also Supplementary Table S1). For "feel" alcohol effects, there was a significant group × episode × time interaction ($\chi^2[2] = 63.14$, $p < 0.001$) with LD reporting greater "feel" than both HD and MS-AUD early in the alcohol drinking episode (i.e., post-first-drink and + 15-min surveys, $ps < 0.05$, Figure 1B) and HD and MS-AUD reporting greater "feel" ratings later in the episode ($ps < 0.05$, 60–180 min for HD and 90–180 min for MS-AUD; Figure 1B). "Feel" did not differ between HD and MS-AUD during the alcohol drinking episode ($ps > 0.76$), and ratings were similar across all three subgroups during the non-alcohol-drinking episodes (all $ps > 0.48$, Figure 1B).

Stimulation, sedation, liking, and wanting more

There was a significant group × episode interaction for stimulation ($\chi^2[2] = 14.39$, $p < 0.001$; Figure 2A and Table S1) with HD and MS-AUD reporting higher stimulation during the alcohol drinking episodes than LD ($\chi^2[2] > 15.00$, $ps < 0.001$; HD = MS-AUD > LD). In contrast, sedation was low throughout both alcohol and nonalcohol episodes with no group main effects or interactions ($ps > 0.10$; Figure 2B and Table S1).

Hedonic reward (liking) ratings differed across the subgroups for episode type and time (group × episode type × time, $\chi^2[2] = 19.17$, $p < 0.001$; Figure 3A, Table S1). During the alcohol drinking episode, HD and MS-AUD endorsed greater liking than LD, and this was evident from the 30- and 60-timepoints onward for HD and MS-AUD, respectively ($ps < 0.05$; Figure 3A). For the non-alcohol-drinking episode, LD and HD reported greater liking than MS-AUD from 60 and 30 min onward, respectively ($ps < 0.05$), with no differences in liking between LD and HD at any time during the non-alcohol-drinking event ($ps > 0.58$). Last, for motivational reward (wanting), there was



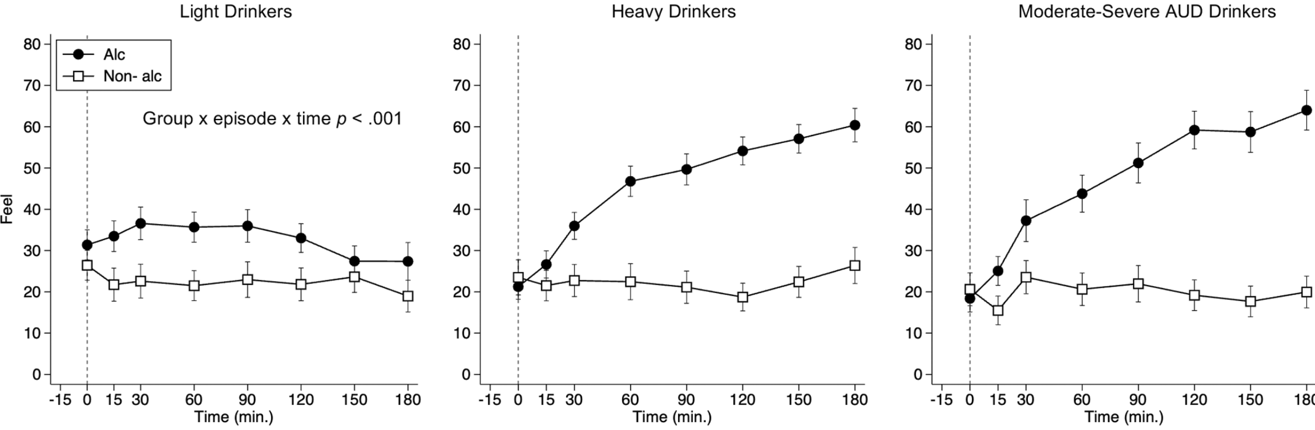


FIGURE 1 Estimated BAC (eBAC) and "feel" across episode type, by group. "Feel" was measured using the Drug Effects Questionnaire. The dotted vertical line at time = 0 indicates the time when the participant finished his or her first beverage of the episode (i.e., the post-first-drink assessment).

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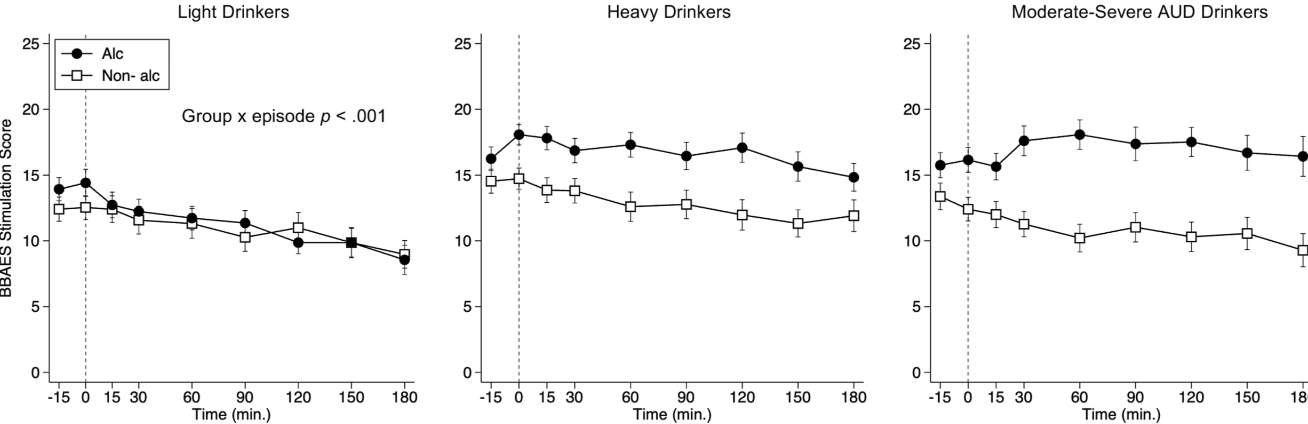

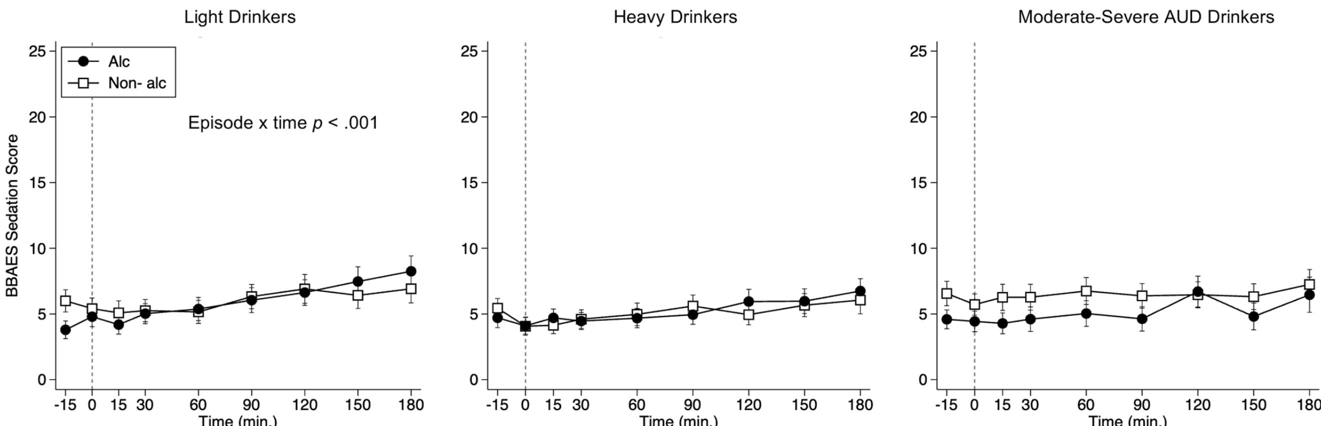

FIGURE 2 Mean ± SEM stimulation and sedation scores across episode type, by group. Alcohol stimulation and sedation were assessed using the Brief Biphasic Alcohol Effects Scale. The dotted vertical line at time = 0 indicates the time when the participant finished his or her first beverage of the episode (i.e., the post-first-drink assessment).

a group × episode type interaction ($\chi^2[2] > 36.82$, $p < 0.001$) such that during the alcohol episode, both HD and MS-AUD reported greater wanting than LD, $\chi^2(2) > 25.00$, $ps < 0.001$; HD = MS-AUD > LD; Figure 3B. The groups did not differ on wanting more of the beverage during the non-alcohol-drinking episodes ($ps > 0.39$). Removing eBAC and its interaction terms from the models (i.e., removing the effect of individual differences in alcohol consumption during the alcohol drinking episodes) did not substantively change the alcohol subjective response outcomes described above, with the exception that the group × episode type × time interaction was significant for subjective stimulation, $\chi^2[2] > 8.16$, $p = 0.02$. When eBAC and its interaction terms were excluded from the model, HD and MS-AUD showed greater increases in stimulation from baseline during the alcohol drinking episodes than did LD, $ps < 0.001$ (HD = MS-AUD, $p = 0.70$).

Effects of drinking context on study outcomes

The effects of drinking context (presence of absence of others and location) on study outcomes are presented in Table S1. Briefly, eBAC was higher when participants were with others (versus alone) and in a bar/restaurant versus all other locations, $ps < 0.05$. Similarly, reported alcohol stimulation, liking, and wanting more were greater, and sedation was lower, when participants were in the presence of others versus alone, $ps < 0.01$. Drinking in a bar/restaurant versus other locations was associated with greater alcohol stimulation and wanting more and lower sedation. There were no other significant effects of drinking context on subjective response outcomes, $ps > 0.57$.

Next-day survey results

Table 2 shows results from the next-day surveys. The risky drinker subgroups were more likely than LD to drink alcohol after the HR-EMA period for both episode types ($\chi^2[2] > 6.60$, $ps < 0.05$; Table 2). MS-AUD reported significantly greater alcohol consumption (mean 4.6 drinks after the alcohol-drinking episode versus 6.0 drinks after the non-alcohol-drinking episode; Table 2), relative to HD (mean 2.8 versus 1.7 drinks, Table 2) episodes ($Fs \geq 5.44$, $ps < 0.05$). LD were not

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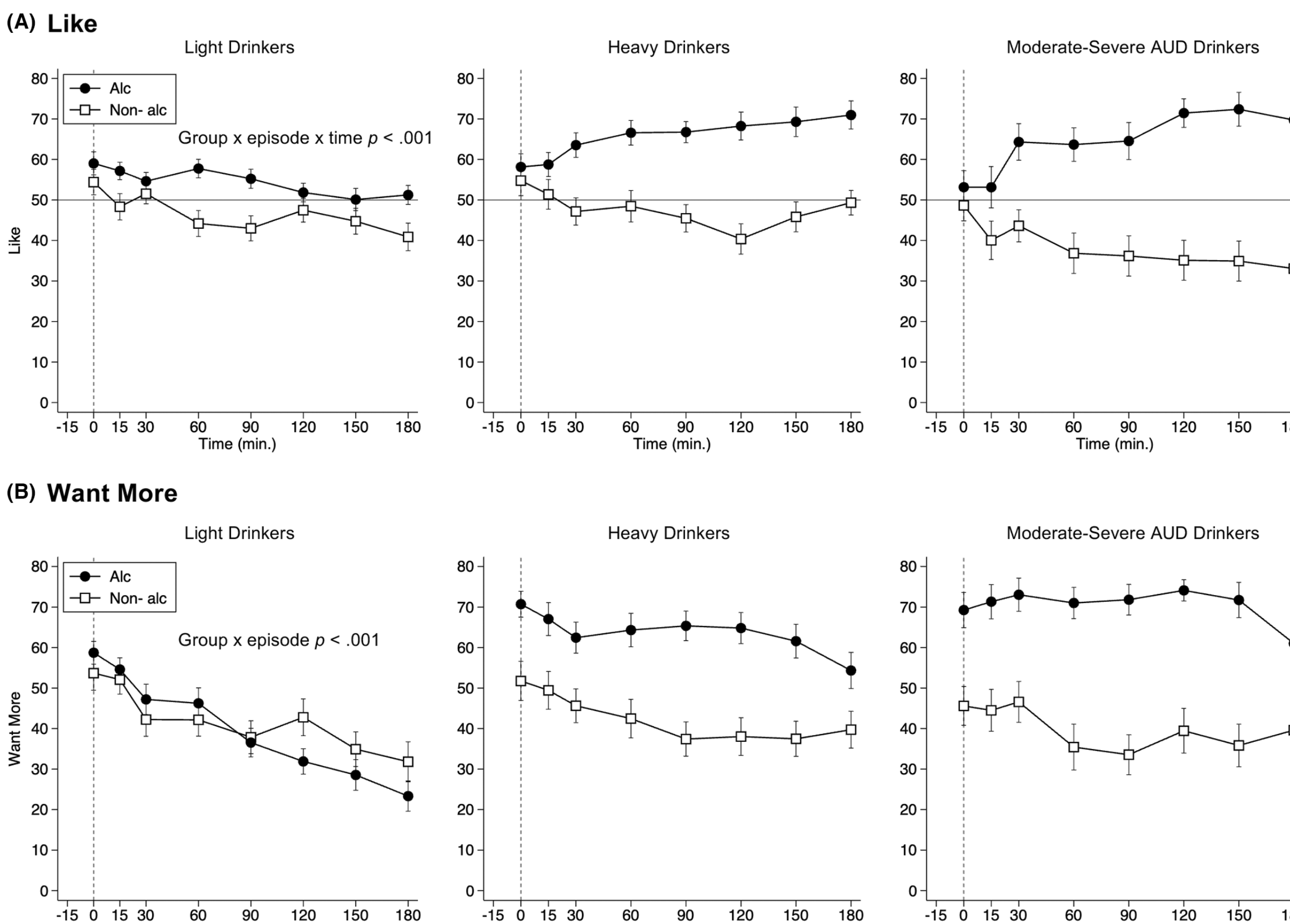

FIGURE 3 Mean ± SEM "like" and "want more" ratings for each episode type, by group. Alcohol like and want more were measured using the Drug Effects Questionnaire. For like the horizontal line at 50 indicates neutral. (i.e., neither like nor dislike). The dotted vertical line at time = 0 indicates the time when the participant finished his or her first beverage of the episode (i.e., the post-first-drink assessment).

included in those comparisons as only two LD endorsed any alcohol use after the HR-EMA episodes.

MS-AUD endorsed more alcohol-related consequences following the alcohol drinking episode than did LD or HD, $F(2, 218) = 12.91$, $p < 0.001$ (Table 2). Participants found the HR-EMA approach easy to use, minimally intrusive, and not overly lengthy, with high overall satisfaction (Table 2). MS-AUD drinkers rated the HR-EMA app as slightly easier to use than did LD participants ($p < 0.01$; Table 2).

DISCUSSION

The present study is the first to use HR-EMA to capture alcohol responses in drinkers with moderate-to-severe AUD during a typical, real-world heavy drinking episode. As expected, MS-AUD consumed more alcohol than HD, who drank more than LD, over the 3-h period. When accounting for individual differences in alcohol use (eBAC), risky drinkers (MS-AUD and HD) reported greater alcohol "feel," stimulation, liking, and wanting more relative to LD. Sedation was low overall and, contrary to expectations, did not differ across groups. Subjective responses were similar across groups during a non-alcohol-drinking episode, suggesting that differences observed during alcohol drinking events were not due to a nonspecific response bias. Response rates to the HR-EMA prompts were excellent, which is particularly notable for MS-AUD drinkers who, to our knowledge, have not been examined previously with HR-EMA during heavy drinking episodes. Finally, the next-day surveys indicated that nearly two-thirds of MS-AUD participants continued to drink beyond the 3-h assessment interval and experienced more drinking-related consequences relative to HD or LD.

By assessing naturalistic alcohol consumption and subjective responses in drinkers across the alcohol-use spectrum and including a subgroup of people with moderate-to-severe AUD, this study provides an important component missing from prior HR-EMA work capturing primarily low-to-moderate drinking events in lighter drinkers (Carpenter et al., 2017; Miranda et al., 2014; Piasecki et al., 2012) or targeting risky drinkers without severe AUD (Fridberg et al., 2021). In the present study, by the end of the first hour, MS-AUD participants achieved the legal limit for intoxication (eBAC = 0.08 g/dL) and showed the greatest increases in alcohol consumption during the second and third hours of the HR-EMA. Even after controlling for drinking levels that differed across groups, positive subjective

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TABLE 2 Next-day survey results by group and episode type (nonalcohol drinking or alcohol drinking).

	Light drinkers (LD; $n=39$)		Heavy drinkers (HD; $n=41$)		Moderate–severe AUD drinkers (MS-AUD; $n=32$)		
	Non- alcohol-drinking Episode	Alcohol drinking episode	Non-alcohol-drinking episode	Alcohol drinking episode	Non-alcohol-drinking episode	Alcohol drinking episode	Significance testing
Postepisode alcohol use and consequences							
N reporting any alcohol use after HR-EMA period (%)	0 (0%)	2 (5%)	8 (20%)	20 (49%)	5 (16%)	21 (66%)	Group $p<0.05$, MS-AUD = HD > LD
Additional alcohol drinks reported consumed[a]	—	2.0 (1.4)	1.7 (1.0)	2.8 (2.2)	6.0 (3.4)	4.6 (2.9)	Group $p<0.001$, MS-AUD > HD
BYAACQ[b] total score	0.02 (0.2)	0.8 (1.2)	0.3 (0.8)	1.4 (1.7)	1.2 (2.9)	3.2 (2.9)	Group $p<0.001$, MS-AUD > HD > LD Episode $p<0.001$, alcohol drinking > nonalcohol drinking
Study acceptability (rated 1 = "strongly disagree" to 5 = "strongly agree")							
App easy to use	4.3 (0.8)	4.4 (0.8)	4.6 (0.7)	4.5 (0.8)	4.7 (0.6)	4.7 (0.5)	Group $p=0.02$, MS-AUD > LD
Intrusiveness	2.2 (1.3)	1.9 (1.2)	1.8 (1.0)	1.9 (1.4)	2.0 (1.3)	2.3 (1.4)	—
Too long	2.2 (1.2)	2.1 (1.2)	1.9 (1.1)	2.0 (1.2)	2.1 (1.1)	2.1 (1.2)	—
Would recommend to others	4.5 (0.7)	4.5 (0.7)	4.4 (0.8)	4.3 (0.9)	4.7 (0.6)	4.7 (0.5)	Group $p=0.03$, MS-AUD > HD
Overall satisfaction	4.4 (0.7)	4.5 (0.8)	4.5 (0.8)	4.5 (0.7)	4.5 (0.7)	4.5 (0.6)	—

Note: Values shown are percentages or mean (SD) as indicated. Postepisode drinking and consequences outcomes were compared via group by episode type ANOVA or chi-squared tests, as appropriate. Significance testing indicates significant main effects of group or episode, with post hoc comparisons to determine the source of the effect(s).

[a] Among those who reported consuming alcohol after the episode; LD were not included in the between-group comparisons examining additional alcohol drinks consumed due to the low number of LD participants ($n=2$) who reported drinking alcohol following the HR-EMA episodes.

[b] Brief Young Adult Alcohol Consequences Question.

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effects of alcohol (stimulation, liking, and wanting) were higher in risky drinkers relative to the low-risk LD group. This is consistent with research identifying heightened experiences of stimulation and reward in response to alcohol as an endophenotype for continued excessive drinking and AUD risk over time (King et al., 2021; Quinn & Fromme, 2011).

The outcomes of this study further validate findings from well-controlled, fixed-dose laboratory alcohol challenge studies showing heightened sensitivity to alcohol stimulation and reward in heavy/risky drinkers relative to LD (King et al., 2011, 2021). This is important as the natural environment is not as well-controlled as the laboratory. The present findings, in line with those of controlled human laboratory alcohol challenge studies (King et al., 2011, 2016, 2021, 2022), suggest persistence of the reward-dominant initial "binge-intoxication" stage of the allostasis model of addiction (Koob, 2003) in MS-AUD. The increases among risky drinkers in liking alcohol's effects over time with consistently elevated alcohol wanting also lend support for earlier stages of incentive-sensitization processes, when both hedonic and motivational drug effects predominate (Robinson & Berridge, 1993). Notably, neither the results of the current study nor those of prior oral alcohol laboratory studies (King et al., 2011, 2016, 2021, 2022) support the low level of response theory (Schuckit, 1994) that purports that low alcohol sensitivity spurs a desire to achieve intoxication. A low level of response to alcohol sedation was observed in risky drinkers and likely indicated tolerance to those effects.

Considering the results of the present study with both oral (King et al., 2011, 2016, 2021, 2022) and intravenous (Bujarski et al., 2017) laboratory findings together, we propose that heightened pleasurable effects and motivational salience of alcohol in risky drinkers fueled their excessive drinking during the alcohol drinking episode, but were minimal-to-absent in LD, which may have served as a protective effect against binge drinking. While the slopes of the positive alcohol effects observed in risky drinkers (Figures 2 and 3) suggest some degree of acute tolerance in the positive-like effects over time (Plawecki et al., 2019), there was no evidence for a "satiation" of responses, as both HD and MS-AUD continued to drink through the 3-h interval, with 49% and 66% of participants in those groups continuing to drink afterward, respectively. We also found that eBAC and alcohol stimulation and reward (liking and wanting more) were greater, and sedation was lower, when participants drank with others versus alone, and that drinking in a bar/restaurant was associated with greater alcohol stimulation and wanting, but lower sedation. These findings are in line with prior findings by our group from HR-EMA of a naturalistic heavy drinking event in young adult heavy drinkers (Fischer et al., 2023) and highlight the importance of assessing potential contextual effects on real-world alcohol subjective responses.

Strengths of this study included a more diverse array of participants from across the alcohol-use continuum than in prior studies (Carpenter et al., 2017; Piasecki et al., 2012), use of a highly feasible and acceptable HR-EMA method (Fridberg et al., 2019, 2021), and direct comparison of real-time responses during alcohol- and non-alcohol-drinking episodes collected at a similar time of day. At the same time, there were some limitations worth noting. First, as in prior work (Fridberg et al., 2021), the duration for the HR-EMA periods was capped at 3h to capture acute heavy drinking effects while minimizing participant burden; this precluded us from capturing effects during the descending BAC/eBAC limb, when sedative-type experiences may be more prominent (King et al., 2011). This is a known issue in the field as attempts to measure descending limb effects may be limited by the fact that many participants may go to bed shortly after finishing a drinking episode (Piasecki, 2019). Future studies could address this limitation by using HR-EMA to examine heavy drinking behavior and associated subjective effects during daytime heavy drinking events (e.g., sporting events; Neal & Fromme, 2007) when individuals may remain awake long enough to complete assessments during the descending eBAC limb. However, many of these drinkers may continue to consume alcohol during evening hours after their daytime event, thus presenting a challenge to examining subjective effects in natural environment drinking during the descending limb.

A second limitation is that alcohol drinking data were not captured over multiple drinking episodes (Piasecki et al., 2012). Additional episodes may bolster confidence in the observed findings, but prior research has shown good concurrence of alcohol drinking and subjective responses across HR-EMA episodes (Fridberg et al., 2021), and the alcohol consumption reported here was nearly identical to participants' typical drinking quantity and frequency from their past month TLFB. Each HR-EMA study must weigh the quality and quantity of data obtained versus participant burden (Fridberg et al., 2019, 2021) and potential reduced response rates over time due to fatigue or boredom (Piasecki, 2019). In addition, eBAC is a proxy estimation of breath alcohol concentration and its accuracy may be affected by recall or reporting bias. However, alternative technologies for measuring real-world alcohol consumption (e.g., portable breathalyzers or transdermal alcohol biosensor technology; Wang et al., 2021) are not yet viable as they either alter the behavior of interest by requiring a waiting period before measurement (breathalyzers) or are not yet sufficiently mature to support widespread deployment across variable users and environments (Sirlanci et al., 2019). Last, participants in this study were mostly White (75%), young (mean age = 27 years), and educated (mean education = 16 years). Future work should examine whether samples of more diverse drinkers show similar patterns of results.

In sum, the present study used HR-EMA to determine natural environment alcohol responses across clinically meaningful drinker subgroups. Results demonstrated positive subjective alcohol responses in risky drinkers in line with prior laboratory research (Fridberg et al., 2021; King et al., 2011, 2021). This study uniquely featured a non-alcohol-drinking comparison episode and supported the feasibility of a targeted HR-EMA approach even in drinkers with MS-AUD. Risky drinkers (HD and MS-AUD) drank to intoxication with high sensitivity to stimulation, liking and wanting more alcohol throughout the 3-h reporting interval, in contrast to low-risk LD

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drinkers. Future work should examine whether real-world alcohol responses vary across risky drinkers with psychiatric comorbidities and integrate HR-EMA with emerging biosensor technologies to gain further insight into real-world drinking experiences to identify targets for intervention.

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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