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RESEARCH ARTICLE

Correspondence between the alcohol-P3 event-related potential and alcohol reward phenotypes among young adults

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Abstract

Background: Behavioral economic theory suggests that the value of alcohol depends upon elements of the choice context, such that increasing constraints on alternatives (e.g., price) or increasing the benefits of alcohol (e.g., social context) may result in greater likelihood of heavy drinking. The P3 event-related potential elicited by alcohol-related cues, a proposed marker of incentive salience, may be an electrophysiological parallel for behavioral economic alcohol demand. However, these indices have not been connected in prior research, and studies typically do not disaggregate social influences in the context of alcohol cue reactivity.

Method: The current study recruited heavy drinking young adults ($N = 81$) who completed measures of alcohol use and alcohol demand, in addition to a 2 (social/nonsocial) × 2 (alcohol/nonalcohol) visual oddball task to elicit the P3.

Results: In multilevel models controlling for demographic characteristics, P3 reactivity was greater to alcohol ($p < 0.001$) and social ($p < 0.001$) cues than to nonalcohol and nonsocial cues, but without a significant interaction. Higher alcohol consumption ($p = 0.02$) and lower elasticity of demand ($p = 0.01$) were associated with greater P3 response to alcohol than nonalcohol cues.

Conclusions: The results highlight a brain-behavior connection that may be an important marker for alcohol reward across units of analysis and may be sensitive to changes in the economic choice contexts that influence the likelihood of alcohol use.

KEYWORDS
alcohol demand, behavioral economics, cue reactivity, electroencephalography, social

INTRODUCTION

Young adults consume alcohol at higher rates than any other age group (Chen et al., 2004), resulting in adverse consequences (Hingson et al., 2017) that can interfere with achieving developmental milestones such as college graduation and career development, and heavy drinking is associated with a greater likelihood for alcohol use disorder (AUD) later in life (Jennison, 2004). Identification of risk factors for harmful drinking can alleviate burdens of alcohol use during young adulthood and prevent development of chronic patterns of harmful alcohol use.

Behavioral economic theory

Behavioral economic theory merges concepts from economics and operant psychology to explain decision making and is a useful framework

for understanding developmentally persistent harmful alcohol use. From the behavioral economic perspective, alcohol use and misuse represent a contextually dependent preference for alcohol, which provides immediate reinforcement (euphoric, stimulant, anxiolytic, or analgesic effects) but longer-term costs in important life-health domains (e.g., good health, educational and vocational success), as compared to alcohol-free alternatives that typically have lower short-term, but higher long-term, value. From the perspective of behavioral economic theory, levels of alcohol use are determined in part by the value of alcohol, and therefore measurement of alcohol value relative to constraints is a critical goal of behavioral economic theory. In humans, relative alcohol value is commonly measured with hypothetical alcohol purchase tasks (APT) (Petry & Bickel, 1998), modeled after progressive ratio tasks quantifying behavioral output across escalating constraints. In an APT, individuals report drink purchasing during a hypothetical drinking scenario across a series of escalating prices (i.e., financial constraint). Responses across prices reflect the impact of a specific constraint (i.e., monetary cost) on choice behavior, thus capturing a contextualized index of alcohol value (Murphy & MacKillop, 2006). Purchase task data is plotted as a demand curve, with elements of the curve representing distinct facets of motivation to consume alcohol. Research demonstrates that, in general, alcohol consumption is high when freely available, yet decreases as response cost increases (Hursh, 1980). Between-person variation in consumption behavior across escalating prices theoretically reflects variability in the motivational significance of alcohol. Responses on APTs correspond to real-world alcohol purchase behavior (Amlung & MacKillop, 2015) and with changes in real-world alcohol use over time (Acuff & Murphy, 2017). Alcohol demand indices are robustly correlated with alcohol consumption (Lemley et al., 2016; Martínez-Loredo et al., 2021; Murphy & MacKillop, 2006), use-related problems (Martínez-Loredo et al., 2021), and AUD (Gaume et al., 2022). Alcohol demand indices also demonstrate promise as prospective within-person predictors of changes in alcohol use behavior (e.g., binge drinking, use-related problems; Acuff et al., 2023). These findings suggest that demand has predictive utility over and above aggregate measures of recent drinking, which only capture one slice of real-world behavior.

Although drinking may cause harm, some emerging adults continue to drink because the short-term benefits (social facilitation, fun, alleviation of boredom) outweigh these costs (Aston et al., 2021). Social connection is a robust natural reward, especially among young adults, and alcohol is more valuable to young adults because it increases social connection (Fairbairn, 2017). Drinkers expect alcohol to enhance social interactions (Brown et al., 1980), and acute alcohol intoxication increases social bonding (Sayette et al., 2012); those who perceive higher alcohol consumption among their peers are more likely to consume more alcohol (Neighbors et al., 2008). Recent behavioral economic demand studies concur with these findings, suggesting demand is greater when drinking with friends, compared to when alone (Acuff, Soltis, & Murphy, 2020), and is monotonically associated with the frequency of binge drinking in a person's social network (Acuff, MacKillop, & Murphy, 2020).

Neurophysiology and behavioral economics

Little is known about the correspondence between alcohol demand and electrophysiological indices of reward reactivity. This represents a barrier to theory refinement, to our understanding of the connections between behavioral and biological mechanisms of risk, and, ultimately, to our ability to predict risk for AUD onset or progression. Confirmation of relations across different operational definitions of reward is critical to establishing construct validity (Campbell & Fiske, 1959), advancing assessment, intervention, and treatment of harmful alcohol use, and will add to recent gains in understanding consilience between behavioral economics and other areas of addiction neuroscience, including hemodynamic brain imaging (Owens et al., 2017) and behavioral genetics (MacKillop et al., 2015).

Event-related brain potentials (ERPs) provide a direct measure of electrocortical activity known to reflect neurocognitive processes unfolding in real time (Luck, 2005) and may hold promise as neurophysiological analogs of behavioral economic reward-relevant markers of heavy drinking risk. The P3 ERP elicited by reward-relevant stimuli seems promising as a neurophysiological index of behavioral economic demand. Although the P3 is elicited by virtually any attended stimulus processing context, the P3 tends to be most pronounced in various "oddball" paradigms (e.g., Figure 1), in which infrequent target stimuli are presented amid sequences of more frequent non-target stimuli (Squires et al., 1975). Across all types of paradigms, P3 amplitude appears to index the incentive-motivational value of eliciting stimuli (Begleiter et al., 1983; Franken et al., 2011; Hajcak & Foti, 2020; Pfabigan et al., 2014) and has been used in numerous studies to assess the incentive-motivational value of alcohol-related cues (Bartholow et al., 2007, 2010, 2018; Namkoong et al., 2004). Enhanced P3 amplitude to alcohol-related compared to neutral images is associated with increasing hazardousness of alcohol use (Webber, de Dios, et al., 2022). For example, P3 reactivity to alcohol cues is enhanced among heavy compared to light social drinkers (Herrmann et al., 2001), people with DSM-IV alcohol dependence compared to controls (Namkoong et al., 2004), and emerging adult heavy compared to lighter drinkers (Bartholow et al., 2007; Petit et al., 2015). Thus, behavioral economic demand for alcohol may serve as a behavioral analog corresponding to the amplitude of the P3 elicited by alcohol cues, both of which have been identified as indices that quantify the incentive-motivational value of alcohol.

Current study

Behavioral economic research has demonstrated that self-reports of alcohol demand show robust associations with harmful alcohol use. However, little is known about the correspondence between these self-report indices and electrophysiological indices of incentive-motivational value (Webber, Yoon, et al., 2022). Further, no studies have examined neural reactivity to images depicting natural, social

rewards among heavy-drinking emerging adults. The work attempts to contribute to recent gains in consilience between behavioral economics and other areas of addiction neuroscience. We have two aims and accompanying hypotheses.

Hypothesis 1. We will examine differences in P3 reactivity to cues for social alcohol reward, social nonalcohol reward, nonsocial alcohol reward, and nonsocial nonalcohol reward, as well as neutral stimuli. We predict that social alcohol reward cues will produce the greatest P3 reactivity, given that such cues pair two robust motivationally salient rewards, followed by social nonalcohol, nonsocial alcohol, nonsocial nonalcohol, and neutral (i.e., frequent) cues.

Hypothesis 2. We will examine the relations between P3 reactivity, typical number of drinks per week, and behavioral economic demand indices. We predict that greater alcohol demand and greater typical drinks per week will be associated with greater P3 reactivity to alcohol-related and social cues.

METHODS

Participants

The current study uses cross-sectional, baseline data from a two session (separated by 4 months) survey study that included additional counterbalanced EEG tasks. Participants were 81 young adults recruited from the community and a local university in the mid-South (demographics reported in Table 1). Inclusion criteria were: (1) 24 to 28 years old, (2) one or more instances of past month alcohol consumption meeting or exceeding 4/3 standard alcoholic drinks for males/females; (3) stable contact information; and (4) English language fluency. Exclusion criteria were: (1) current or past psychosis; (2) current or past treatment for AUD; and (3) a history of seizures. Participants were recruited in two separate phases: (1) through an ongoing longitudinal study and (2) within university recruitment streams. The original longitudinal study explored trajectories of "maturing out" among emerging adults (initially recruited between ages 21.5 and 24.99). This secondary EEG study recruited participants from the initial pool of participants in the longitudinal study when participants were between 24 and 28 years old. All other inclusion and exclusion criteria were identical for Phase 2 of recruitment. Sensitivity analyses (Table S1) suggested that participants recruited in Phase 2 were more likely to be students but did not differ from participants recruited in Phase 1 in terms of gender/sex assigned at birth, race, typical number of drinks per week, or age. Additional details regarding recruitment strategies, compensation, etc., are provided in supplemental materials. The sample initially included 101 emerging adults; 11 were excluded from analyses for failing to complete any of the necessary self-report measures, and two were excluded from analyses because they did not comprehend task instructions. An additional seven participants were excluded from analyses because, based on prior psychometric work with P3 amplitude scores from a similar task (Cofresí et al., 2022), they had too few (<6) artifact-free EEG segments per electrode for psychometrically reliable measurement of P3 amplitude on at least one of the four key stimulus conditions in the task.

TABLE 1 Demographic statistics.

	M (SD)	*n* (%)
Age	25.70 (1.17)	
Sex assigned at birth (female)		44 (54.3%)
Race		
White		51 (63.0%)
Black		23 (28.4%)
Asian		6 (7.4%)
Other		1 (1.2%)
Student status (≥ part time)		67 (76.5%)
Typical drinks per week	9.99 (7.04)	
Intensity	5.60 (2.75)	
O_{max}	24.59 (18.44)	
Elasticity (alpha)	0.0106 (0.0082)	

Note: Total $N = 81$.

Self-report measures

Alcohol purchase task

Alcohol demand was measured with a hypothetical alcohol purchase task (Murphy & MacKillop, 2006). Participants reported the number of standard drinks they would purchase at each price in a series of 30 escalating prices ($0.00–$40.00 per drink). Consumption at each price is plotted to create demand curves from which indices can be extracted. The current study examined two observed indices: intensity (consumption with no constraint) and O_{max} (maximum expenditure). We also derived the elasticity index alpha (the rate of change in consumption as a function of price) using an exponentiated equation which allows for the inclusion of zeros (Koffarnus et al., 2015). Greater elasticity means a greater impact of price on consumption, thus reflecting lower alcohol demand. In the current study, k was held constant at 2.1, calculated by subtracting the $\log_{10}$ transformed average consumption at the highest price from the $\log_{10}$ transformed average consumption at the lowest price across participants (Koffarnus et al., 2015). Data were cleaned based on the following criteria: (1) trend (detection limit for $\Delta Q < 0.025$); (2) bounce (detection limit for $B = 0.10$); (3) reversal from zero (detection limit number for reversals = 2 or more). No participants were flagged for having nonsystematic data. Demand elasticity was derived using the beezdemand program (Kaplan et al., 2019).

Alcohol consumption

Typical number of drinks per week was measured with the Daily Drinking Questionnaire (DDQ) (Collins et al., 1985). Participants reported their typical alcohol consumption on each day of a typical week in the past month. Values are summed to create a total score.

Oddball paradigm

Participants completed a visual "oddball" paradigm in which infrequent target stimuli (oddballs) were presented amid more frequent standard stimuli (Figure 1). These stimuli were presented in five-image sequences, with the "oddball" always occurring in the fourth or fifth position, consistent with previous research (Martins et al., 2019). The frequent/standard stimuli were pictures of everyday objects (evaluated by authors SFA, BDB, JGM, and JM to be neutral in valence, low in arousal), such as a woven basket or a bar of soap, which were copied from the internet. Participants encountered four different categories of infrequent target stimuli: social alcohol cues, social nonalcohol cues, nonsocial alcohol beverage cues, and nonsocial nonalcohol appetitive cues. The social alcohol cues, which depicted people in groups of 2–3 drinking alcohol, were taken from the Galician Beverage Picture Set (Pronk et al., 2015), a set of color images validated for use in alcohol cue-reactivity research. The social nonalcohol cues depicted groups of 2–3 people engaged in social interaction but without alcohol and were matched for numbers of people in the images with the social alcohol cues. The nonsocial alcohol cues depicted alcoholic beverages (i.e., beer, wine, and cocktails) in isolation. The nonsocial nonalcoholic cues depicted food. This category was selected instead of a nonalcoholic beverage condition because food is an evolutionarily, salient and appetitive nonalcohol reward that serves as a more robust comparator than nonalcoholic beverages (Epstein et al., 2007). All infrequent stimuli were evaluated by authors SFA, BDB, JGM, and JM to be positive in valence, moderate in arousal, and to fit into the relevant categories. Each trial consisted of a visual fixation cross presented for 500 ms, followed by one of the five picture types presented centrally for 1200 ms.

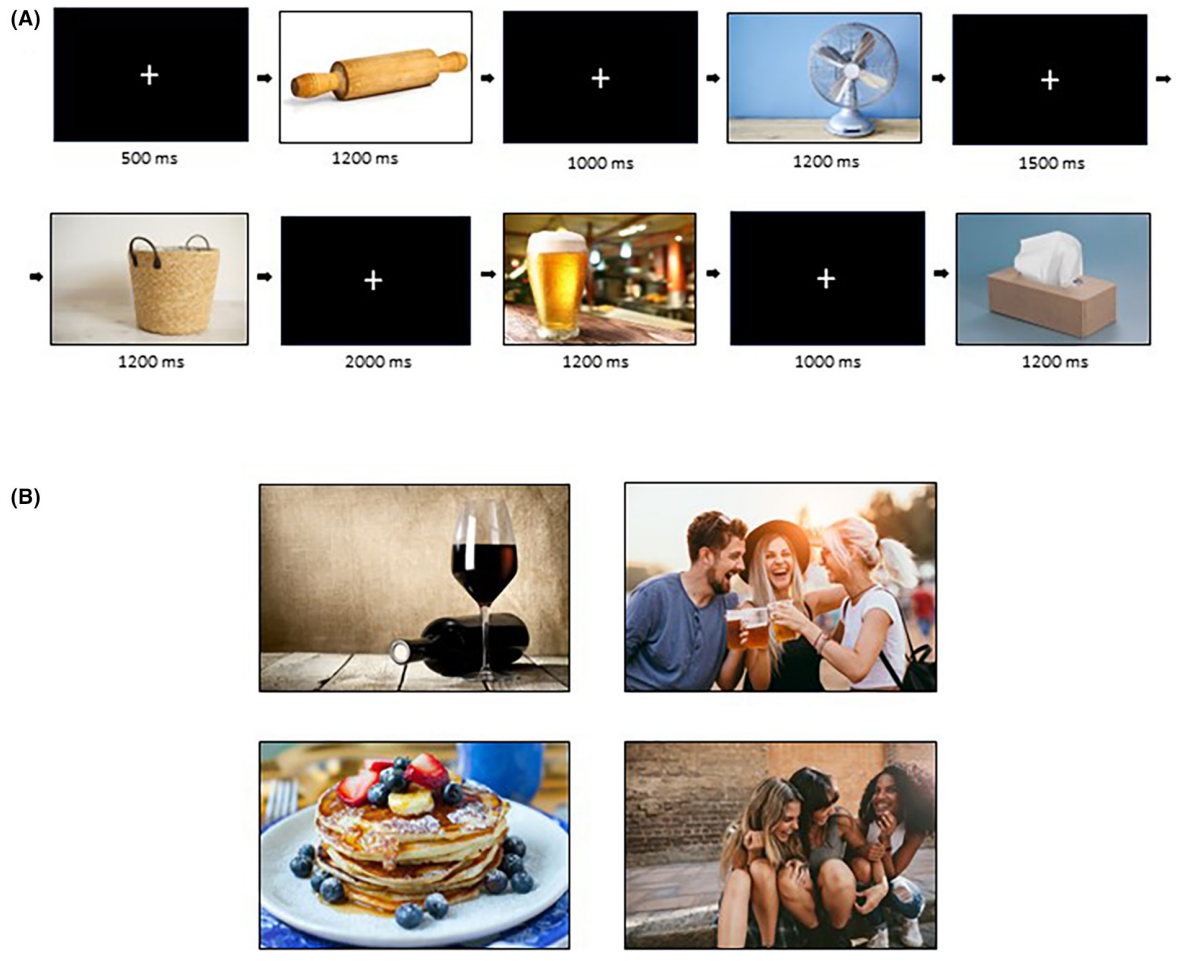

FIGURE 1 Oddball paradigm. (A) In the oddball paradigm, frequent non-target stimuli were presented for 1200 ms, with an infrequent target image interspersed in the fourth or fifth position. Interstimulus intervals varied between 500 and 1500 ms. (B) Examples for each image category used in primary analyses: non-social alcohol (top left image), social alcohol (top right image), non-social non-alcohol (bottom left image), and social non-alcohol (bottom right image).

Trials were separated by an inter-trial interval that varied randomly from 1000 to 2000 ms (500-ms increments; Bartholow et al., 2007; Martins et al., 2019). To ensure participants actively attended to each image and remained engaged throughout the task, participants were instructed to categorize each image as either alcohol-related or non-alcohol-related using a keyboard.

Images from each infrequent target category were presented a total of 24 times each, for a total of 16% of trials per infrequent image category, and images in the frequent target category were presented a total of 126 times each, for a total of 86% of trials from this category. The task was completed in four blocks (126 frequent target category trials per block and 24 trials per each of four infrequent target categories = 150 trials total per block), and participants were given a brief break between blocks. The oddball task took 32 min (8 min per block).

Procedure

When participants arrived at the lab, they provided informed consent and were then prepared for EEG recording (described below). Participants were seated ~1 m away from a computer monitor (10.5 × 21.5-inch dimensions) in a private room to complete the cue reactivity task. Participants also completed two versions of the Doors Task, the results of which are not reported in this manuscript. Tasks were presented in counterbalanced order. Study visits took ~2 h total. Study visits took place on any day of the week between 8 a.m. and 7 p.m. All study procedures were approved by the University of Memphis Institutional Review Board.

EEG recording and P3 scoring

Recording

The EEG was recorded continuously from 16 scalp locations (C3, C4, CPZ, CZ, F3, F4, FC3, FC4, FCZ, FZ, P3, P4, POZ, PZ, M1, M2 [online reference], and AFZ [ground]) using tin electrodes in an electrode cap (Electro-Cap International, Eaton, OH, USA) based on the standard 10–20 system (American Encephalographic Society, 1991). Scalp electrodes were referenced online to the right mastoid (M2), with a forehead ground. Additional electrodes were placed above and below the left eye to record vertical eye movements. Electrode impedances was kept below 10 kΩ. The EEG signal (recording bandwidth: 0.005–0.100 Hz) was amplified with a Biopac EEG100C unit at 10,000× and collected at a sampling rate of 500 Hz using Acq*Knowledge* software (Biopac Systems, Inc., Goleta, CA, USA).

Processing and ERP derivation

EEG data processing was done offline in Matlab version 2022b (The MathWorks Inc., Natick, MA, USA) using the packages EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). First, data were re-referenced to an average of the two mastoids. Then, data were downsampled to 256 Hz and filtered using a 0.1- to 30-Hz band-pass (second order Butterworth). The CleanLine plug-in for EEGLAB was used to identify bad channels (i.e., excessively noisy electrodes, e.g., due to poor contact with scalp) and attenuate line noise (Mullens, 2012). Ocular artifacts, such as blinks and eye movements, were then removed from the EEG using an independent components analysis procedure (Iriarte et al., 2003) ($M \pm SD$ artifactual independent components removed: 1.67 ± 0.81 per person, Median = 2, Min = 1, Max = 5). After interpolation of previously identified bad channels using the spherical spline method in EEGLAB (0.28 ± 0.60 interpolated per person, Median = 0, Min = 0, Max = 2), the ocular artifact-corrected continuous EEG data were segmented into stimulus-locked epochs from −200 to 1200 ms and averaged separately for each participant, electrode channel, and stimulus condition. Trials from incorrectly categorized stimuli were not included in the analyses. Epochs were baseline corrected using the mean voltage across the 200-ms period before stimulus onset. Finally, trials containing voltage fluctuations exceeding ±3 SD from a person's mean voltage for a given electrode were rejected ($M \pm SD$ trials rejected: 16.57 ± 1.84% of all valid epochs per electrode per person; see Table S2 for accepted [artifact-free] trial counts per stimulus condition per electrode per person).

Previous work on visual alcohol oddball tasks has shown that the P3 component of the ERP is evident from ~300 to 800 ms after stimulus onset, and is maximal over parietal and occipital scalp locations (Bartholow et al., 2007; Martins et al., 2019). Inspection of the electrode-level grand average ERP waveforms (see Figure S1) confirmed that in the current study, the P3 was maximal at parietal electrodes (P3, PZ, P4, POz). Inspection of the grand average ERP waveform averaged across parietal electrodes (see Figure 2) indicated that in the current study the bulk of the P3 component occurred from 300 to 600 ms after stimulus onset. P3 peak latency did not differ among the four oddball stimulus conditions nor among the four parietal electrodes (see Table S4). Thus, P3 component amplitude was quantified as the mean voltage during this time-window at each parietal electrode for each stimulus condition. Table S3 shows the standardized measurement error (Luck et al., 2021) and internal consistency reliability of the P3 scores by stimulus condition aggregated across parietal electrodes.

Data analysis

First, data distributions were checked for normality. Outliers were defined as values greater than four SD from the mean. Skewness and kurtosis values between −2 and 2 were considered to indicate a normal distribution (Trochim & Donnelly, 2006). Next, we examined descriptive statistics and correlations among self-report data. The first hypothesis was tested using a 2 (alcohol cue: nonalcohol = 0, alcohol = 1) × 2 (social cue: nonsocial = 0, social = 1) factorial multilevel

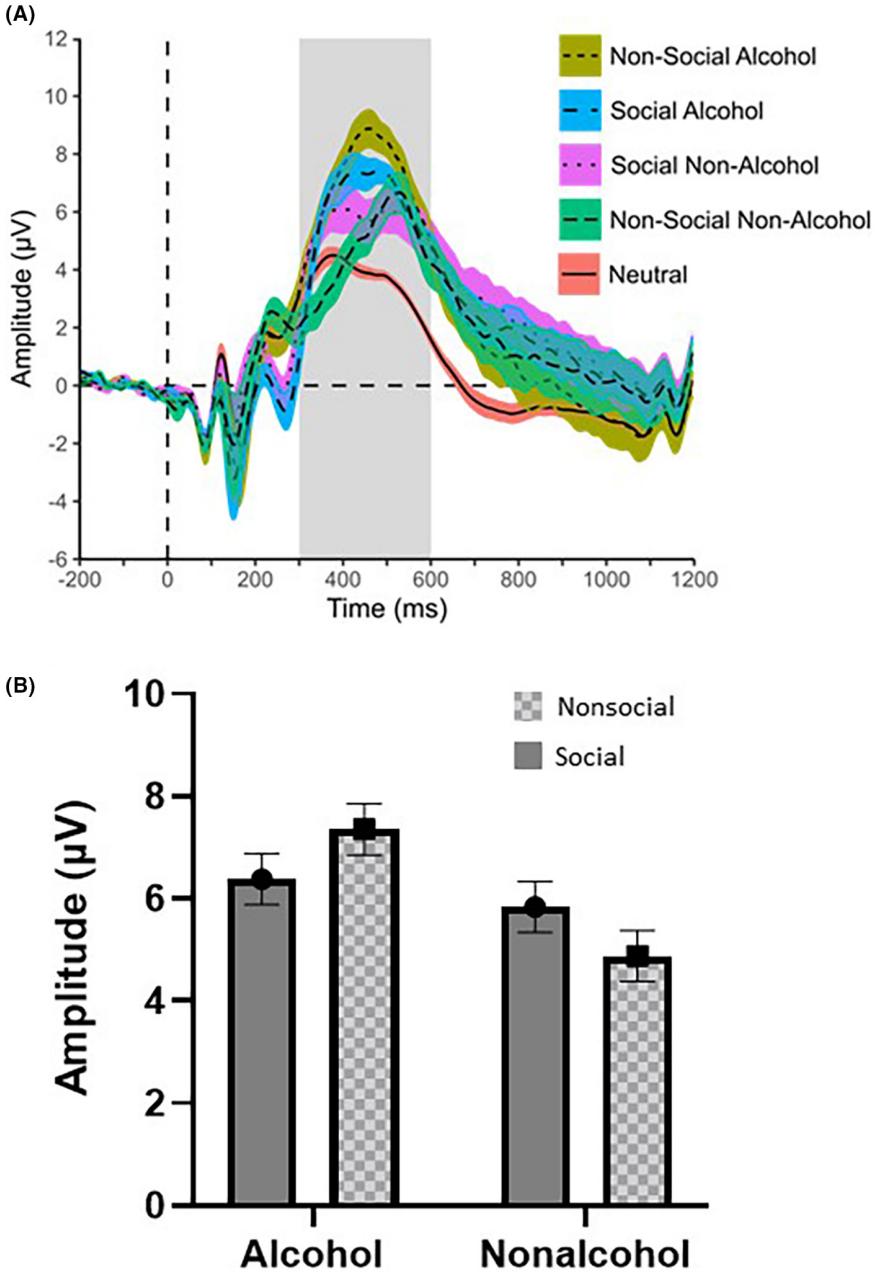

FIGURE 2 Event-related potential (ERP) grand average waveforms for different trial types in the oddball. (A) Differently colored ribbons show ERP waveforms by trial type aggregated across artifact-free trials for 81 persons and for electrodes per person across which the P3 response was maximal (P3, PZ, P4, and POZ). The line at the center of each ribbon shows the M across people. The boundaries of each ribbon show the SD across people. ERPs were baseline corrected using the 200-ms period before image onset, which occurred at 0 ms. Neutral images (e.g., box of tissues, fan) were frequent (84% out of 600 total trials) whereas other image categories were infrequent (16% each out of 600 total trials). P3 responses were quantified as the mean amplitude between 300 and 600 ms post-stimulus relative to the mean amplitude across the pre-stimulus baseline window (−200 to 0 ms). The quantification window is depicted by the gray rectangle in the plot. Data represent $N = 81$ persons. (B) Least squares means and standard error of P3 amplitudes for each condition in the oddball paradigm controlling for race, sex, and student status.

model with random intercepts specified for participants and electrodes within participants. We also attempted models including random slopes for the primary oddball (social and alcohol) task effects. However, the Hessian matrix was nonpositive definite in these models, and ultimately the random slopes were excluded. Next, we included typical number of drinks per week as a moderator. In other words, typical drinks per week was included as an individual predictor, along with all possible interactions with alcohol cues and social cues.

Next, we tested separate models in which the P3 amplitudes were regressed onto the relevant behavioral indicator in the presence of the following control variables: sex (0 = Female, 1 = Male), race (0 = non-White, 1 = White), student status (0 = non-student, 1 = At least part-time), and age. All task-related effects were dummy coded, whereas all dichotomous covariates were effect coded; continuous predictors were mean centered.

RESULTS

Sample characteristics and drinking/behavioral economic means and standard deviations can be found in Table 1. Least square means of each condition can be found in Figure 2B.

Hypothesis 1. All results modeling P3 amplitude outcomes can be found in Table 2, with each additional moderator included in separate models. Covariate effects can be found under Model 1, the baseline model establishing the effects of social and alcohol cues. Neither race, sex assigned at birth nor student status was associated with P3 amplitude in any model. All covariates were included in all models, but their statistics are only reported for Model 1.

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TABLE 2 Estimates of the effects of social and alcohol cues and their interactions with typical drinks per week and alcohol demand indices on P3.

	Estimate	S.E.	df	*t*-value	*p*-value
Model 1: Effects of cue type					
Intercept	5.12	1.08	79.6	4.74	<0.001
Race	0.51	0.91	76.9	0.56	0.58
Sex	0.43	0.89	76.9	0.49	0.63
Student	−1.35	1.02	76.9	−1.32	0.19
Social (Reference = non-social)	0.88	0.23	965	3.76	<0.001
Alcohol (Ref. = non-alcohol)	2.27	0.23	965	9.73	<0.001
Social × Alcohol	−1.77	0.33	966	−5.36	<0.001
Model 2: Moderation by typical drinks per week					
Drinks per Week	0.10	0.07	92.8	1.60	0.11
Drinks per Week × Social	0.04	0.03	962	1.19	0.24
Drinks per Week × Alcohol	0.08	0.03	962	2.36	0.02
Drinks per Week × Social × Alcohol	−0.03	0.05	962	−0.60	0.55
Model 3: Moderation by APT-intensity					
Intensity	0.19	0.17	92.8	1.13	0.26
Intensity × Social	−0.10	1.03	75.9	−1.16	0.25
Intensity × Alcohol	0.06	0.09	962	0.73	0.47
Intensity × Social × Alcohol	0.08	0.12	962	0.66	0.51
Model 4: Moderation by APT-O_{max}					
O_{max}	0.01	0.03	92.5	0.50	0.62
O_{max} × Social	0.02	0.01	962	1.91	0.06
O_{max} × Alcohol	0.01	0.01	962	1.14	0.25
O_{max} × Social × Alcohol	−0.03	0.02	962	−1.46	0.14
Model 5: Moderation by APT-elasticity					
Elasticity	−66.86	55.97	93	−1.19	0.24
Elasticity × Social	−46.70	28.52	962	−1.64	0.10
Elasticity × Alcohol	−70.90	28.52	962	−2.49	0.01
Elasticity × Social × Alcohol	22.81	40.32	962	0.57	0.57

Note: All estimates are unstandardized. Covariate effects are included in all models, but are only reported in Model 1, the baseline model establishing the effect of social stimuli and alcohol cues on the P3 amplitude. df are estimated degrees of freedom from the mixed effects procedures in SAS.
Abbreviations: APT, alcohol purchase task; df, degrees of freedom; S.E. standard error.

In Model 1, main effects demonstrated that both social (relative to nonsocial) and alcohol (relative to nonalcohol) images elicited larger P3 amplitudes (Table 2). There was also a significant interaction between alcohol and social image content on P3 amplitude. Within alcohol images, those excluding people ($M = 7.18$, $SE = 0.54$) elicited greater P3 amplitude relative to those including people ($M = 6.29$, $SE = 0.54$; Est. = −0.89, df = 967, $t = -3.83$, $p < 0.001$); however, within nonalcohol images the effect was reversed, such that images with people ($M = 5.79$, $SE = 0.54$) elicited greater P3 amplitudes than those without people ($M = 4.91$, $SE = 0.54$; Est. = 0.88, df = 965, $t = 3.76$, $p < 0.001$).

Hypothesis 2. Model 2 indicated significant moderation of alcohol content by typical number of drinks per week. As shown in Figure 3A, there was no effect of drinks/week on P3 to non-alcohol images ($b = 0.12$ [SE = 0.06], df = 81.34, $t = 1.96$, $p = 0.053$); however, P3 response to alcohol images increased as the number of typical drinks per week rose ($b = 0.19$ [SE = 0.06], df = 81.34, $t = 2.98$, $p = 0.004$). These two slopes differed significantly ($b = 0.06$ [SE = 0.02], df = 961.7, $t = -2.74$, $p = 0.006$).

In Model 3 and Model 4, there were no significant moderation effects involving the behavioral economic index of intensity or O_{max}. Model 5 showed a significant interaction between alcohol content and the behavioral economic index of elasticity (Figure 3B). There was no effect of elasticity on P3 to non-alcohol images ($b = -90.21$ [SE = 54.12], df = 81.39, $t = -1.67$, $p = 0.10$); however, consistent with hypotheses, P3 to alcohol images increased as demand became *less* elastic ($b = -149.70$

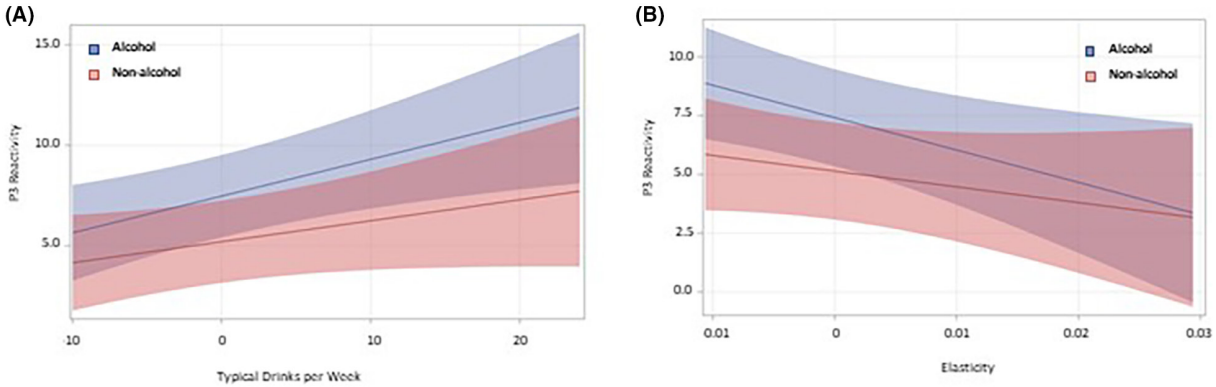

FIGURE 3 Significant interaction effects between typical drinks per week, O_{max}, and elasticity with oddball task conditions. Illustrations of predicted means ±95% confidence intervals of significant interactions between dependent variables and P3 variables predicted *M* ± 95*CI*. Across all figures, the *x*-axis represents a continuous dependent variable; the *y*-axis represents P3 reactivity. All dependent variables are mean centered. (A) There was no association between typical drinks per week and P3 reactivity for non-alcohol images; however, P3 reactivity to alcohol images significantly increased as the number of typical drinks per week rose. There was a significant difference in slopes for alcohol compared to non-alcohol images. (B) There was no effect of typical drinks per week on P3 reactivity for non-social images; however, P3 reactivity to social images increased as the number of typical drinks per week rose. The slopes for the effect of typical drinks per week on the P3 for social and non-social images were not significantly different. (C) Both slopes were nonsignificant for O_{max} on P3 reactivity for both non-social images and social images. The slopes for the effect of O_{max} on the P3 for social and non-social images were, however, significantly different. (D) There was no effect of elasticity on P3 reactivity for non-alcohol images; however, P3 reactivity to alcohol images increased as demand became more inelastic. The slopes for the effect of elasticity on the P3 for alcohol and non-alcohol images were not significantly different. (E) There was no effect of elasticity on P3 reactivity for non-social images; however, P3 reactivity to social images increased as the demand became less elastic. The slopes for the effect of typical number of drinks per week on the P3 for social and non-social images were not significantly different.

[SE = 54.12], df = 81.36, $t = -2.77$, $p = 0.007$). These slopes were significantly different from one another ($b = 59.49$ [SE = 20.16], df = 962.3, $t = 2.95$, $p = 0.003$). There was no significant interaction between the behavioral economic index of elasticity and social cue.

DISCUSSION

The present study connected electrophysiological and behavioral economic indicators of alcohol-related reward, and moderation by social cues, among young adults reporting recent heavy drinking. Unsurprisingly, given the heavy-drinking, young adult sample, we observed larger P3 amplitudes to alcohol than nonalcohol beverage cues, and to social relative to nonsocial context cues. Moreover, we observed an interaction between the two cue conditions. However, the form of this interaction was unexpected. Within alcohol conditions, P3 amplitude was greater when alcohol was presented alone compared to with people; however, within nonalcohol images, the effect was reversed such that images with people elicited greater P3 amplitudes than those without. Since most heavy drinking occurs in social contexts (Acuff et al., 2021), we expected the combination of alcohol and social content to produce a super-additive effect on P3 amplitude. Yet, the pattern observed here is consistent with a study conducted by Martins et al. (2019). Although the Martins study did find a main effect of the image category such that alcohol images in social settings elicited greater P3 relative to those devoid of social context, the authors could not test the full interaction with nonalcohol social images, and the main effect were moderated by sensitivity to alcohol such that those with higher sensitivity to alcohol had higher P3 for alcohol alone images relative to those in a social context. Considered together, the findings from these two studies may indicate that, among heavy-drinking young adults, the presence of people dilutes the salience of alcohol beverage cues. Social connection is a robust, evolutionarily engrained reinforcer (Ellis et al., 2012) that theoretically should evoke greater motivated attention than alcohol. It could be that the social and drug-related components of these complex cues compete for attention. Prior research (Watter et al., 2001) has shown that as attentional demands for specific stimuli increase, P3 amplitude decreases. However, additional research is needed to directly evaluate such an account.

Consistent with previous research (Bartholow et al., 2007; Begleiter et al., 1984; Petit et al., 2014), typical number of drinks per week was associated with greater P3 reactivity for alcohol cues relative to non-alcohol stimuli. This interaction was no longer significant after using a strict *p*-value cutoff to control for multiple tests. More importantly, our study found enhanced P3 amplitudes to alcohol compared to non-alcohol images among individuals with less elastic demand for alcohol (i.e., less price sensitivity), whereas P3 amplitudes to alcohol and non-alcohol cues where comparable among individuals with low alcohol demand. Consistent with previous studies (Acuff, Amlung, et al., 2020; MacKillop et al., 2012), these findings provide further evidence that alcohol demand may index affective-motivational reactivity to alcohol cues, as reflected by the P3. Demand elasticity is the primary indicator in a factor known as "persistence"—the endurance of motivation to consume alcohol across escalating constraints—whereas demand intensity is thought to represent a separate factor of alcohol motivation

known as "amplitude"—the "raw" motivation without accounting for changes in constraints (Skidmore et al., 2014). P3 amplitudes may correspond to behavioral economic motivational "persistence", sensitive to constraints known to influence alcohol consumption, explaining why demand intensity was not associated with any P3 amplitudes. Previous research has demonstrated that P3 reactivity to alcohol cues is sensitive to important contextual manipulations, such as symbols of status (i.e., university logos) included in images of alcohol (Bartholow et al., 2018). Future research may consider exploring university-related effects on motivational elasticity to further validate the P3 as an electrophysiological index of motivational "persistence."

The contributions of the present study must be understood in the context of its limitations. First, as in most cue-reactivity research, the visual cues in this study were static, 2-dimensional photographs devoid of actual social or drinking contexts. Studies using wireless (mobile) EEG technology in combination with simulated or real drinking environments may better capture neural reactivity to alcohol cues experienced by drinkers in both social and solitary conditions. Second, the sample was not large or diverse enough to permit examination of individual difference factors (race, sex assigned at birth) or differences across visual stimuli that may influence the P3 amplitude, such as whether strangers or friends are depicted. Third, the current study explored associations of interest in a sample of emerging adults in the Southern United States. Future studies should replicate these associations in other samples to increase generalizability.

More research is necessary to confirm and extend these findings. However, the P3 may serve as a biomarker that could be targeted through novel interventions to reduce the motivational salience of alcohol. P3 reactivity may also serve as a useful indicator of pharmacotherapy response. No research to our knowledge has compared alcohol P3 reactivity in the context of a clinical trial for pharmacotherapeutics being evaluated as a treatment for alcohol use disorder. The P3 may serve as a marker sensitive to context, which could help determine in early-stage clinical trials how the drug may react in other contexts. More research is needed to test these future directions.

CONCLUSION

With the current study, we connect behavioral indices of alcohol reward and temporally bound decision-making with electrophysiological indices of reward valuation and motivation. Our findings bolster construct evidence for alcohol demand and alcohol cue P3 as indices capturing motivational or reward value and suggest a brain-behavior connection capturing an important mechanism for alcohol use across units of analysis. The findings also provide preliminary support for the idea that P3 amplitude may be impacted by social content other than alcohol, which may more closely resemble real-world decision-making contexts.

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CONFLICT OF INTEREST STATEMENT

The other authors declare no conflicts 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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