Integration of Electrophysiological and Behavioral Economic Models of Reward Among Heavy Drinking Emerging Adults

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Abstract

According to behavioral economics, alcohol consumption is most likely when alcohol is overvalued relative to alternatives and when the individual steeply discounts delayed rewards. Recent studies exploring electrophysiological models of reward suggest there may be specific event-related potentials (ERPs) associated with behavioral economic constructs, namely, the P3 (a proposed marker of incentive salience) and RewP (a marker of the amplitude of response to reward). Although some studies suggest the P3 may be associated with alcohol use, none have disaggregated social influences in the context of alcohol cue reactivity. Further, no study has explored the effect of delay to reward receipt on RewP amplitude among heavy drinking young adults. The current study recruited heavy drinking young adults (N = 23) to complete behavioral economic (alcohol demand, alternative reinforcement, and delayed reward discounting) and drinking measures (typical drinks per week), in addition to an electroencephalography (EEG) session in which the participants completed a 2 (social/nonsocial) x 2 (alcohol/nonalcohol) oddball task, an immediate doors task, and a delayed doors task. In multilevel models controlling for sex assigned at birth, race, and college status, there were no significant differences between oddball conditions or between immediate and delayed RewP amplitudes. However, those who consumed more alcohol in a typical week had reduced P3 response to non-social, compared to social, images. Further, all three alcohol demand indices interacted with the alcohol condition, such that higher demand was associated with reduced P3 amplitude for alcohol, compared to nonalcohol images. Further, there was a three-way interaction between delayed reward discounting, feedback type, and time to reward receipt condition, such that there were no differences in RewP for negative and positive feedback across both delayed and immediate conditions, but among those with steep delayed discounting, RewP magnitude for immediate
gains was greater than RewP magnitude for delayed gains. The results highlight a brain-behavior connection which may be important marker for alcohol use across units of analysis and may be sensitive to changes in the economic choice contexts that influence the likelihood of alcohol consumption.
Young adults (ages 18-30) consume alcohol at higher rates than any other age group (Chen et al., 2004). Heavy drinking is associated with a range of adverse consequences, including alcohol-induced blackouts (Wetherill & Fromme, 2016), driving after drinking (Hingson et al., 2017; Paschall, 2003), physical injury, alcohol-related cirrhosis (Tapper & Parikh, 2018), and death, resulting in a massive economic burden to the United States (Sacks et al., 2015). Alcohol use during emerging adulthood can also interfere with achieving developmental milestones such as college graduation, career development, and optimal cognitive and social development and is associated with a greater likelihood for substance misuse later in life (Jennison, 2004). Although most emerging adults “mature out” of heavy drinking, many continue or escalate use despite experiencing moderate to severe problems. Behavioral economics, which posits that alcohol use decisions are cost benefit analyses influenced by the choice context, suggests that emerging adults may be more likely to continue drinking at high levels in part because alcohol is often paired with social connection, a salient reinforcer particularly among emerging adults, and because of an increased likelihood of preferring immediate to delayed rewards. Although findings in behavioral economic are robust, little work has connected these variables with biomarkers of reward. In the current study, I propose to examine correspondence between electrophysiological and behavioral economic indices of alcohol and alcohol-free rewards, and delayed and immediate rewards, among emerging adult drinkers.

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 alcohol use. From the behavioral economic perspective, decisions are cost benefit analyses in which the outcome maximizes utility, or value (Rachlin et al., 1981). As the costs increase and
the benefits decrease, the overall value decreases, whereas increasing benefits and decreasing cost results in increased overall value. Costs and benefits are defined broadly to include any perceived physical, psychological, economic, or emotional cost or benefit. A fundamental finding is that the value of any commodity is dependent on the availability of other activities or commodities in the choice context (Herrnstein, 1974; Hursh, 1980; Vuchinich & Tucker, 1988). Further, costs and benefits for different choice options are unevenly distributed across time, such that time becomes a critical variable in understanding behavioral allocation. As benefits, or rewards, move further away in time, their value decreases systematically. This is known as delay discounting, a cross-species, developmentally mediated tendency to prefer smaller, sooner rewards compared to larger, later rewards. Delayed rewards decrease in value in a manner consistent with a hyperbolic decay function (Ainslie & Herrnstein, 1981), such that preference between smaller immediate and larger delayed rewards shifts dynamically as a function of time to reward availability. Thus, humans and animals generally prefer larger, later rewards when reward receipt of both options is distal, but preference often reverses as the availability of the smaller, more immediate reward becomes imminent (Ainslie & Herrnstein, 1981). Individuals vary in the rate at which they devalue delayed rewards, and some have shorter time horizons for behavioral allocation or steeper discounting rates than others.

**Alcohol Use and Behavioral Economics**

Behavioral economics has been widely applied to harmful substance use, which was the seminal translational connection between the basic science of choice and human risk behavior (Vuchinich, 1995; Vuchinich & Tucker, 1988). The research suggests that substance use is a function of (1) the response cost; (2) the availability of alternative rewards in the choice context; and (3) the degree to which one discounts delayed rewards.
Response Cost. Early research demonstrated that animals and humans consume alcohol at high levels when it is freely available (Ahmed & Koob, 1998); however, as response cost for alcohol increases, self-administration decreases (Hursh, 1980; Hursh & Winger, 1995). These findings have been applied with the same outcome in samples of humans who use drugs (Cohen et al., 1971; Griffiths et al., 1974; Vuchinich & Tucker, 1983). However, these fixed ratio tasks where humans consume alcohol can be costly and time consuming. Consequently, researchers have developed hypothetical purchase tasks that are both cost- and time-effective to administer (Petry & Bickel, 1998b, 1998a). In a typical alcohol purchase task (APT), individuals report how many drinks they would purchase during a hypothetical drinking scenario at each price in a series of escalating prices. 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 can be plotted to create a demand curve, and various parts of the curve (e.g., peak consumption, peak response output, proportional reduction in consumption with increasing price) represent different aspects of motivation to consume alcohol.

Research suggests that hypothetical responding on APTs correspond to real behavior (Amlung et al., 2012; Amlung & MacKillop, 2015; MacKillop, Amlung, et al., 2010) and that alcohol demand corresponds closely with actual changes in drinking over time (Acuff & Murphy, 2017). Individuals differ in the rate of decline in responding as price increases, and individual differences in the reinforcing efficacy of alcohol is theoretically related to alcohol use and related problems. Indeed, alcohol demand indices have robust correlations with alcohol consumption (Lemley et al., 2016; Martínez-Loredo et al., 2021; Murphy & MacKillop, 2006), alcohol problems (Acuff et al., 2018; Martínez-Loredo et al., 2021), and alcohol use disorder.
(AUD; Bertholet et al., 2015). Demand indices are also robust prospective predictors of drinking behavior even after controlling for past alcohol consumption, suggesting that this measure, which aggregates a series of hypothetical drinking decisions across escalating constraints, has predictive utility over and above measures of drinking practices, which only capture one slice of behavior in the real world.

**Alternative Reinforcement.** A great deal of literature also demonstrates that the introduction of an alternative, substance-free reinforcer into the choice environment decreases alcohol self-administration. Early work in animals and humans attempting to establish the reinforcing efficacy of drugs tested response rates for drugs in fixed ratio schedules in isolation (i.e., no alternatives) and found that alcohol is self-administered at high rates (Ahmed & Koob, 1998). However, this is ecologically invalid, as humans are rarely presented with only one choice in a choice context (Field & Kersbergen, 2019). Indeed, when an alternative is available concurrently with self-administration, alcohol consumption decreases (Augier et al., 2018). This general finding among animals has been demonstrated across substances (Cosgrove et al., 2002; Ginsburg & Lamb, 2018; Huynh et al., 2017; Lenoir & Ahmed, 2008; Smith & Pitts, 2011) and various alternative rewards (Ginsburg & Lamb, 2018; Miller et al., 2012) and is partially moderated by genetically mediated risk factors (Augier et al 2018).

Introduction of an alternative reward can reduce alcohol self-administration in humans as well. In the seminal translation, Vuchinich and Tucker (1983) offered choices between alcohol and money in a 2 x 3 design, manipulating the amount of money available (either 2¢ or 10¢ per series of button presses) and delay in receipt of the money (either no delay, a 2-week delay, or an 8-week delay). Under conditions of no delay, subjects chose alcohol 42% of the time when the alternative was 2¢, but only chose alcohol 29% of the time when the alternative was 10¢.
These findings reflect principles of the matching law (Herrnstein, 1974), which suggests that the allocation of time or resources to any given commodity or activity is equivalent to reinforcement derived from this activity. Introducing alternatives shifts the allocation of resources and therefore also shifts the allocation of reinforcement across the choice options. Thus, the allocation of time or resources to various reinforcers may serve as measures of reinforcement. In line with this theoretical premise, researchers have developed various indices of reinforcement that capture time allocation and discretionary spending for alcohol and non-alcohol activities in humans (Acuff et al., 2019). The most commonly used measures, reinforcement schedules, ask participants to report frequency and enjoyment of various activities while under the influence of alcohol and while sober (Correia et al., 1998; Murphy et al., 2005). The frequency and enjoyment ratings are multiplied to create a cross-product representing reinforcement from substance-free and substance-related activities. The matching law suggests that reinforcement from alcohol should be considered in the context of a person’s total reinforcement; thus, a ratio can be calculated reflecting substance-related reinforcement relative to total reinforcement. This reinforcement ratio is associated with heavy drinking (Acuff et al., 2018; Delmée et al., 2017; Murphy et al., 2005) and use of other substances (Andrabi et al., 2017; Audrain-McGovern et al., 2009; Correia et al., 1998). Further, changes in reinforcement ratio mediates change in drinking following a brief intervention (Murphy et al., 2019).

**Delayed Reward Discounting.** Delayed reward discounting, which is a cross-species, developmentally mediated tendency to prefer smaller, sooner rewards compared to larger, later rewards, has been widely studied among substance using populations (Amlung et al., 2017; MacKillop et al., 2011a). The phenomenon of delayed reward discounting was initially documented in a series of experiments in which pigeons were given the opportunity to choose
between a smaller or larger amount of food access at varying delays (Mazur, 1984, 1986, 1987). Mazur (1987) found that pigeons equally preferred 2 seconds of food delivered after a 6 second delay and 6 seconds of food delivered after a 17-second delay. These findings, in addition to a great deal of animal and human results that have been published since (Dennhardt et al., 2015; Kirby et al., 1999; Vuchinich & Simpson, 1998), fit a hyperbolic function (Mazur, 1987):

\[ V = \frac{A}{1 + kD} \]

Where \( V \) is the present value of the delayed reward \( A \) at delay \( D \), and \( k \) is a free parameter that can be thought of as an impulsivity rate, that freely varies across subjects (Herrnstein, 1981; Kirby et al., 1999). The hyperbolic function suggests that preference between smaller immediate and larger delayed rewards shifts dynamically as a function of time to reward availability. Thus, the larger, later reward is preferred when reward receipt of both options is distal, but preference often reverses as the availability of the smaller, more immediate reward becomes imminent (Ainslie & Herrnstein, 1981).

Critically, alcohol use is characterized by the almost immediate euphoric effects of ingestion, whereas many of the consequences are delayed in nature. Indeed, individuals vary in the rate at which they devalue delayed rewards—i.e., some have briefer time horizons for behavioral allocation or steeper discounting rates than others. Researchers developed hypothetical delayed discounting tasks to assess rates of discounting in humans (Kirby et al., 1999). In a typical discounting task, participants choose between a series of smaller, shorter rewards and larger, later rewards. The resulting data can be fitted in Mazur's (1987) hyperbolic decay function to solve for \( k \), which represents the discounting rate for each individual. Higher \( k \) values indicate steeper delay discounting. Across a range of populations, higher delay discounting is associated with riskier engagement with a variety of substances (Amlung et al.,
Reinforcer Pathology

From this perspective, alcohol use is viewed as a reinforcer pathology (Bickel et al., 2014) that involves persistent preference for alcohol rewards providing 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. Thus, drinking with friends at a party provides immediate reward but may be associated with delayed costs (e.g., hangover, missing school or work), whereas staying at home and studying for a test the next day has immediate costs (i.e., missing the party), but higher delayed rewards (e.g., performing well on the test, long-term academic success). In most natural environments, alcohol and drugs are readily available and can be obtained and ingested with only modest delays, whereas access to rewards in important life-health domains are often delayed, uncertain, and require a temporally extended pattern of behavior comprised of many discrete choices that form a highly valued reward “bundle” that yields benefits over extended intervals (Vuchinich, 1995). These rewarding patterns of substance-free behavior serve to increase the opportunity cost of drinking or drug use, thereby constraining or reducing use.

Behavioral Economics and Drinking among Emerging Adults

Behavioral economics provides a hypothesis explaining persistent heavy drinking among emerging adults. Although drinking may result in harmful acute and chronic consequences, emerging adults continue to drink because, for many, the short-term benefits (social facilitation, fun, alleviation of boredom) outweigh the short-term costs (Aston et al., 2021; Lee et al., 2011). Although developmental theories have largely considered risky behaviors (e.g., heavy drinking)
to be psychopathological, and thus irrational or unwarranted, an evolutionary perspective highlights the fitness costs and benefits associated with risky behaviors, namely, as a means to achieve status (Ellis et al., 2012). Indeed, sociality (Alexander, 1974) and impulsivity (Stevens & Stephens, 2010) have developed as primary characteristics in human evolution as they increase the likelihood of survival. This is particularly true during the developmental span from adolescence through emerging adulthood, an exigent period for establishing social status and reproductive trajectories (Ellis et al., 2012), which might at times be facilitated by some degree of novelty seeking and related traits including impulsivity.

From this perspective, social connection is a robust natural reward, and any behavior that increases social connection will be more likely to be reinforced. Indeed, some research suggests that acute alcohol intoxication can actually increase social bonding. Sayette et al. (2012) randomized young adults into unacquainted triads across three drink conditions: alcohol, placebo, and juice. Facial expressions and speech were coded, and participants also self-reported levels of social bonding. Compared to participants in non-alcohol conditions, participants who drank alcohol engaged in more sequential conversation and smiling and self-reported higher levels of social bonding. Perhaps for this reason, alcohol has been of cultural and societal importance for virtually every civilization since its discovery. Anthropologists have observed the role of alcohol in facilitating group cohesion in social gatherings and rituals across cultures (MacAndrew & Edgerton, 1969). Some research also suggests that drinkers expect alcohol to enhance social interactions (Brown et al., 1980), and research suggests that drinking does confer social benefits (Rosenquist et al., 2010). Further, those who perceive higher alcohol consumption among their peers are also more likely to consume alcohol at higher levels (Neighbors et al., 2008).
These findings suggest that peer influences and social connection can increase the value of alcohol, shifting the cost benefit analysis such that drinking becomes more likely. Acuff et al. (2020) explored this directly by examining the relationship between alcohol demand and social network drinking in a cross-sectional sample of emerging adults. Each participant reported past year typical drinking and binge drinking for their four closest relationships, excluding parents. Alcohol demand was monotonically greater for each additional person in the social network reporting binge drinking and explained the variance in the relationship between the density of alcohol in the social network and the participant’s own alcohol use. Another study extended these findings by examining alcohol demand under two different hypothetical conditions: drinking with two friends or alone (Acuff, Soltis, et al., 2020). Social alcohol demand was significantly higher than solitary demand across all indices. Specifically, the mean intensity for solitary demand was below the binge drinking threshold; however, the mean intensity value jumped above the binge threshold when friends were included, suggesting that friends may present unique risk for increased risk of binge drinking on any given occasion.

**Neurophysiology and Behavioral Economics.** A majority of the research in behavioral economics has used self-report and behavioral methodologies to illuminate the relationship between the context and behavior. Although these findings are robust and show clinical and predictive utility, it is unclear whether these indices are consistent with underlying biomarkers of reward. Failure to connect these forms of measurement with biological risk variables inherently creates barriers to understanding connections between behavioral and biological risk pathways and in optimal prediction of risk. Indeed, even B. F. Skinner, who was often accused of being hostile to research at units of analysis other than behavioral, emphasized the importance of using behavioral principles to inform physiological research, suggesting that behaviors are
manifestations of internal physiological processes and therefore must be connected (Skinner, 1974). To this point, little is known about the correspondence between these self-report indices and neural indices of reward reactivity. These gaps in knowledge represent critical barriers to progress in understanding harmful drinking in emerging adults. Confirmation of similar relations across different operational definitions of reward and reinforcement is critical to establishing construct validity (Campbell & Fiske, 1959) and can also advance assessment, intervention and treatment of harmful alcohol use among emerging adults.

Research using neuroimaging and genetic methods recently have begun to identify potential biological correlates of behavioral economic variables in a developing field known as neuroeconomics (Amlung et al., 2014; MacKillop, 2016; MacKillop et al., 2014; Owens et al., 2019). Much of the work in this area has utilized functional magnetic resonance imaging (fMRI) to study delay discounting among individuals with an alcohol use disorder (Boettiger et al., 2007; McClure et al., 2004). Results generally suggest that differences in behavioral indices of executive functioning and delay discounting are related to greater frontoparietal brain activity among individuals with AUD compared to controls (MacKillop, 2016), findings that mirror results found among individuals exhibiting methamphetamine and tobacco use disorders (Clewett et al., 2014; Monterosso et al., 2007). Other research highlights the role of the anterior insula (Claus et al., 2011; Clewett et al., 2014), and of a relation between steeper discounting and generally greater functional connectivity between the anterior insula and left fronto-parietal network (Clewett et al., 2014). Although such research sheds light on differences in neural response that may be related to alcohol-related decision-making processes, fMRI studies suffer from a number of limitations with respect to understanding biologically based risk processes underlying behavioral economic indicators. First, fMRI studies are expensive and generally rely
on small sample sizes. Second, the hemodynamic response measured with fMRI is relatively slow (a delay of 4-6 sec following the onset of relevant stimuli) and does not represent a direct reflection of neural activity but rather a proxy of such activity.

One alternative is electroencephalography (EEG). Measurement of EEG is far less expensive than fMRI, making the use of relatively large samples more practical and adding the capacity to detect smaller effect sizes. Further, event-related brain potentials (ERPs), derived from EEG, are a direct measure of the electrical activity generated by the firing of cortical neurons, and they provide a continuous measure of neurocognitive processes as they unfold in real time (Luck, 2005). Thus, ERPs have the potential to provide an efficient and temporally precise approach for identifying biomarkers of relevant behavioral economic indicators of AUD risk, such as diminished alcohol-free and delayed reward responsiveness. Indeed, robust ERP indicators of the relative incentive value of drug-related rewards, and of sensitivity to reward-related feedback more generally, have been identified and validated in other contexts (Bartholow et al., 2010; Littel et al., 2012; Namkoong et al., 2004; Proudfit, 2015). The proposed research would be the first to leverage the combined utility of a behavioral economic approach with validated psychophysiological assessment of neurobiological risk variables to examine the predictive utility of alcohol-related reward processing in emerging adult problem drinkers. Two event-related potentials in particular seem promising as biomarkers of behavioral economic phenomena: the P300 (P3) and the Reward Positivity (RewP).

**P3.** The incentive sensitization theory of addiction (Robinson & Berridge, 1993, 2003) posits that repeated pairing of drug-taking with reward leads to the development of conditioned associations between the experience of reward and the presence of drug-related cues. Although the incentive salience of drug-related cues most often has been measured with behavioral
indicators in preclinical animal models (Berridge & Robinson, 2016; Robinson & Berridge, 1993), in the human psychophysiology laboratory the amplitude of the P3 can be used for this purpose. The P3 is typically elicited with an oddball paradigm in which frequent non-target stimuli are presented one after another with less frequent target stimuli (i.e., the oddball) interspersed (Squires et al., 1975). The P3 is the positive amplitude that occurs, on average, 300 ms post-stimuli presentation, at least in auditory oddball tasks, which predominated the early oddball literature (Squires et al., 1975). The P3 elicited through visual oddball tasks, which have become increasingly common, more often occur 600-700 ms post-stimuli onset. For a visual representation of the oddball task and the P3, see Figure 1.

P3 amplitude is thought to, among other things, reflect the incentive value of eliciting stimuli (Begleiter et al., 1983; Franken et al., 2011; Nieuwenhuis, Aston-Jones, et al., 2005; Pfabigan et al., 2014), and specifically has been used in numerous studies to assess the incentive salience of alcohol-related cues as a neurobiological risk factor for harmful alcohol use (Bartholow et al., 2007, 2010, 2018; Namkoong et al., 2004). In one study (Namkoong et al., 2004), alcohol and neutral images were shown to patients who met DSM IV criteria for alcohol dependence (American Psychiatric Association, 1994) and to controls who did not meet criteria for alcohol dependence and who did not drink more than heavy drinking limits set by the NIAAA (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015). The results suggested that, for patients meeting criteria for alcohol dependence, P3 amplitudes at the central and parietal scalp locations were significantly larger for alcohol images compared to the neutral images, whereas these differences were not significant among controls. Enhanced P3 reactivity to alcohol cues compared to neutral images has also been found to be associated with alcohol consumption and heavy drinking (Littel et al., 2012). Similar findings
have been found among social drinkers (Herrmann et al., 2001) albeit at smaller magnitudes (Herrmann et al., 2001), and among emerging adult heavy drinkers (Bartholow et al., 2007; Geraldine Petit et al., 2013; Géraldine Petit et al., 2012, 2015). Smaller effect sizes in these populations may be moderated by individual risk factors such as alcohol sensitivity (Bartholow et al., 2007). In addition, harmful alcohol use is associated with reduced P3 reactivity to neutral, nonalcohol-related stimuli (Bartholow et al., 2007, 2010). These neurophysiological indicators of alcohol incentive salience may reflect the value of alcohol and could serve as biomarkers of behavioral economic demand.

Behavioral economic theory underscores the importance of alcohol-free, nonappetitive social activities as an alternative to alcohol-related reward. This is especially critical given that most drinking among emerging adults occurs in social settings (Murphy et al., 2006). However, studies examining neural reactivity to alcohol cues often compare P3 amplitudes from alcohol images to neutral images. It is important to understand P3 reactivity to alcohol cues relative to the P3 response to alcohol-free reward image cues, such as social connection. A residualized change index accounting for the relative P3 amplitude to alcohol cues compared to alcohol-free rewarding images may serve as a micro-level electrophysiological biomarker of the behavioral economic concept of alternative reinforcement.

**Reward Positivity.** Research examining sensitivity to reward has established the validity of another neurophysiological marker, the reward positivity (RewP), as a useful tool for identifying aberrant reward processing (Proudfit, 2015). The RewP is often elicited with a “Doors Task” in which participants must choose between two virtual doors and subsequently receive either positive or negative feedback regarding door selection. The RewP is the positive amplitude
occurring approximately 150-250 ms following feedback onset. A visual representation of the Doors task and the RewP can be found in Figure 2.

The RewP has previously been called the feedback-related negatively due to a characteristic negative deflection following loss feedback in gambling tasks. More recently, researchers have found this deflection to be a default response even in neutral feedback, with the absence of the deflection indicative of a response to positive reward feedback (Holroyd et al., 2006; Nieuwenhuis, Slagter, et al., 2005). A blunted RewP to positive feedback in such tasks has been associated with both depression and harmful alcohol use, possibly reflecting anhedonic responses to task outcomes (Kamarajan et al., 2010). Of particular importance, behavioral economic theory posits that heavy drinkers are biased toward preferring immediate, smaller rewards over delayed, larger rewards (i.e., delay discounting; Bickel et al., 2014; MacKillop, 2016). Recent research suggests that the RewP is sensitive to the temporal parameters of reward, being generally smaller for delayed compared to immediate rewards (Bismark et al., 2013; Huang et al., 2017; Weinberg et al., 2012). In one study, researchers asked both adolescents and adults to complete two versions of the doors task: one in which the gains and losses represented money they would be receiving immediately after the task, and one in which the gains and losses represented money they would receive at a later time (Huang et al., 2017). They also compared the findings to an index of delay discounting. Adolescents demonstrated steeper delay discounting compared to adults. Both adolescents and adults had greater RewP responses to immediate rewards compared to delayed rewards; however, the difference in RewP reactivity was greater among adolescents than adults, which is consistent with delay discounting research (Green et al., 1999). Finally, the magnitude of the RewP difference for immediate vs. delayed rewards was associated with behavioral rates of delay discounting (Huang et al., 2017). These results suggest that RewP may
be a biomarker for delay discounting processes. However, these associations have not been examined among emerging adults or heavy drinkers, nor has the magnitude of the RewP elicited by immediate vs. delayed rewards been associated with drinking outcomes.

**Current Study**

Behavioral economic research has demonstrated that self-reports of alcohol demand, proportionate alcohol-related reward, and delayed reward discounting show robust associations with harmful alcohol use. However, little is known about the correspondence between these self-report indices and neural indices of reward reactivity. Further, no studies have examined neural reactivity to natural, social, and delayed rewards among heavy-drinking emerging adults. These gaps in knowledge represent critical barriers to progress in understanding harmful drinking in emerging adults. To address these gaps, I propose to augment data collection in an ongoing longitudinal study of emerging adult drinkers by adding measurement of noninvasive neural indicators of reward processing to the existing behavioral economic assessment battery. Specifically, we propose to measure two ERP components that are robustly associated with reward processing: (1) P3, which reflects the incentive salience of reward-related stimuli (in this case, alcohol and nonalcohol cues), and (2) RewP, which reflects sensitivity to reward (in this case, immediate vs. delayed rewards). We will use two reliable and well-validated ERP paradigms to measure these indicators at in a subsample of participants from the larger ongoing study. I propose to address the following aims:

**Aim 1:** Establish neural responses for (1) alcohol and non-alcohol stimuli when paired with social stimuli, and (2) immediate and delayed rewards among heavy drinking young adults, and to examine between-subject relations between these variables and alcohol use.

**Aim 2:** Examine the relations between ERPs and behavioral economic variables.
To address Aim 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, followed by social nonalcohol, nonsocial alcohol, nonsocial nonalcohol, and neutral cues. However, this will depend partially upon the degree of alcohol consumption. We will also examine differences in RewP reactivity to gains in the doors task between an immediate and a delayed doors task. We predict that RewP reactivity for immediate rewards will be greater than RewP reactivity for delayed rewards, and that this difference will be greater among those with greater levels of alcohol use compared to those with lower levels of alcohol use.

To address Aim 2, we will explore cross-sectional relationships between neural reactivity and behavioral economic indices. We predict: (1) greater alcohol demand will be associated with greater P3 reactivity to alcohol-related cues; (2) proportionate alcohol-related reinforcement will be associated with greater P3 reactivity to alcohol-related cues, relative to alcohol-free reward cues; (3) greater behavioral discounting of delayed rewards will be associated with reduced RewP reactivity to delayed reward feedback, relative to immediate reward feedback.

Examining relations between behavioral and neurophysiological indices of incentive value, proportionate alcohol-related reward, and delay discounting 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 (Gray & Mackillop, 2014; MacKillop et al., 2015; Sanchez-Roige et al., 2017). If the hypotheses advanced for this work are supported, the findings would add substantially to the understanding of biobehavioral determinants of harmful alcohol use in emerging adults, as well as the more basic brain-behavior relationships underlying alcohol motivation. Further, the results
would make a significant and sustained impact by elucidating clinically relevant biomarkers for behavioral economic indicators of AUD risk, and by bridging gaps between behavioral economic theory and other theoretical frameworks for understanding substance abuse (e.g., incentive sensitization theory).

**Method**

**Participants**

Participants were recruited to complete two EEG sessions separated by four months from a sample of 602 emerging adults enrolled in a longitudinal study of trajectories of alcohol use among emerging adults. Parent trial eligibility at baseline included: (1) verification of age between 21.5 and 24.99 years; (2) self-reported consumption of at least 3 or 4 alcoholic drinks for women or men, respectively, on at least two occasions in the past month; (3) no past alcohol use treatment; (4) no current or past psychosis; and (5) adequate literacy, assessed through a brief screening questionnaire. All participants enrolled for the current study reported a heavy drinking episode on at least one occasion in the past month. Those with a history of seizures were excluded (assessed in the brief screening questionnaire). Due to in-person restrictions imposed by the COVID-19 pandemic, data collection was pushed back one year, during which most of the sample from the parent study completed the longitudinal portion of the study. Thus, in total, 34 participants completed an EEG session from the parent sample. Due to personnel error, eleven participants did not complete a corresponding self-report assessment during the baseline session and were therefore excluded from the study. An additional seven did not complete the second session, leaving only 15 participants with longitudinal data.

Demographic characteristics for 23 participants at the baseline EEG session can be found in Table 1. We examined differences in age, sex assigned at birth, race, education, and typical
drinks per week at the baseline of the parent study between those whose data was included in analyses and those whose data was excluded. We used baseline data because data was not available at the first BETA-E timepoint for many who were excluded. The results suggested no difference between those included and those excluded based on age (Included M [SD] = 23.00 [1.04], Excluded M [SD] = 22.27 [1.10], t [32] = -1.87, p = .07), typical drinks per week (Included M [SD] = 16.48 [12.09], Excluded M [SD] = 13.18 [6.11], t [32] = .85, p = .40), race (Included: 52.2% White, 39.1% Black, 8.7% Multiracial; Excluded: 45.5% White, 45.5% Black, 9.1% Other; χ2 [3] = 2.81, p = .42), sex assigned at birth (Included: 65.2% Male, 34.8% Female; Excluded: 54.5% Male, 45.4% Female; χ2 [1] = .12, p = .73), and education level (Included: 39.1% with less than a bachelor’s level education; Excluded: 36.4% with less than a bachelor’s level education; χ2 [4] = 2.84, p = .59).

**Procedures**

For the parent study, participants complete a survey every 4 months. Since the start of COVID, all surveys have been completed remotely. For the current study, we recruited participants to complete two EEG sessions, coinciding with two of these remote survey sessions. Two weeks before a parent-study follow-up appointment, study personnel contacted participants and invited them to participate in the proposed EEG assessment. Interested participants scheduled an appointment within 1 week of completion of their remote survey.

Because data collection occurred during COVID, study personnel took precautions to mitigate the risk of viral transmission. When EEG participants arrived for EEG sessions, study personnel met the participants outside and checked the participants temperature. The participant also completed a COVID checklist to ensure they have not had any recent symptoms. Both parties wore masks for the entirety of the session. After describing the study and receiving
informed consent, study personnel applied electrodes to the participant’s skull. Next, participants sat approximately one meter away from a computer monitor in a private room and engage in an oddball task and two versions of the doors task. All tasks were counterbalanced to offset order effects and the effects of fatigue on any single task. The supplemental EEG sessions took approximately 2 hours. For the session, participant were compensated $65. Self-report data was pulled from corresponding surveys from the parent study for use in analyses with electrophysiological data. All procedures were approved by the University of Memphis Institutional Review Board (project #4320). All data collection took place during COVID. The University of Memphis Institutional Review Board also approved all COVID-related modifications, which included temperature checks, symptom checklists before entering the building, and required masks for the duration of all sessions. These modifications were strictly enforced in order to protect the health and safety of both research personnel and participants.

Self-report Measures

Alcohol Purchase Task. Alcohol demand was measured with a hypothetical alcohol purchase task (Murphy & MacKillop, 2006). In this version of the APT, individuals are presented with the following instructions, which are consistent with other studies examining trait-level demand (Kaplan et al., 2018):

Please respond to these questions as if you were actually in this situation.

Imagine that you are in a TYPICAL SITUATION when you drink alcohol. Imagine where you typically drink, what you typically drink, and who you typically drink with, if anyone. The following questions ask how many drinks you would consume if they cost various amounts of money. The available drinks are standard size beer (12 oz.), wine (5 oz.), shots of liquor (1.5 oz.), or mixed drinks containing one shot
of liquor. Assume that you did not drink alcohol before you are making these
decisions and will not have the opportunity to drink elsewhere after making these
decisions. In addition, assume that you would consume every drink you request;
that is, you cannot stockpile drinks for a later date or bring drinks home with you.

Next, participants were asked to report 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 \( O_{\text{max}} \)
(maximum expenditure). We also derived elasticity (the rate of change in consumption as a
function of price) using the exponentiated equation (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 was 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). Data was calculated using the exponentiated equation, which
allows for the inclusion of zeros. Responding on hypothetical purchase tasks are correlated with
actual purchasing behavior (Amlung & MacKillop, 2015), and test-retest reliability for alcohol
purchase tasks are robust (Acuff & Murphy, 2017).

**Delay Discounting.** Delay discounting was measured with the 5-trial adjusting delay task
(Koffarnus & Bickel, 2014). Participants are presented with the following instructions:
“You will now answer five questions about whether you would prefer to receive a certain amount of money now or a different amount of money at a later time. Even though the choices are hypothetical and you will not receive any of the money from these options, we want you to try your best to choose the amount you would prefer if the money and delays were real.”

Next, participants make a choice between $500 now or $1000 in 3 weeks. Depending on the participant’s choice, the delay amount then adjusts up (delayed choice) or down (immediate choice) for the next choice. This continues for a total of five items. The participant’s choice for the final item is associated with a set $K$ value, with greater values representing greater rates of delay discounting.

**Alternative Reinforcement.** Alternative reinforcement was measured with the Activity Level Questionnaire (ALQ; Meshesha et al., 2020). The ALQ is a self-report measure of the relative reinforcement of substance-free vs. substance-related activities. On the ALQ, participants reported the frequency (0 – 0 times to 4 – More than once a day) and enjoyment (0 – Unpleasant or neutral to 4 - Extremely pleasant) of a series of 37 activities. They provide ratings for these activities both while under the influence of any substance(s) and while sober. A cross-product reflecting substance-related and substance-free reinforcement will be calculated by multiplying the frequency and enjoyment ratings for substance-related and substance-free activities. Next, a ratio (r-ratio) was calculated to index substance-related reinforcement relative to total reinforcement (substance-related reinforcement / [substance-free reinforcement + substance-related reinforcement]). Similar survey measures of reinforcement ratio have shown good reliability and validity among young adult drinkers (Hallgren et al., 2016).
Alcohol Consumption. Typical drinks per week was measured with the Daily Drinking Questionnaire (DDQ; Collins, Parks, & Marlatt, 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.

Event-related Potential Measurement

Participants sat one meter away from a 24-inch monitor and completed three, full screen tasks: one oddball task and two doors tasks.

Oddball Paradigm. Participants completed a visual “oddball” paradigm in which infrequent target stimuli were presented amid more frequent neutral stimuli. Participants encountered four different categories of infrequent target stimuli: social alcohol cues (people together with alcohol), social nonalcohol cues (e.g., people together without alcohol), nonsocial alcohol beverage cues (e.g., pictures of beer or wine), and nonsocial nonalcohol appetitive cues (e.g., food). The neutral stimuli are pictures of random objects, such as a basket or a bar of soap. The social alcohol cues depict people in groups of 2-3 drinking alcohol, taken from the Galician Beverage Picture Set (GBPS; Pronk et al., 2015), a set of color images validated for use in alcohol cue-reactivity research. The social nonalcohol cues depict groups of 2-3 people engaged in social interaction but without alcohol and are matched for numbers of people in the images with the social alcohol cues. Nonalcoholic beverage cues depict nonalcoholic beverages in isolation from any social context. Each trial consists of a visual fixation cross presented for 500 ms, followed by one of the five picture types presented centrally for 1200 ms. Trials were separated by an inter-trial interval varying randomly between 1000-2000 ms (500 ms increments). Participants’ task were to categorize each image as either alcohol-related or not alcohol-related using one of two buttons. These stimuli were presented in five-image sequences,
with the oddball always occurring in the fourth or fifth position. Images from each infrequent target category will be presented a total of 24 times each. Trials were equally divided into four blocks, and participants were given a brief break between blocks.

**Doors task.** Neural response to positive and negative feedback was measured with two versions of a doors task (Proudfit, 2015). In a typical doors task trial, the participant chooses either the left-hand or right-hand door by clicking the left or right arrow on a keyboard. Each trial has a 50% chance of eliciting gain or loss feedback. Following selection, a central fixation cross appears for 1000 ms, followed by visual feedback (green up arrow or red down arrow) regarding the outcome of the selection, presented for 2000 ms. After a variable inter-trial interval, the next trial commences. Gains and losses are worth 50 and 25 cents, respectively, in order to account for robust effects of loss aversion (Tversky & Kahneman, 1992). For our study, participants completed two versions of the doors task in counterbalanced order. One version presented immediate gains and losses. Prior to completing this version of the task, participants were informed that they will receive the money earned at the end of that day’s EEG session. The other version of the task presented delayed gains and losses. Prior to completing this second version, participants were told that they would receive the money earned in 4 months’ time, at the next follow-up. Completion of the tasks at the next follow-up will be associated with similar delays in payment.

**Electrophysiological Recording.**

The EEG was recorded continuously from 16 standard scalp locations using tin electrodes in an electrode cap (Electro-Cap International, Eaton, OH) using the standard 10-20 system (American Encephalographic Society, 1991). Figure 3 represents approximate electrode configuration on the scalp. Scalp electrodes were referenced on-line to the right mastoid and re-
referenced off-line to an average of the two mastoids. Electrodes were placed above and below the left eye to record vertical eye movements. Electrode impedances was kept below 10 KΩ. Data was collected at a sampling rate of 500. The EEG signal was amplified with a Biopac EEG100C unit at 10000 and filtered online using a 0.1 to 35 Hz band-pass. Offline, blinks were removed from the EEG using an independent components analysis procedure (Iriarte et al., 2003). All data for all trials and participants was visually represented and scanned for abnormalities. Any trials with artifacts, including but not necessarily limited to electrophysiological patterns resembling excessive movement, chewing, and foot tapping were removed. Finally, we created stimulus-locked epochs of 1,000 ms for each trial (including a 200-ms pre-stimulus baseline). Next, trial data at the millisecond level was aggregated by condition/stimuli within electrodes.

Previous work examining neural responses during visual alcohol oddball tasks has shown that the P3 is most pronounced 400 to 600 ms after stimulus presentation, primarily at parietal and occipital scalp locations (Bartholow et al., 2007; Martins et al., 2019). Thus, for the current study, the P3 amplitude was quantified as the voltage occurring during this epoch within electrodes in this region (P3, Pz, CPz, P4, POz). Electrophysiological reactivity within 400-600 ms was averaged across trials within each electrode. Following previous research (Holroyd et al., 2006; Levinson et al., 2017; Proudfit, 2015), the RewP was operationalized as the activity across fronto-central scalp locations (F3, Fz, F4, C3, Cz, and C4) occurring 150-250 ms following feedback onset. Similar to P3 data, RewP electrophysiological reactivity within 150-250 ms was averaged across trials within each electrode.

Data Analysis
First, outliers and data distributions were checked. For all data, outliers were defined as values greater than 3.29 standard deviations from the mean (Tabachnick & Fidell, 2013). Skewness and kurtosis values between -2 and 2 were considered to indicate a normal distribution (Trochim & Donnelly, 2006). Next, we examined descriptive data and correlations among self-report data. This included one-way ANOVAs testing differences in P3 and RewP amplitudes across electrode sites and trial conditions. Due to the nested nature of P3 and RewP reactivity, we did not examine zero-order correlations with electrophysiological data. The hypothesis that social cues will enhance the motivational salience of alcohol cues was tested using a 2 (alcohol cue: nonalcohol = 0, alcohol = 1) x 2 (social cue: nonsocial = 0, social = 1) factorial multilevel model with random intercepts specified for participants and electrodes within participants. Next, we included typical drinks per week as a moderator.\(^1\) In other words, typical drinks per week was included as an individual predictor, along with all possible interactions with alcohol cues and social cues. The hypothesis that the RewP for immediate gains are greater than those from delayed gains was tested with a multilevel model, with random intercepts specified for participants and electrodes within participants. Next, we included typical drinks per week as a moderator in a separate model, following the same method as used for moderation analysis above.

Each of the primary hypotheses under Aim 2 was tested using separate models in which the relevant ERP indicator was regressed onto the relevant behavioral indicator, in the presence of the control variables. The first hypothesis was that greater demand would be associated with

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\(^1\) In the proposal, frequency of drinking in solitary conditions (i.e., typical drinking context) was also proposed as a moderator. However, these items were only administered at every other timepoint in the parent study. Given that our data were not collected at a single assessment time, but instead participants could enroll at any assessment, roughly half of participants did not have these data and thus this variable was excluded from analyses.
greater P3 reactivity to alcohol-related cues relative to non-alcohol cues. The second hypothesis was that greater proportionate alcohol-related reinforcement would be positively associated with P3 reactivity to social alcohol cues, relative to both social nonalcohol cues and nonsocial, nonalcoholic beverage cues. The third hypothesis was that behavioral discounting of delayed (relative to immediate) rewards would be associated with reduced RewP reactivity to delayed relative to immediate reward feedback.²

Significant interactions were probed further by visually exploring differences in mean levels of electrophysiological reactivity split by the different moderators. Continuous variables were mean split for presentation purposes. Detectable statistical power was explored using the freely available webtool “Power tools for multilevel studies” (Kleiman, 2021). Assuming five electrodes per participant (the conservative estimate given that the P3 only has five electrodes), our study has .10 power to detect a small effect, .30 power to detect a medium effect, and .70 power to detect a large effect. In other words, our sample is not adequately powered to detect small and medium effect sizes, and thus these results should be interpreted with caution. There is no agreed upon method for calculating effect sizes for multilevel data. Thus, I reported unstandardized effects.

Results

Data Distribution, Descriptives, and Zero-Order Correlations among Self-Report Data

Outliers were identified and winsorized to one unit above the next highest nonoutlying value (Tabachnick & Fidell, 2013). There were outlier values for typical drinks per week, 

² This dissertation proposal also included (1) a structural equation model known as the construct network approach testing the joint utility of behavioral and electrophysiological indices of reward functioning as predictors of drinking behavior, and (2) longitudinal analyses predicting changes in EEG and behavioral data as prospective predictors of alcohol consumption and problems. Due to the small sample size, our analyses are underpowered to such a degree that these models will not converge. Therefore we were unable to complete longitudinal analyses or structural equation modeling.
delayed reward discounting, and $O_{\text{max}}$. Outliers for electrophysiological variables were identified and winsorized at the electrode level. All variables had skewness and kurtosis values within -2 and 2, indicating a normal distribution (Trochim & Donnelly, 2006). Thus, no data transformations were made.

Sample characteristics and drinking/behavioral economic means and standard deviations can be found in Table 1. Approximately 65% of the sample identified as male; just over half of the sample identified as White, while almost 40% identified as Black and 8.7% identified as multiracial. No other racial group was represented. Only 21.7% of the sample was a current student. The sample reported consuming an average of almost 11 drinks during a typical week in the past month. The mean values for delayed reward discounting and elasticity were comparable to our previous work reporting these variables in similar samples (Acuff et al., 2017, 2018, 2021; Acuff, MacKillop, et al., 2020; Acuff, Soltis, et al., 2020). Average demand elasticity was also within normal limits. Both delayed discounting and elasticity values are derived mathematical functions without real world behavior analogs; further, elasticity and discounting rates have not been formally normed. However, demand intensity, $O_{\text{max}}$, and $r$-ratio correspond directly to real world behavior and thus can be more formally interpreted. Average sample demand intensity, which is thought to represent raw “amplitude”, or motivation to consume alcohol when there are no constraints (Skidmore et al., 2014), was above the NIAAA standards demarcating a heavy drinking episode for both men and women, highlighting the heavy drinking nature of the sample. This suggests that, under conditions of minimal or no costs (at least monetary), the sample would, on average, consume enough alcohol to meet criteria for a heavy drinking episode. Participants were willing to spend, on average, a maximum of $26.70 in the alcohol purchase task across all prices. Finally, just over one-fourth of total reinforcement was obtained while
using alcohol or other substances, on average. This value is slightly lower than previous studies examining proportionate alcohol-related reinforcement among college students (Murphy et al., 2019). Drinking decreases over the twenties, and the current sample is older than typical college samples, which may explain this finding.

Least square means for P3 by scalp site and cue condition are reported in Table 2. One-way ANOVAs were used to explore differences in site amplitude within each condition, and across each condition within each electrode site. A series of one-way ANOVAs revealed a significant difference in amplitude across electrode sites within each of the five conditions. Table 2 reports results of the one-way ANOVAs in the bottom two rows. Post hoc Tukey’s tests was used to probe which specific sites differed within each condition separately. Across all conditions, CPz tended to be significantly smaller than at least one of the other sites, with all other sites demonstrating no significant differences. In the neutral condition, the amplitude at the CPz site was significantly smaller compared to all other amplitudes (all ps < .031). CPz was smaller than only the P4 site in the nonsocial alcohol (p = .01) and the nonsocial nonalcohol (p = .003) conditions. The amplitude at the CPz electrode site was also smaller than the amplitude at the P4 electrode site in the social alcohol (p = .01) and social nonalcohol conditions (p = .005); however, there were also nonsignificant trend level differences between CPz and both Pz and POz for both the social alcohol (Pz: p = .051, POz: p =.051) and social nonalcohol conditions (Pz: p = .057, POz: p =.057) and a nonsignificant trend level difference between CPz and the P3 electrode site in the social alcohol condition (p = .077).

A series of one-way ANOVAs also revealed a significant difference in amplitude across conditions within the P4 electrode site, and nonsignificant trend level differences in amplitude across conditions with the P3, Pz, and POz electrode sites. The result of the one-way ANOVA
exploring differences in amplitude across conditions within the CPz electrode site was
nenonsignificant. The results of these one-way ANOVAs are reported in the right two columns of
Table 2. Within significant or trend-level one-way ANOVAs, post hoc Tukey’s tests were used
to probe which specific conditions differed within each electrode site. At the P3 electrode site,
there was a nonsignificant trend level difference between amplitudes elicited by the neutral
condition and amplitudes elicited by the social alcohol condition (p = .051); there were no other
differences (all ps > .18). At the P4 electrode site, the neutral condition elicited significantly
smaller amplitudes compared to the nonsocial alcohol (p = .02), nonsocial nonalcohol (p = .049),
social alcohol (p = .016), and the social nonalcohol (p = .005) conditions. At the Pz and POz
electrode sites, there were nonsignificant trend level differences between the neutral condition
and the social alcohol (p = .08 for both electrode sites) and social nonalcohol (p = .07 for both
electrode sites) conditions.

Least square means for RewP by scalp site and condition are reported in Table 3. One-
way ANOVAs were used to explore differences in site amplitude within each condition, and
across each condition within each electrode site. The one-way ANOVAs revealed no significant
differences in amplitudes across any of the scalp sites within conditions, or across any conditions
within scalp sites.

Intensity was significantly and negatively correlated with elasticity (r = -.53; p = .01) and
demonstrated a nonsignificant trend level association with O_{max} (r = .38; p = .07). Intensity
exhibited a nonsignificant, medium effect sized relationship with delayed reward discounting (r
= .35; p = .11) and a nonsignificant relationship with r-ratio (r = .00; p = .99) and typical drinks
per week (r = .02; p = .94). O_{max} was also significantly associated with elasticity (r = -.60 p =
.003). However, correlations with r-ratio (r = -.14; p = .52), delayed reward discounting (r = .26;
p = .23), and typical drinks per week (r = -.14; p = .53). Elasticity was not associated with r-ratio (r = .08; p = .74). delayed reward discounting (r = -.19; p = .39), or typical drinks per week (r = .11; p = .62). R-ratio was significantly and positively correlated with delayed reward discounting (r = .49; p = .02) and typical drinks per week (r = .65; p < .001). Finally, there was not a significant correlation between delayed reward discounting and typical drinks per week (r = .17; p = .45).

Effects of Alcohol and Social Cues on P3, Moderation by Typical Drinks per Week and Behavioral economic Variables

Millisecond level data split by event condition for the oddball task can be found in Figure 3. All results modeling P3 as an outcome can be found in Table 4, 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, or student status were associated with P3 amplitude. All covariates were included in all other models, but the statistics are not reported.

In Model 1, there was a nonsignificant trend-level effect of social cues on P3, such that social images were associated with a greater P3 relative to non-social images. Neither alcohol nor the interaction between alcohol and social cues were associated with the P3.

In Model 2, there was no significant effect of typical drinks per week on P3, there was a nonsignificant trend-level effect of the interaction between typical drinks per week and social cues on P3. The interaction is illustrated in Figure 5. Probing the interaction revealed that those with low levels of typical drinks per week had comparable P3 magnitudes across social and non-social images, whereas those with high levels of typical drinks per week reported greater P3 cues.
for social images compared to non-social images. Typical drinks per week did not interact with alcohol or alcohol x social cues.

In Model 3, r-ratio was not associated with P3, nor did it interaction with social cues, alcohol cues, or social x alcohol cues to predict P3.

In Model 4, Intensity was not associated with P3. There was, however, a significant interaction between intensity and alcohol cues. The interaction is illustrated in Figure 6. Probing the interaction revealed that, among those with low levels of intensity, P3 magnitudes for alcohol and non-alcohol images were comparable, whereas P3 magnitudes for non-alcohol images were slightly smaller than P3 magnitudes for alcohol images for those with high levels of intensity. There were no other significant interactions between intensity and other variables in the model.

O_max results were similar to Intensity. In Model 5, O_max was not significantly associated with P3. There was, however, a significant interaction between O_max and alcohol cues. The interaction is illustrated in Figure 7. Probing the interaction revealed that, among those with low levels of O_max, P3 magnitudes for alcohol and non-alcohol images were comparable, whereas P3 magnitudes for non-alcohol images were slightly smaller than P3 magnitudes for alcohol images among those with high levels of O_max. There were no other significant interactions between O_max and other variables in the model.

The results for elasticity were similar to O_max. In Model 6, elasticity was not significantly associated with P3. There was, however, a significant interaction between elasticity and alcohol cues. The interaction is illustrated in Figure 8. Probing the interaction revealed that, among those with more elastic demand, P3 magnitudes for alcohol and non-alcohol images were comparable, whereas P3 magnitudes for non-alcohol images were slightly smaller than P3 magnitudes for
alcohol images among those with inelastic demand. There were no other significant interactions between elasticity and other variables in the model.

**Effects of Feedback and Delay to Receipt on RewP**

Millisecound level data demonstrating magnitude of RewP for losses and gains in both delayed and immediate conditions can be found in Figure 9. All results modeling RewP as an outcome can be found in Table 5, 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, or student status were associated with P3 amplitude. All covariates were included in all other models, but the covariate estimates are only reported for the baseline model exploring the effects of time to reward receipt and feedback on RewP magnitude.

In Model 1, neither time to receipt or feedback, nor the interaction between the time to reward receipt and feedback, were associated with the RewP. Further, no covariate was associated with the magnitude of RewP.

In Model 2, there was no significant main effects or interactions.

In Model 3, there was a significant interaction between person-level delayed reward discounting and the time to reward receipt. This interaction is displayed in Figure 10. Probing the interaction revealed that low discounters had greater magnitude RewP overall, and comparable RewP across the delayed and immediate reward conditions. However, high discounters demonstrated lower RewP overall, and a difference between RewP magnitudes for immediate and delayed rewards, such that delayed reward magnitudes were smaller.

There was also a three-way interaction between delayed reward discounting, time to reward receipt, and feedback in Model 3. This interaction is displayed in Figure 11. Probing the
interaction revealed that among low discounters, RewP magnitudes for the full factorial time to receipt x feedback interaction were relatively comparable, with perhaps slightly larger RewP magnitudes for trials with positive feedback. Among high discounters, trials with negative feedback resulted in comparable (albeit, smaller compared to low discounter) RewP magnitudes for both delayed and immediate conditions, but greater RewP reactivity to positive feedback in the immediate condition relative to the delayed condition.

**Discussion**

No study has explored the correspondence between electrophysiological reactivity to alcohol-related cues and behavioral economic measures of motivation to consume alcohol. The oddball P3 measures allocation of attentional resources and may be a marker of incentive sensitization (Robinson & Berridge, 2008), whereas alcohol demand measures motivation to consume alcohol across different constraints and attempts to capture. Research has demonstrated that individual differences in both measures predict alcohol use behavior (Acuff et al., 2018; Bartholow et al., 2007; MacKillop, Miranda Jr, et al., 2010; Martins et al., 2019). Further, despite the fact that most alcohol use occurs in social settings (Gonzalez et al., 2009), and alcohol facilitates deeper social connection (Sayette et al., 2012), no study has explored social influences on electrophysiological reactivity to alcohol cues. Likewise, no study has explored the correspondence between electrophysiological reactivity to immediate, relative to delayed, rewards and behavioral economic discounting of delayed rewards among heavy drinking young adults. Measures of delayed reward discounting has been used widely to quantify the influence of time on the value of a reward, whereas the RewP is thought to represent a biological marker of the value of monetary gains and losses.
Finding a relationship between these behavioral economic and electrophysiological variables may suggest a physiological basis for these reward constructs that can help guide interventions targeting multiple levels of analysis. More generally, exploring the correspondence between such variables is essential to establishing construct validity for relative alcohol value and delayed reward discounting and enhances confidence that we are accurately measuring and representing important constructs of interest that correspond to real world behavior and predict alcohol use over time (Campbell & Fiske, 1959). Exploring the effects of choice contexts (such as differences in P3 amplitude based on social or nonsocial stimuli, or differences in RewP based on immediate or delayed conditions) may highlight the flexible nature of brain response to contextual variables, which research suggests are of broad importance to understanding alcohol-related behavior as a whole.

Effects of Social Stimuli on the Alcohol P3: Relations with Drinking and Behavioral Economic Variables

The current study is the first to explore electrophysiological reactivity to alcohol cues in social relative to non-social conditions in young adults who report recent heavy drinking. The oddball used for the current study explored four target conditions interspersed with neutral stimuli: social alcohol, nonsocial alcohol, social nonalcohol, and nonsocial nonalcohol. We predicted that social alcohol reward cues would demonstrate the greatest P3 reactivity, followed by social nonalcohol, nonsocial alcohol, nonsocial nonalcohol, and neutral cues. All active cue conditions elicited a greater P3 compared to neutral images, lending evidence to the idea that all target conditions contain important motivational value that evokes greater attentional capacity compared to neutral stimuli. The greatest reactivity was for social alcohol images followed by alcohol alone; however, multilevel model results suggested no effect of social cues or alcohol
cues on differences in P3. Both social connection and food rewards (i.e., the non-social, non-alcohol condition) are robust, evolutionarily engrained reinforcers that should theoretically evoke greater motivational attention compared to alcohol. Thus, comparable P3 reactivity across conditions demonstrates the potency of alcohol as a reinforcer. However, while there is some observable evidence for a summative effect of social and alcohol cues on P3 reactivity, a post hoc power curve examination revealed that our sample size was ill-powered to detect multilevel effects. Thus, a larger sample size may be needed to detect a statistically significant effect.

The finding that there was not a difference in P3 as a function of typical drinks per week diverges from previous research demonstrating generally blunted P3 reactivity among people at risk for alcohol use disorder. Most studies demonstrating this effect have compared children of parents with a history of harmful alcohol use with a control sample without such a history (Bartholow & Heinz, 2006; Begleiter et al., 1984). Interestingly, severity of harmful alcohol use as measured by typical drinks per week was not associated with greater P3 reactivity for alcohol cues relative to non-alcohol stimuli. This also runs contrary to other studies, which have often focused on categorical analysis of drinkers versus controls (Bartholow et al., 2007; Begleiter et al., 1984; Géraldine Petit et al., 2014). The level of drinking in the current sample was relatively mild in comparison to these other studies, which may explain these findings. It may also explain why high levels of typical drinks per week reported greater P3 cues for social images compared to non-social images. Emerging and young adulthood tends to be a critical point for social development (Ellis et al., 2012). Although we do not have the data to contextualize the typical drinking contexts for this sample (i.e., drinking with friends or drinking alone), drinking with others is common in this age demographic (Gonzalez et al., 2009) and represents an important way people connect with one another. Thus, this finding may reflect the importance of the
combination of social and direct pharmacological reinforcement as factors that motivate young adults to drink. However, the three-way interaction between typical drinks per week, alcohol cues, and social stimuli was not significant. It is important to point out that our study was underpowered to detect these effects and that a greater sample size is necessary to feel confidence about these results.

Our study found that those with high levels of alcohol demand had diminished P3 magnitudes for non-alcohol images relative to P3 magnitudes for alcohol images, whereas those with low demand had comparable P3 magnitudes across alcohol and non-alcohol stimuli. This was consistent across all three indices of alcohol demand included in the study. These results increase confidence in both constructs as indices of motivation and suggest that alcohol demand may be a marker of electrophysiological activity as indexed by the P3. Previous research has identified greater reactivity in the parietal cortex during decisions to drink in the context of an event-related fMRI alcohol demand paradigm (MacKillop et al., 2014). These results are consistent with our study, which calculated the P3 by aggregating amplitudes in and around the parietal-occipital sites. However, the MacKillop study also found greater activation in frontostriatal regions during decisions to drink that were more affected by the cost of alcohol, perhaps suggesting that decisions to drink may activate one brain circuit that encompasses different parts of the brain. Perhaps the parietal region contributes to some aspect of motivational decision making that is also captured with measures of alcohol demand.

In general, our study found P3 amplitudes that were approximately 10 times smaller than those found in other studies exploring the alcohol-P3 (Bartholow et al., 2007; Géraldine Petit et al., 2012, 2014). Our rate of amplification was much smaller compared to these other studies, which likely explains the difference. Although the mean P3 amplitudes are not comparable to
other studies, our results largely supported theory and suggested that the amplitudes were affected consistently across all trials and conditions, meaning our variance and covariances were not influenced and the results are still useful. Interestingly, one-way ANOVAs suggested that the P3 amplitude elicited by the stimuli in the current study may not be predominant at the CPz electrode site. P3 appears to become stronger as you move toward the back of the scalp (Bartholow et al., 2007). In our study, the CPz site was the only central site used and demonstrated the weakest signal. We decided to retain the electrode because electrode sites were determined a priori, but future research should consider exploring the implications of different quantifications of the P3 itself.

**Effects of Time to Reward Receipt on the RewP: Relations with Drinking and Behavioral Economic Variables**

In the current study, RewP was elicited by asking participants to choose one of two doors that would result in a gain while trying to avoid losses. The gains and losses were presented randomly. Participants completed two versions of the doors tasks: one in which they would be given the money immediately upon completion, and one in which they would receive the money four months later. We hypothesized that the RewP for delayed rewards would be reduced relative to that for immediate rewards. In order to check whether the task worked properly, we examined RewP for gains versus loses. Our results found that RewP reactivity was evident for gains, but not for losses. This is consistent with a long line of emerging research supporting the reframing of this electrophysiological index as “reward positivity” instead of feedback-related negativity (Meyer et al., 2017; Proudfit, 2015). However, there was no evidence that RewP was greater for immediate relative to delayed rewards, which suggests that our hypothesis was not supported. However, these findings appear to be consistent with previous research. The only other study to
explore the effects of delay to reward receipt on the RewP explored differences between adolescent and adult samples (Huang et al., 2017). The results found differences between delayed and immediate conditions among adolescents, but not among adults, highlighting the developmental nature of this phenomenon. The previous study did not report the age of the sample of adults, and it is therefore difficult to compare our findings with those findings. Even so, our sample was, on average, 26 years old, which may suggest that the population-level average effect dissipates by the middle to late 20s. However, I found that delayed reward discounting interacted with the time to reward condition, such that those who more steeply discount delayed rewards demonstrated reduced RewP magnitude for the delayed condition compared to the immediate condition, whereas those with shallow discounting if delayed rewards demonstrated comparable RewP magnitudes across conditions. This suggests that delayed reward discounting and the RewP are indicators of the same process. Delayed reward discounting, which is measured at the behavior level, and the RewP, which is measured at the brain level, are not isolated mechanisms operating independently at different levels of analysis, but in fact are likely tapping the same mechanism across increasingly broad units of analysis. Interventions attempting to extend temporal windows, whether psychotherapy, pharmacotherapy, or something else, may have an impact across these various domains and also may be used in tandem to increase the overall efficacy.

More generally, our results suggest that RewP may be sensitive to economic decision making. Previous research has also demonstrated the impact of probability and effort on value derivation (Botvinick et al., 2009; Green et al., 2014; Rachlin et al., 1991; Stuppy-Sullivan et al., 2020; Vanderveldt et al., 2015). Although time is perhaps the most studied and robust factor in value allocation, future research may confirm RewP as a sensitive index of value allocation by
exploring these other variables indicated in economic decision-making models. Further, these measures are based in the assumption that decisions are cost benefit analyses; future studies should consider exploring the full factorial by comparing delayed loss discounting with the RewP magnitude across time to reward and feedback conditions. Like the P3, the RewPs elicited in our study were general smaller than previous research (Proudfit, 2015). We did not change the amplification rates between study paradigms, meaning that the same error (i.e., using a lower amplification rate) may be responsible for the lower than typical RewP amplitudes. However, our results suggest that the stimuli elicited the expected responses and that our results still provide important information about the influence of time to reward receipt and relations with delayed reward discounting. One-way ANOVA’s also revealed no difference across conditions within electrodes or across electrodes within conditions, suggesting that these particular electrode sites may represent a rather homogenous construct.

Limitations and Future Directions

The current study used a multimethod framework to explore the relationship between biological and behavioral indicators of alcohol reward value and the effect of delay on reward value. However, the current study was not without limitations. First, the COVID-19 pandemic interrupted data collection and limited the pool of potential participants, limiting the statistical power and preventing some effects from being properly interpreted. This also limited our ability to run certain analyses, like a construct network approach and the longitudinal data analysis. Second, the study used photo cues instead of real-life drinking scenarios. Real-world drinking occurs in dynamic contexts with extensive sensory input, which may influence motivation to consume alcohol. Indeed, part of the theoretical framework of the current study is that the contextual environment plays a role in determining likelihood of alcohol consumption. However,
the current study only isolated the specific effects of visual social and alcohol stimuli using traditional EEG techniques that are sensitive to noise in the natural environment. The results of the study may be bolstered with studies using novel EEG equipment that can be worn in the real-world in simulated or real drinking environments to better capture what is actually experienced by drinkers in both social and solitary conditions. Third, we were missing critical data from some participants, including social context data which limited our ability to explore an important brain-behavior connection. Although the results of the sensitivity analyses were encouraging and suggested that the data were missing at random, the missing data impacted the power of the sample to detect significant effects. Fourth, reactivity to the stimuli in the current study may be partially dependent on person-level individual difference factors such as race, sex assigned at birth, culture, and level of social anxiety, to name a few. Further, reactivity to images may be different for people the participant already knows. It is likely that those individuals who look most like the participants and people they know best may elicit the largest amplitudes, and greater differences between groups may emerge when examining these factors rather than pictures of strangers drinking together. Fifth, it is important to note that our electrophysiological amplitudes were smaller than other studies in general. Our amplifying rate was lower compared to other studies, which may account for some of reduction in amplitude size. The fact that our results are generally consistent with other studies is encouraging and suggests that the findings and methodology are internally consistent, even if reduced in amplitude relative to other studies.

**Conclusion**

The current study connects behavioral indices of alcohol reward and temporally bound decision making with electrophysiological indices of reward valuation and motivation. Our results bolster evidence of construct for alcohol demand and P3 and suggests a brain-behavior connection
capturing an important mechanism for alcohol use across units of analysis. The results also provide preliminary support for the idea that P3 for alcohol cues may be impacted by social content other than alcohol, which may capture real-world decision-making processes. Further, these results bolster the connection between delayed reward discounting and the RewP, which may be an electrophysiological marker of mechanisms responsible for valuation of rewards. Future research should continue to explore the impact of the social environment on alcohol-related motivation using modern EEG devices that can measure brain response under real-world conditions. Studies should also continue to explore the interplay between brain-behavior as it pertains to the influence of temporal windows on choice by exploring alternative experimental manipulations, such as the impact of probability and effort.
References


Acuff, S. F., Soltis, K. E., & Murphy, J. G. (2020). Using demand curves to quantify the


Delmée, L., Roozen, H. G., & Steenhuis, I. (2017). The engagement of non-substance-related pleasant activities is associated with decreased levels of alcohol consumption in university
students. *International Journal of Mental Health and Addiction.*

https://doi.org/10.1007/s11469-017-9857-5


https://doi.org/10.1111/add.14764


Gray, J. C., & Mackillop, J. (2014). Genetic basis of delay discounting in frequent gamblers:
Examination of a priori candidates and exploration of a panel of dopamine-related loci.

*Brain and Behavior, 4*(6), 812–821. https://doi.org/10.1002/brb3.284


F. Lowe (Eds.), *Quantification of steady-state operant behavior* (pp. 3–20). Elsevier/NorthHolland Biomedical Press.


https://kleimanlab.org/resources/power-curves/

discount rates in less than 60 seconds. *Experimental and Clinical Psychopharmacology,*
22(3), 222–228. https://doi.org/10.1126/scisignal.274pe36.Insulin

behavioral economic demand model to better describe consumption data. *Experimental and
Clinical Psychopharmacology, 23*(6), 504–512.
https://doi.org/10.1161/CIRCRESAHA.116.303790.The

Related Consequences: Associations with Past Drinking. *Journal of Adolescence, 34*(1),

Reinforcer pathologies: Predicting alcohol related problems in college drinking men and
https://doi.org/10.1016/j.drugalcdep.2016.07.025

consumption. *Neuropsychopharmacology, 33*(9), 2272–2282.
https://doi.org/10.1038/sj.npp.1301602

607. https://doi.org/10.1111/psyp.12813


Experimental Analysis of Behavior, 46(1), 67–77.


https://doi.org/10.1097/NT.0b013e31826e50af

Vanderveldt, A., Green, L., & Myerson, J. (2015). Discounting of monetary rewards that are


Table 1.

Participant Demographics.

<table>
<thead>
<tr>
<th></th>
<th>%</th>
<th>M (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>26.49 (1.03)</td>
<td></td>
</tr>
<tr>
<td>Sex (% Male)</td>
<td>65.2%</td>
<td></td>
</tr>
<tr>
<td>Race</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>52.2%</td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>39.1%</td>
<td></td>
</tr>
<tr>
<td>Multiracial</td>
<td>8.7%</td>
<td></td>
</tr>
<tr>
<td>Current Student (Yes)</td>
<td>21.7%</td>
<td></td>
</tr>
<tr>
<td>Delayed Reward Discounting</td>
<td>.0365 (.0922)</td>
<td></td>
</tr>
<tr>
<td>Demand Intensity</td>
<td>6.26 (3.15)</td>
<td></td>
</tr>
<tr>
<td>Demand $O_{\text{max}}$</td>
<td>26.70 (24.65)</td>
<td></td>
</tr>
<tr>
<td>Demand Elasticity</td>
<td>.0071 (.0053)</td>
<td></td>
</tr>
<tr>
<td>$r$-ratio</td>
<td>.27 (.17)</td>
<td></td>
</tr>
<tr>
<td>Typical Drinks per Week</td>
<td>10.83 (8.03)</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* $M =$ Mean; $SD =$ Standard deviation
Table 2.  
P3 magnitudes by site and condition.

<table>
<thead>
<tr>
<th></th>
<th>Neutral</th>
<th>Nonsocial Alcohol</th>
<th>Nonsocial Nonalcohol</th>
<th>Social Alcohol</th>
<th>Social Nonalcohol</th>
<th>F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.040 (0.030)</td>
<td>0.071 (0.050)</td>
<td>0.070 (0.039)</td>
<td>0.0813</td>
<td></td>
<td>2.23</td>
<td>.07</td>
</tr>
<tr>
<td>P4</td>
<td>0.051 (0.03)</td>
<td>0.093 (0.046)</td>
<td>0.090 (0.044)</td>
<td>0.095 (0.053)</td>
<td>0.10 (0.059)</td>
<td>4.09</td>
<td>.004</td>
</tr>
<tr>
<td>CPz</td>
<td>0.011 (0.038)</td>
<td>0.046 (0.048)</td>
<td>0.041 (0.047)</td>
<td>0.038 (0.057)</td>
<td>0.034 (0.069)</td>
<td>1.53</td>
<td>.20</td>
</tr>
<tr>
<td>Pz</td>
<td>0.046 (0.034)</td>
<td>0.079 (0.047)</td>
<td>0.067 (0.045)</td>
<td>0.084 (0.057)</td>
<td>0.084 (0.063)</td>
<td>2.43</td>
<td>.052</td>
</tr>
<tr>
<td>PO z</td>
<td>0.046 (0.034)</td>
<td>0.079 (0.047)</td>
<td>0.070 (0.045)</td>
<td>0.084 (0.057)</td>
<td>0.084 (0.062)</td>
<td>2.43</td>
<td>.052</td>
</tr>
<tr>
<td>p-val</td>
<td>&lt; .001</td>
<td>.02</td>
<td>.01</td>
<td>.01</td>
<td>.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. Scalp sites determined according to the standard 10-20 system (American Encephalographic Society, 1991). All one-way ANOVAs had 4 degrees of freedom.
Table 3.
Least Mean Squared RewP amplitudes Split by Gain/Loss Condition, Immediate/Delay Condition, and Scalp Site.

<table>
<thead>
<tr>
<th></th>
<th>Immediate Gain</th>
<th>Immediate Loss</th>
<th>Delayed Gain</th>
<th>Delayed Loss</th>
<th>F</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>0.42 (0.30)</td>
<td>0.37 (0.35)</td>
<td>0.42 (0.28)</td>
<td>0.34 (0.26)</td>
<td>.43</td>
<td>.73</td>
</tr>
<tr>
<td>F4</td>
<td>0.32 (0.30)</td>
<td>0.34 (0.29)</td>
<td>0.31 (0.27)</td>
<td>0.28 (0.24)</td>
<td>.19</td>
<td>.91</td>
</tr>
<tr>
<td>C3</td>
<td>0.35 (0.32)</td>
<td>0.31 (0.33)</td>
<td>0.37 (0.31)</td>
<td>0.30 (0.29)</td>
<td>.31</td>
<td>.82</td>
</tr>
<tr>
<td>C4</td>
<td>0.28 (0.30)</td>
<td>0.25 (0.30)</td>
<td>0.32 (0.30)</td>
<td>0.27 (0.27)</td>
<td>.22</td>
<td>.89</td>
</tr>
<tr>
<td>Fz</td>
<td>0.43 (0.32)</td>
<td>0.41 (0.34)</td>
<td>0.43 (0.32)</td>
<td>0.35 (0.27)</td>
<td>.31</td>
<td>.82</td>
</tr>
<tr>
<td>Cz</td>
<td>0.46 (0.33)</td>
<td>0.40 (0.35)</td>
<td>0.49 (0.36)</td>
<td>0.43 (0.35)</td>
<td>.31</td>
<td>.82</td>
</tr>
<tr>
<td>F</td>
<td>.79</td>
<td>1.18</td>
<td>1.00</td>
<td>1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-value</td>
<td>.56</td>
<td>.32</td>
<td>.42</td>
<td>.31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. Scalp sites determined according to the standard 10-20 system (American Encephalographic Society, 1991). All one-way ANOVAs exploring differences in scalp sites had 5 degrees of freedom. All one-way ANOVAs exploring differences in conditions had 3 degrees of freedom.
Table 4.  
*Estimates of the Effects of Social and Alcohol Cues and their Interactions with Typical Drinks per Week, R-Ratio, and Alcohol Demand Indices on P3.*

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>S.E.</th>
<th>df</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.05</td>
<td>0.02</td>
<td>19.8</td>
<td>2.39</td>
<td>0.27</td>
</tr>
<tr>
<td>Race</td>
<td>0.01</td>
<td>0.02</td>
<td>19</td>
<td>0.46</td>
<td>0.65</td>
</tr>
<tr>
<td>Sex</td>
<td>-0.01</td>
<td>0.02</td>
<td>19</td>
<td>-0.61</td>
<td>0.55</td>
</tr>
<tr>
<td>Student</td>
<td>0.02</td>
<td>0.02</td>
<td>19</td>
<td>1.16</td>
<td>0.26</td>
</tr>
<tr>
<td>Social (Reference = Non-social)</td>
<td>0.01</td>
<td>0.005</td>
<td>342</td>
<td>1.81</td>
<td>0.07</td>
</tr>
<tr>
<td>Alcohol (Ref. = Non-alcohol)</td>
<td>0.01</td>
<td>0.005</td>
<td>342</td>
<td>1.44</td>
<td>0.15</td>
</tr>
<tr>
<td>Social*Alcohol</td>
<td>-0.01</td>
<td>0.007</td>
<td>342</td>
<td>-0.85</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Model 2: Typical Drinks per Week.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Drinks per Week</td>
<td>-0.0001</td>
<td>0.001</td>
<td>21.5</td>
<td>-0.58</td>
<td>0.57</td>
</tr>
<tr>
<td>Typical Drinks per Week x Social</td>
<td>0.001</td>
<td>0.0005</td>
<td>339</td>
<td>1.96</td>
<td>0.05</td>
</tr>
<tr>
<td>Typical Drinks per Week x Alcohol</td>
<td>0.0005</td>
<td>0.006</td>
<td>339</td>
<td>0.8</td>
<td>0.42</td>
</tr>
<tr>
<td>Alcohol</td>
<td>-0.0009</td>
<td>0.0008</td>
<td>339</td>
<td>-1.04</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Model 3: r-ratio</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r-ratio</td>
<td>-0.03</td>
<td>0.08</td>
<td>18.7</td>
<td>-0.43</td>
<td>0.67</td>
</tr>
<tr>
<td>r-ratio x Social</td>
<td>-0.01</td>
<td>0.03</td>
<td>339</td>
<td>-0.46</td>
<td>0.65</td>
</tr>
<tr>
<td>r-ratio x Alcohol</td>
<td>-0.02</td>
<td>0.03</td>
<td>339</td>
<td>-0.73</td>
<td>0.47</td>
</tr>
<tr>
<td>r-ratio x Social x Alcohol</td>
<td>0.04</td>
<td>0.04</td>
<td>339</td>
<td>1.03</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Model 3: Intensity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td>-0.002</td>
<td>0.003</td>
<td>20</td>
<td>-0.57</td>
<td>0.58</td>
</tr>
<tr>
<td>Intensity x Social</td>
<td>-0.001</td>
<td>0.001</td>
<td>339</td>
<td>-0.99</td>
<td>0.32</td>
</tr>
<tr>
<td>Intensity x Alcohol</td>
<td>0.005</td>
<td>0.001</td>
<td>339</td>
<td>3.38</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Intensity x Social x Alcohol</td>
<td>0.0004</td>
<td>0.002</td>
<td>339</td>
<td>0.17</td>
<td>0.86</td>
</tr>
<tr>
<td><strong>Model 3: Omax</strong></td>
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<td></td>
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<tr>
<td>Omax</td>
<td>-0.0005</td>
<td>0.0004</td>
<td>19.8</td>
<td>-1.11</td>
<td>0.28</td>
</tr>
<tr>
<td>Omax x Social</td>
<td>0.0001</td>
<td>0.0002</td>
<td>339</td>
<td>0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>Omax x Alcohol</td>
<td>0.0004</td>
<td>0.0002</td>
<td>339</td>
<td>2.35</td>
<td>0.02</td>
</tr>
<tr>
<td>Omax x Social x Alcohol</td>
<td>-0.0005</td>
<td>0.0003</td>
<td>339</td>
<td>-1.87</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Model 3: Elasticity</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Elasticity</td>
<td>2.14</td>
<td>1.9</td>
<td>20.1</td>
<td>1.13</td>
<td>0.27</td>
</tr>
<tr>
<td>Elasticity x Social</td>
<td>-0.08</td>
<td>0.88</td>
<td>339</td>
<td>-0.1</td>
<td>0.92</td>
</tr>
<tr>
<td>Elasticity x Alcohol</td>
<td>-2.01</td>
<td>0.88</td>
<td>339</td>
<td>-2.29</td>
<td>0.02</td>
</tr>
<tr>
<td>Elasticity x Social x Alcohol</td>
<td>-0.21</td>
<td>1.24</td>
<td>339</td>
<td>-0.17</td>
<td>0.87</td>
</tr>
</tbody>
</table>

*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. S.E. = Standard error; df = degrees of freedom.
Table 5.
Estimates of the Effect of Time to Reward Receipt and Feedback, and their Interactions with Typical Drinks per Week and Delayed Reward Discounting, on P3.

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>S.E.</th>
<th>df</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>0.35</td>
<td>0.16</td>
<td>19</td>
<td>2.23</td>
<td>0.04</td>
</tr>
<tr>
<td>Race</td>
<td>0.03</td>
<td>0.13</td>
<td>19</td>
<td>0.21</td>
<td>0.84</td>
</tr>
<tr>
<td>Sex</td>
<td>-0.07</td>
<td>0.14</td>
<td>19</td>
<td>-0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>Student</td>
<td>0.05</td>
<td>0.15</td>
<td>19</td>
<td>0.32</td>
<td>0.75</td>
</tr>
<tr>
<td>Time to Reward Receipt (Ref. = Immediate)</td>
<td>0.02</td>
<td>0.02</td>
<td>411</td>
<td>0.73</td>
<td>0.46</td>
</tr>
<tr>
<td>Feedback (Ref. = Positive)</td>
<td>-0.03</td>
<td>0.02</td>
<td>411</td>
<td>-1.66</td>
<td>0.10</td>
</tr>
<tr>
<td>Time to Reward x Feedback</td>
<td>-0.03</td>
<td>0.03</td>
<td>411</td>
<td>-1.12</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Model 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Drinks per Week</td>
<td>-0.002</td>
<td>0.002</td>
<td>408</td>
<td>-1.11</td>
<td>0.27</td>
</tr>
<tr>
<td>Typical Drinks per Week x Time to Reward</td>
<td>-0.004</td>
<td>0.002</td>
<td>408</td>
<td>1.49</td>
<td>0.14</td>
</tr>
<tr>
<td>Typical Drinks per Week x Feedback</td>
<td>-0.004</td>
<td>0.002</td>
<td>408</td>
<td>-1.84</td>
<td>0.07</td>
</tr>
<tr>
<td>Typical Drinks per Week x Time to Reward x Feedback</td>
<td>0.005</td>
<td>0.003</td>
<td>408</td>
<td>1.49</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Model 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Delayed Reward Discounting</td>
<td>-0.43</td>
<td>0.77</td>
<td>17</td>
<td>-0.56</td>
<td>0.58</td>
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<tr>
<td>Delayed Reward Discounting x Time to Reward</td>
<td>-0.9</td>
<td>0.2</td>
<td>408</td>
<td>-4.48</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Delayed Reward Discounting x Feedback</td>
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<td>0.2</td>
<td>408</td>
<td>-0.81</td>
<td>0.42</td>
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<tr>
<td>Delayed Reward Discounting x Time to Reward x Feedback</td>
<td>0.76</td>
<td>0.29</td>
<td>408</td>
<td>2.66</td>
<td>&lt;.008</td>
</tr>
</tbody>
</table>

**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. S.E. = Standard error; df = degrees of freedom.
Demonstration of the Oddball Paradigm and Example P3 Data

Note. (A) In a typical oddball trial, frequent non-target stimuli are presented for 1000 ms, with an infrequent target image interspersed. Interstimulus intervals typical vary between 1000-2000 ms. Here, three neutral images are presented, followed by a target alcohol image and another neutral image. (B) Average amplitudes for alcohol and neutral cues from two participants who completed an alcohol cue-reactivity task. The average amplitudes are plotted on the y-axis, and time is plotted on the x-axis. The P3 is evident in the positivity 500-700 ms following stimulus onset.

Figure 2.
Demonstration of the Doors Task and Example RewP Data

Note. (A) In a typical doors task, the subject is presented with an image of two doors. Using the left arrow or the right arrow, participants select one of the two doors, which is followed by a 1000 ms interstimulus window and a randomly presented positive or negative feedback, presented for 2000 ms. Figure taken from Proudfit (2015). (B) Average amplitudes for loss and gain feedback from two participants who completed a doors task. The average amplitudes are plotted on the y-axis, and time is plotted on the x-axis. The RewP is evident in the positivity ~200 ms following feedback onset.

Figure 3.
Electrode configuration.

Note. Configuration of the electrode cap. Electrode placements followed the standard 10-20 system (American Encephalographic Society, 1991). The first symbol for each scalp electrode representing a different cortex region, with F representing frontal, C representing central, P representing parietal, and O representing occipital. The symbols 3, z, and 4 represent the left, middle, and right side of the scalp, respectively. M1 and M2 represent the two electrodes placed on the mastoid bone directly behind the ear. EOG1 and EOG2 represent the eye blink channels, and Grd represents the ground electrode.

Figure 4.

Grand Mean ERP Waveforms for the Oddball Task, Separated by Condition.
Note. Grand mean event-related potentials aggregated at the millisecond level across conditions. The neutral condition evoked the smallest amplitude, followed by the nonsocial nonalcohol, social nonalcohol, nonsocial alcohol, and social alcohol conditions. The two-level multilevel model found no effect of social stimuli ($p = .07$), alcohol cues ($p = .15$), or the interaction between social stimuli and alcohol cues ($p = .40$) on the amplitude of the P3. Neutral images were not included in the analysis.

Figure 5.
Illustration of the Interaction between Typical Drinks per Week and Social Cue Condition in Predicting the Magnitude of P3.

Note. P3 magnitude for social and non-social stimuli separated with mean split by those with low and high levels of typical drinks per week. Social and non-social stimuli evoked comparable P3 magnitudes among those with low typical drinks per week, but social cues evoked greater P3 reactivity compared to non-social stimuli among those with high typical drinks per week.
Illustration of the Interaction Between Alcohol Demand Intensity and Alcohol Cue Condition in Predicting the Magnitude of P3.

Note. P3 magnitude for alcohol and non-alcohol stimuli separated with mean split by those with low and high levels of demand intensity. Alcohol and non-alcohol stimuli evoked comparable P3 magnitudes among those with low demand intensity, but alcohol cues evoked greater P3 reactivity compared to non-alcohol stimuli among those with high demand intensity.
Illustration of the Interaction Between Alcohol Demand $O_{\text{max}}$ and Alcohol Cue Condition in Predicting the Magnitude of P3.

Note. P3 magnitude for alcohol and non-alcohol stimuli separated with mean split by those with low and high levels of demand $O_{\text{max}}$. Alcohol and non-alcohol stimuli evoked comparable P3 magnitudes among those with low demand $O_{\text{max}}$, but alcohol cues evoked greater P3 reactivity compared to non-alcohol stimuli among those with high demand $O_{\text{max}}$.

Figure 8.
Illustration of the Interaction Between Alcohol Demand Elasticity and Alcohol Cue Condition in Predicting the Magnitude of P3.

Note. P3 magnitude for alcohol and non-alcohol stimuli separated with mean split by those with low and high levels of demand elasticity. Alcohol and non-alcohol stimuli evoked comparable P3 magnitudes among those with elastic demand, but alcohol cues evoked greater P3 reactivity compared to non-alcohol stimuli among those with inelastic demand.

Figure 9.
Grand Mean ERP Waveforms for the Doors Task, Separated by Time to Reward Condition and Gains and Losses.

Note. Grand mean event-related potentials aggregated at the millisecond level across conditions and feedback. As expected, gains demonstrated the RewP, whereas the RewP was not evident for loss trials. The immediate and delayed conditions evoked similar magnitude RewPs.

Figure 10.
Illustration of the Interaction Between Delayed Reward Discounting and Time to Reward Receipt Condition in Predicting the Magnitude of RewP.

Note. RewP magnitude for the delayed and immediate doors tasks, mean split by delayed reward discounting. Among those with relatively shallow discounting, RewP was comparable across both delayed and immediate conditions. For those with steep delayed discounting, RewP magnitude in the immediate condition was greater than RewP magnitude in the delayed condition.

Figure 11.
Illustration of the Three-way Interaction Between Delayed Reward Discounting, Trial Feedback, and Time to Reward Receipt Condition in Predicting the Magnitude of RewP.

Note. RewP magnitude for negative and positive trials in both the delayed and immediate doors tasks, mean split by delayed reward discounting. Among those with relatively shallow discounting, RewP was comparable for negative and positive feedback across both delayed and immediate conditions. For those with steep delayed discounting, RewP magnitude was
comparable for negative feedback across delayed and immediate reward conditions, but RewP magnitude for immediate gains was greater than RewP magnitude for delayed gains.