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Lifetime History of Concussions and Behavioral Measures of Anhedonia

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LIFETIME HISTORY OF CONCUSSIONS AND BEHAVIORAL MEASURES OF ANHEDONIA

by

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ABSTRACT

Concussions are the most common neuropsychological problem in the United States and are associated with sequelae such as cognitive complaints and depression-related symptoms. Recent research suggests that head trauma is associated with anhedonia and that concussions have the potential to damage axons and postsynaptic connections in neural circuits that play a role in reward processing. Anhedonia may be better understood as an overarching construct with multiple subtypes including motivational, decisional, and consummatory. The current study examines the relationship between lifetime concussion history and subtypes of anhedonia using behavioral measures of reward processing: the Effort Expenditure for Rewards Task (EEfRT), Probabilistic Reward Task (PRT), and Sweet Taste Test (STT). 62 participants (53.2% women; mean age: 19.19) completed an in-person interview assessing for concussion history followed by administration of the three behavioral tasks. Within participants who reported at least one lifetime concussion, effort expended on the EEfRT when the probability of winning is high, as compared to low, tends to increase the further in time someone reports that their most recent concussion occurred, suggesting that motivational anhedonia may be more apparent in the period of time shortly following a concussion. Conversely, concussion history was not related to performance on the PRT. Furthermore, participants reporting two or more lifetime concussions had, as a group, significantly reduced hedonic slope on the STT than those reporting none, supporting a relationship between consummatory anhedonia and concussion history. Clinical implications are discussed.

To Jennifer, Emerald, and Everett: You are the best motivation anyone could ever ask for. This thesis is dedicated to you.

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INTRODUCTION

Concussions, sometimes referred to as mild traumatic brain injuries (mTBI), are the most common neuropsychological problem in the United States, and may affect between 1.6 and 3.8 million people in the United States per year (Langlois et al., 2006; Centers for Disease Control and Prevention, 2015) and up to 42 million people around the world (Gardner & Yaffe, 2015). Concussions are broadly defined as a blow to the head that causes a person to have symptoms for any amount of time, including dizziness, blurred vision, sensitivity to light, nausea, difficulty in memory or concentration, and loss of consciousness (Robbins et al, 2014). These injuries often go unreported and untreated and, consequently, it is difficult to determine a concrete prevalence rate across the general population (Vynorius, Paquin, & Seichepine, 2016). Furthermore, women may have a greater concussion incidence and rate of associated symptoms than men (Dick, 2009). Concussions are associated with a myriad of sequelae, with cognitive complaints and depression-related symptoms being the most common (Moldover, Goldberg, & Prout, 2004; Darkazalli et al., 2016). Post-concussion depression has been associated with lower processing speed, cognitive flexibility, and episodic memory, and higher overall concussion symptom prevalence (Terry et al., 2018).

Anhedonia is a transdiagnostic symptom characterized by loss of interest or pleasure and dysfunction in reward processing, which is particularly resistant to current treatments (Vittengl et al., 2015). Past research has demonstrated that single instances of severe head trauma are associated with higher anhedonia compared to individuals with no head trauma history, even when measured decades after the injury. Lewis et al. (2015) conducted a study that examined outcomes among combat veterans with penetrating head injuries. They found that damage to the

right ventrolateral prefrontal cortex was associated with higher anhedonia compared to lesions in other brain areas. While this finding illuminates the possible impact of severe head traumas on general anhedonia, little is known about the relationship between lifetime history of mTBIs—concussions—on motivation and reward. Studies that examined repeated concussions in mice (Goddeyne et al., 2015) and humans (Vynorius et al., 2016; Koerte et al., 2017) found that repeated concussions were associated with a reduction in performance on a variety of cognitive tasks that endured past the acute effects of the most recent injury. A recent study examined former high school and college football players and found that cumulative head impacts, defined as concussive and subconcussive injuries, across time are associated with higher self-reported apathy (i.e., lack of motivation), a construct related to one aspect of anhedonia, later in life (Montenigro et al., 2017).

Anhedonia has been examined in schizophrenia and depression research, but typically as a single construct derived from a broader self-report measure rather than anhedonia-specific self-report scales or behavioral measures (Vynorius et al., 2016; Lewis et al., 2015). Anhedonia, however, may be better understood as a domain of functioning that consists of three factors: motivational, decisional, and consummatory (Treadway & Zald, 2011). This comprehensive model of anhedonia is based on recent cognitive neuroscience research. A better understanding of the pathology related to these subtypes of anhedonia in relation to concussion history may lead to more efficacious treatments for individuals post-concussion who present with this typically treatment-resistant symptom.

Motivational anhedonia, a subtype of general apathy, is characterized by diminished approach motivation, and most previous research in this area has implicated reduced dopamine signaling (Treadway & Zald, 2011). Reduced dopamine signaling can have a variety of causes,

but recent research has shown that chronic brain inflammation secondary to immune activation (particularly through increased interleukin-6) can reduce dopamine and performance on behavioral effort and reward learning tasks (Felger & Treadway, 2017; Treadway et al., 2017), but not reward sensitivity (Draper et al., 2018). Dopamine plays a role in predicting and learning from reward outcomes (Takahashi et al., 2011) and increasing effort to pursue rewards (Treadway et al., 2012a). Recent evidence indicates that concussions have the potential to damage axons and postsynaptic connections, and the long axonal projections in dopaminergic circuits may be particularly vulnerable to such damage, resulting in adverse alterations to dopamine release and receptor expression (Chen et al., 2015; Chen et al., 2017; Lan et al., 2019). Clinical trials lend further support to a concussion-dopamine connection by suggesting that treatment with dopamine agonists attenuates post-injury dysfunction (See Lan et al., 2019 for review).

Motivational anhedonia can be measured using the Anticipatory subscale of the Temporal Experience of Pleasure Scale (TEPS), a self-report measure of anhedonia (Gard et al., 2006). Such self-report measures rely on hypothetical reports, asking participants to respond based on how they believe they would feel in presented scenarios. This creates a confound that participants may instead rely on how they generally feel or lack sufficient insight or memory to respond in the manner intended by the instruments. To reduce these confounds, researchers have used behavioral tasks in an attempt capture the construct in the moment. In particular, the Effort Expenditure for Rewards Task (EEfRT; Treadway et al., 2009) has been used to as an objective measure of motivation and anhedonia. The EEfRT is a concurrent choice paradigm adapted for use with humans from a paradigm designed to explore effort-based decision making in rodents (Salamone et al., 1994). Participants are presented with a series of repeated trials in which they

are given the choice between a physically "hard-task" or "easy-task" from which they can earn money (Treadway et al., 2009). Trials are presented with varying levels of probability for receiving any reward and varying amounts of money that can be won from the hard-task. The ratio of hard-task decisions by probability and reward value is then used to reflect motivational anhedonia.

Decisional anhedonia, first introduced by Treadway and Zald (2011), refers to abnormal reward-based decision making and is typically measured using reward learning paradigms (Pizzagalli, Jahn, & O'Shea, 2005; Gold et al., 2012). Reward learning involves detecting the difference between expected and received rewards via signaling in dopaminergic circuits which increases an individual's response bias (Nasser et al., 2017). Acutely increasing dopamine signaling using an presynaptic reuptake receptor antagonist led to increased reward learning performance in a unipolar depression sample (Admon et al., 2017), and increased self-reported anhedonia has been associated with reduced reward learning performance across mood disorder samples (Morris et al., 2015; Pechtel et al., 2013; Pizzagalli et al., 2008; Vrieze et al., 2013;).

The Probabilistic Reward Task (PRT; Pizzagalli et al., 2005) is a computer-based signal detection task wherein participants are briefly shown one of two different circular faces and asked to identify which one appeared. Forty percent of the correct responses are randomly followed by feedback informing participants that they were correct. For half of the participants, correct identification of a particular face is related to three times more positive rewards than correct identification of the other face. This is reversed for the other half of the participants. This task provides a measure of response bias toward the more frequently rewarded stimuli. Since reward learning performance on cognitive tasks can be increased by dopamine (Nasser et al., 2017) and response bias from the PRT is negatively associated with anhedonia (Pechtel et al.,

2013), the PRT appears to be a valid behavioral measure of reward learning and decisional anhedonia

Consummatory anhedonia refers to diminished initial responsiveness to reward attainment. This construct can be measured via self-report using the Consummatory subscale of the TEPS (Gard et al., 2006). In contrast to other positive valence systems, initial responsiveness to reward attainment is associated with the μ- and δ-opioid receptors (Bilbao et al., 2015; Selleck & Baldo, 2017) and endocannabinoids (Monteleone et al., 2016). Stimulation of μ-opioid "hedonic hotspots" in rodent brains increased sucrose liking behavior (Castro & Berridge, 2017). Given this, sweet liking may be a behavioral model for overall initial responsiveness to reward. The Sweet Taste Test (STT; Dichter et al., 2010; Kampov-Polevoy et al., 1997) is a behavioral paradigm that administers randomized trials of five sucrose solutions, that range from very low concentration to concentrations sweeter than Coca-Cola® (Kampov-Polevoy et al., 1997). A study using the STT with a non-psychiatric male sample demonstrated that sweet liking decreased after the administration of naltrexone, an opioid antagonist, and increased following administration of morphine, a μ-opioid agonist, but only for the sweetest concentration (Eikemo et al., 2016). This suggests that the STT, and the hedonic rating of the sweetest solution in particular, may reflect individual differences in opioid functioning, and thus initial responsiveness to reward attainment.

Previous research suggests that head injuries may increase anhedonia (Lewis et al., 2015; Montenegro et al., 2017), possibly via insult to dopaminergic circuits (Chen et al., 2017). However, the existing research on this topic has been limited to more severe TBIs. Given the substantial prevalence of concussions, it is important to examine the association between lifetime history of concussions and these physiologically validated subtypes of anhedonia. Post-

concussion symptom outcomes tend to be worse for head injuries received after an individual's first concussion (Oyegbile, Delasobera, & Zecavati, 2018) and a greater number of lifetime concussions are associated with greater cognitive complaints (Vynorius et al., 2016; Oyegbile et al., 2018). Therefore, a greater number of lifetime concussions may also be associated with more severe chronic post-concussion anhedonia.

To date, it appears that no published research has explored the relationship between concussion history and current behavioral reward processing performance. A better understanding of how an accumulation of concussions relates behavioral performance on measures reflecting each of the three subtypes of anhedonia, will contribute to the knowledge of how concussions can affect the brain. Furthermore, this knowledge can lead to more effective clinical assessment strategies for individuals endorsing either anhedonic symptoms or a previous history of concussions and may suggest more effective treatment techniques for individuals with this presentation.

The current study assesses details regarding a lifetime history of concussions and current performance on behavioral measures of subtypes of anhedonia in a nonpsychiatric adult sample who have not experienced a concussion in the past six months. The specific aim is to examine the relationship between the number of lifetime concussions, a severity score from the most severe concussion, and time elapsed since last concussion, with performance on three behavioral anhedonia measures. Not all concussions result in a loss of consciousness or memory, but those that do involve greater insult to the brain and perhaps have a greater impact on reward processing. The hypotheses for this study are as follows:

We predicted that concussion group (defined as endorsing zero, one, or more than one concussion across the lifespan) would predict performance on the EEfRT and PRT. Specifically,

the group reporting two or more concussions would have a lower change score of choosing hard-task trials from the high minus low probability conditions on the EEfRT, as well as smaller change in response bias score on the PRT from beginning to end of task, compared to groups reporting one or none. One concussion was also predicted to be associated with a lower change score ratio of EEfRT hard trials from high minus low probability and change in response bias score on the PRT in comparison with zero concussions. Furthermore, in the subset of participants reporting at least one concussion, we predicted that an increased number of past concussions and an increased severity score of the most severe concussion would be negatively associated with change score of the ratio of hard-task trials on the EEfRT (high minus low probability conditions) and PRT change in response bias, whereas length of time since most recent concussion would be positively related to both EEfRT and PRT variables. Exploratory analyses were also conducted with other variables derived from the EEfRT and PRT to examine the existence of possible associations with concussion predictors. We did not have specific predictions about STT relationships with concussion variables, as there does not appear to be existing literature about the relationship between concussions and consummatory reward/anhedonia (assessed by the STT), but exploratory analyses were conducted to inform future research.

METHODS

Participants

Participants were undergraduate students enrolled in a Psychology Department course which offered credit in exchange for research participation at the University of Central Florida. Participants completed an online screener questionnaire (N = 2066) and were excluded for completing the questionnaire too quickly (as defined as < 10^{th} percentile of duration; n = 203; 9.8%) or slowly (> 90^{th} percentile of duration; n = 148; 7.2%), scoring more than 2 SD above the mean on the Abbreviated Marlow-Crowne Social Desirability Scale (n = 102; 4.9%), current use of non-prescribed stimulant (n = 17; 0.8%) or sedative medication (n = 5; 0.2%), excessive chronic alcohol use (n = 15; 0.7%), hypothyroidism (n = 28; 1.4%), a first-degree family member with hypothyroidism (n = 70; 3.4%), significant head injury or neurological disorder (n = 46; 2.2%), failure to endorse willingness to abstain from recreational drugs for 48 hours prior to the in-person session (n = 372; 18.0%) or alcohol for 24 hours prior to the session (n = 15; 0.7%), significant uncorrected vision impairment (n = 44; 2.1%), physical impairment in arms or hands (n = 1; 0.05%), or endorsing more than two items incorrectly on an 8-item Infrequency Scale (n = 84; 4.1%).

The remaining 896 participants were eligible for recruitment into the in-person phase of the study and were invited via email. A total of 83 participants participated in the in-person study. Of the 83, a subset were excluded for occurrence of most recent concussion within six months prior to participation (n = 4) or taking a medication at the time of testing that directly affects the reward networks (e.g., opiate or stimulant medications; n = 2). Of the remaining 77 participants who completed the study, 15 were excluded for having incomplete/invalid data for

more than one of the three behavioral tasks. This resulted in a final sample of 62 used in the analyses for at least one of the behavioral measures (53.2% women; mean age: 19.19; SD = 2.18; range 18 to 27). Regarding race, 66.1% identified as Caucasian/White, 9.7% as Asian, 9.7% as Mixed, 6.5% as African-American/Black, 6.5% as Other, and 1.6% preferred not to answer. Independent of race, 24.2% identified as Hispanic/Latinx. Regarding concussions, 48.4% (*n* = 30) reported never experiencing a concussion in their lifetime, 30.6% (*n* = 19) reported experiencing one concussion, and 21.0% (n = 13) reported experiencing two or more past concussions (mean = 2.38, SD = 0.65, range: 2 to 4). Three participants reported current use of selective-serotonin reuptake inhibitor (SSRI) medication at the time of testing. Removing these participants did not alter the pattern of statistical significance in the results, so they were retained in the final analyses. All remaining participants denied current use of narcotic or other psychotropic medications.

Measures

Ohio State TBI Identification Method Interview (TBI Interview)

This interview assesses for number of concussions, their situational context, and the physical and cognitive outcomes for each concussion endorsed, using an interactive format that allows for follow-up queries from the interviewer to clarify information (Corrigan & Bogner, 2007; Bogner & Corrigan, 2009; see attached Appendix A). The interview has been supported as a reliable and valid method of assessing for concussion history (Corrigan & Bogner, 2007; Bogner & Corrigan, 2009). All participants that completed the in-person phase of the study were administered this interview. Concussion information from this interview was used in final analyses rather than information from the online screening measure used for recruitment

purposes. Four outcome variables were computed based on participants' responses: categorical concussion group (none, one, or more than one), number of lifetime concussions endorsed, worst concussion severity, and length of time since most recent concussion. Worst concussion severity was computed based on reported length of time unconscious and length of anterograde amnesia, in minutes. These were converted into standardized z-scores and averaged to create the variable for worst concussion severity. Time since most recent concussion was measured in months. If participants were unable to report the exact length of time since their most recent concussion, the age at which they received the injury was subtracted from their current age to provide a near approximation.

Beck Depression Inventory – 2nd Edition (BDI-II)

The Beck Depression Inventory is a 21-item self-report questionnaire used to assess presence and severity of depression symptoms. The second edition of the BDI was specifically designed to measure symptoms according to DSM-IV criteria for diagnosing depressive disorders (Beck, Steer, Ball, & Ranieri, 1996). It is reported to have high internal consistency and test-retest reliability along with strong convergent validity with other measures of depressive symptoms (Beck, Steer, & Brown, 1996).

Effort Expenditure for Rewards Task (EEfRT)

The EEfRT is a well-validated task of individual differences in reward motivation (Treadway et al., 2009) and was used as a measure of motivational anhedonia. The EEfRT is a computer-based behavioral task that includes individual trials in which the participant is given a choice between easy or hard task options. These options require different amounts of speeded manual button pressing. For each trial, a fixation screen is presented for 1 second. The next

screen presents trial-specific text that states the probability of given trial being a "win" trial ("high" = 88% probability; "medium" = 50% probability; and "low" = 12% probability) along with the value for both the easy and hard tasks. For easy task selections, participants were instructed that they will win a fixed amount of $1. For hard task selections, they were instructed that they can win a higher amount that varies at random between $1.24 and $4.21. Participants had five seconds to press a key representing their decision or the computer would randomly select one of the tasks. A "Ready?" screen was then displayed for 1 second, followed by a screen in which they were asked to rapidly press a button to gradually raise the level of a virtual meter, while a countdown clock is presented. For the hard option, they had to press a keyboard key with their non-dominant hand pinky finger approximately 100 times in 21 seconds. For the easy option, they had to press a key approximately 30 times in 7 seconds using their dominant index finger. A screen was then presented that stated whether participants successfully completed the task, followed by a screen for three seconds that stated either: "You won $X" or "No money this round." Independent of the easy/hard decision, some trials are "no win," in which they will receive no money, while others are "win" trials in which they will receive the stated amount. See Figure 1 for a depiction of the task flow.

Participants were given exactly 20 minutes to "play the game" after the instructions and practice trials. To be consistent with previous studies using this task, all participants were told in the instructions that they would not be provided with the actual total cash winnings but instead would receive an amount of cash equal to two of their actual trials drawn at random and therefore should try to win as much money as possible on all trials. For a subset of the participants (n = 24), they were provided a fixed amount of $10 in cash at the end of the session.

However, due to financial limitations, the remaining participants (n = 38) did not receive cash at the end. All participants were debriefed at the end of the experiment, during which it was explained that the reason for the two types of deception was because the validity of the task relies on the perception that they are continuously influencing the amount of cash reward throughout the task. All participants received academic credit toward a course for participation in this study.

Participants' change score in the ratio of choosing the hard task from the high minus low probability conditions was the primary dependent variable for motivational anhedonia. The change score of the ratio of hard task choices from the high minus low value conditions and average ratio of hard task choice across all conditions were also examined.

Probabilistic Reward Task (PRT)

The PRT (Pizzagalli et al., 2005) is a computer-based signal detection task and has been validated with electrophysiological measures of reward processing. This task was used to measure decisional anhedonia. The task begins with a statement indicating that the goal is to win as much money as possible. In truth, participants did not earn any real money, which was explained during the debriefing process. As with the EEfRT, if participants do not believe that will earn the variable amount of money, their performance on the task may not be valid. The computer task consists of 300 trials across three ten-minute blocks, with 100 trials in each block for a total of 30 minutes. Each trial begins with a fixation cross at the center of the screen which lasts for 1,400 ms, followed by a circular face with no mouth for 500 ms, followed by a face with a mouth comprised of a straight line that is either shorter (11.5 mm) or longer (13 mm) for 100 ms (see Figure 2). Participants were seated 50 cm from the computer and were asked to identify

whether a “long” or “short” face was presented, using a game controller. Participants were informed that not all correct responses will result in winning money; 40% of the correct responses at random are followed by feedback that states, “Correct, you won 5 cents,” for a duration of 1,500 ms. For half of the participants, at random, the short mouth was more highly rewarded. The long mouth was more highly rewarded for the other half of participants. If participants answered incorrectly, they received no feedback and saw a black screen for 1,750 ms.

Response bias (RB), or differential accuracy toward the more frequently rewarded stimuli (long or short mouth depending on the condition) across three time intervals was used to measure reward learning. Specifically, the change in RB between block 1 and block 3 was used as the primary dependent variable. Additionally, average RB across all blocks and categorical direction of change in RB from block 1 to block 3 (i.e., negative or positive) were also examined.

Sweet Taste Test (STT)

The STT was used to measure consummatory anhedonia. This is a standardized measure of initial responsiveness to reward attainment that has been widely used in human and animal studies, and has been validated as sensitive to changes in μ-opioid receptor activation (Damiano et al, 2014; Eikemo et al., 2016). Five concentrations of sucrose in water are used (0.5M, 0.10M, 0.19M, 0.42M, and 0.86M). The two highest concentrations are sweeter than Coca-Cola, which is equivalent to a 0.33M solution. Participants completed five trials of each solution, resulting in 25 trials total, with the different concentrations presented in a random order and participants blinded to the concentration of each sample. Participants were instructed to sip each solution, swish it around their mouth, and spit it out into a large disposable cup that was be provided.

Immediately following each sample, participants were presented with analog scales using horizontal lines presented on paper. The first scale was for sweet sensitivity with the left end of line marked "Not sweet at all" and the right end marked "Extremely sweet." They were asked to mark a location along the line to indicate their choice. The second scale is similar except that it measured the hedonic response – with the left end marked as "Disliked very much" and the right end marked as "Liked very much." Participants rinsed their mouths with distilled water between each trial.

The participant's mark on the line was measured from the beginning of the line using a ruler and the value in mm was used for analysis. The linear slope of the hedonic rating by molarity value was used as the primary dependent variable for consummatory anhedonia. Hedonic rating of the highest molarity solution and sweet liker status (i.e., rating the highest molarity solution as the most liked) were also examined.

Procedures

The study was approved by the Institutional Review Board and followed ethical principles described in the Declaration of Helsinki. Participants provided informed consent at the beginning of both the online and in-person phases of the study. Participants read a debriefing statement at the end of both portions of the study which provided them with more information about what that part of the study was examining, the reasons for any deception, and the opportunity to have their data removed from the dataset. During the in-person phase of the study, participants completed demographic information, followed by the BDI-II, TBI Interview, EEfRT, PRT, and STT. The order of the EEfRT and PRT were counterbalanced by participant,

while the STT was always administered last in order to increase the time since last consumption of food or beverages.

Statistical Analyses

IBM SPSS Statistics software (Version 23) was used for all analyses. To examine potential confounding variables, initial regressions examined the relationships of each of the behavioral task outcome variables with simultaneous entry of age, sex, time of day during testing (i.e. 24 hour time rounded to the nearest half hour), and BDI-II score. When examining EEfRT variables, the percent of missing decision trials and percent of completed trials were also included in the set of potential confounding variables. Luteal and follicular phase of menstrual cycle were considered but not included in analyses due to only six and seven participants, respectively, being in each phase at the time of testing.

For the primary analyses, regressions were used to examine concussion variable predictors on each of the behavioral task variables as dependent variables (three from each task). Significant covariates from the first step above were included in block 1 of all regressions, with concussion variables included in block 2. The concussion group variable was included as the sole predictor in the first set of regressions, as it also included participants with no concussion history. If this group variable was significant for a particular task variable, ANCOVAs, covarying for the same covariates in the regressions, were used to explore pairwise group comparisons among the three concussion groups. For participants reporting at least one lifetime concussion (n = 32), the three predictors of number of lifetime concussions (range: 1 to 4)**,** worst concussion severity, and time since most recent concussion were entered simultaneously in predicting task performance in a second set of analyses. All relationships were analyzed using

linear regression save for those examining categorical task variables - PRT direction of response bias change and STT sweet liker status - which were analyzed using binary logistic regressions. All regressions were checked for outliers using studentized residuals and Cook's distance. If a participant had both a studentized residual score > +/-3.00 and an elevated Cook's distance (defined as > (4/*n*), in which *n* = the number of participants included in a given analysis) for a particular regression, they would then be excluded from that analysis. Using this method, no outliers were found across regressions.

RESULTS

Of the 77 participants who completed the tasks, 30 participants' EEfRT data was deemed invalid (39.0%) for failure to press a button indicating the decision for an easy vs. hard task within the five second window on > 15% of all trials and/or completing (i.e., pressing the button quickly enough during the countdown) < 85% of all trials. As such, the remaining 47 participants had valid EEfRT data. Twenty-seven participants (35%) had invalid data for the PRT due to either exclusion for > 80% invalid trials (i.e., reaction time: 150 ms < valid < 2500 ms) or outliers (± 3 SD from mean RB), consistent with recommendations in the PRT manual, leaving a subset of 50 participants with valid PRT data. For the STT, the linear slope of sweetness rating by molarity value (i.e., sweet sensitivity slope) was used to check for abnormalities in participants' gustatory sense which could influence hedonic ratings. All participants had intact gustatory sense (i.e., all sweet sensitivity slopes > 61.63). Therefore, all available STT hedonic rating data was considered valid. One participant was missing STT data due to researcher error during testing, leaving a subset of 76 participants with valid SST data.

Following these calculations, 15 of the 77 participants (19.5%) had invalid data from two of the three tasks, which was always the combination of the PRT and EEfRT, and were excluded from all analyses. This was done to reduce the differences in statistical power across the three tasks and ensure that all analyses had a similar subset of participants. As a result, a total of 62 participants were included in at least two sets of behavioral task analyses (see Participants section for demographics characteristics of these 62 participants). As a result of the above exclusions and missing data, final analyses included 47 participants for EEfRT, 50 for PRT, and 61 for STT. There were no statistical differences in age, sex, race, ethnicity, time of day during

testing, BDI-II score, or any of the four concussion variables across the subsamples used in analyses of the three tasks (all *p*s > .21).

For the final sample of 62 participants, the three continuous concussion variables and seven continuous task variables were examined for normality of the distributions. Of these ten variables, four had kurtosis values > 2.00: time since most recent concussion (kurtosis: 2.36, SE = 0.81), worst concussion severity (kurtosis = 7.36, SE = 0.81), PRT RB change score (kurtosis = 3.59, SE = 0.66), and PRT average RB (kurtosis = 3.77, SE = 0.66). Of these four, only worst concussion severity also had a skewness > 2.00 (skewness = 2.81, SE = 0.41). When this variable was included in regression analyses no outliers were found using Cook's distance and studentized residuals. All of the remaining nine variables had skewness < 1.55. Thus, although worst concussion severity in particular did not approximate a normal distribution, parametric statistics were used in analyses based on overall pattern of distributions across all ten continuous variables. For the two categorical task variables, 30% (*n* = 15) of participants with valid PRT data (*n* = 50) had a negative RB change and 70% (*n* = 35) had positive RB change. For the STT, 45.2% (*n* = 28) were categorized as sweet likers. For descriptive statistics and zero-order correlations, see Tables 1 (EEfRT), 2 (PRT), and 3 (STT).

Of the examined covariates, only time of day during testing was related to any of the task variables (see Tables 1 to 3). Specifically, a later time of day was related to a greater change in number of hard trials chosen on the EEfRT from low to high value conditions, a lower PRT RB change value, and a greater likelihood of categorically decreasing PRT RB from block one to three. Therefore, for consistency, time of day was included in the first block of all task regressions.

EEfRT Analyses

See Table 4 for EEfRT regression results. There were no significant relationships between concussion group, number of lifetime concussions for those with one or more, or worst concussion severity with any of the EEfRT variables. Length of time since most recent concussion was positively related to the change in the ratio of hard trials chosen from low to high probability conditions (see Table 4 & Figure 3). Follow-up analyses were conducted to determine which probability condition drove the relationship, including the same covariate and independent variables. Time since most recent concussion was positively related to ratio of hard trials chosen in high probability conditions (β = .43, p = .02) but unrelated to ratio of hard trials in both low and medium probability conditions (both ps > .41). Although exploratory, these follow-up analyses of each probability condition also revealed that number of lifetime concussions for those with one or more (mean = 1.57, SD = 0.73, Range: 1 to 3) was positively related to ratio of hard trials chosen in low probability (12%) condition (β = .56, p = .01). Conversely, the worst concussion severity score was negatively related to ratio of hard trials chosen in the low probability condition (β = -.44, p = .04).

PRT Analyses

See Table 5 for PRT regression results. There were no significant relationships between any concussion variable with any PRT variable.

STT Analyses

See Table 6 for STT regression results. There were no significant relationships between number of lifetime concussions for those with one or more, worst concussion severity, or length of time since most recent concussion with any of the STT variables. Concussion group showed a

statistically significant relationship with hedonic slope (see Table 6). ANCOVAs of the pairwise comparisons between the three groups were used to explore this relationship, with the inclusion of the same covariate. The hedonic slope was significantly smaller in participants with two or more concussions (mean = -33.20, SD = 93.52; range = -193.41 to 125.35) compared to those reporting no concussions (mean = 43.32, SD = 113.12; range = -190.24 to 206.39; $F(1,39) = 4.51$, $p = .04$, $\eta^2 = .10$; see Figure 4). Hedonic slope did not significantly differ between the zero and one, or one and two or more subgroups (both ps > .18). Follow-up ANCOVAs were used to explore if hedonic ratings to each of the sucrose solution concentrations drove this relationship. For the least sweet (0.05M) solution, participants with two or more concussions (mean = 121.02, SD = 40.86, Range = 46.20 to 180.40) had higher hedonic ratings than those with none (mean = 84.97, SD = 51.32, Range = 7.40 to 200.00; $F(1,39) = 4.84$, $p = .03$, $\eta^2 = .11$). For the 0.42M solution, those with multiple concussions (mean = 77.66, SD = 35.92; Range = 15.80 to 144.20) had lower hedonic ratings than those with no concussions (mean = 109.70, SD = 49.46; Range = 12.40 to 196.40; $F(1,39) = 4.31$, $p = .04$, $\eta^2 = .10$). The remaining three sweetness concentrations did not show significant group differences (all ps > .11).

"Invalid/Incomplete Data" variables for the final 62 participants were computed for the EEfRT and PRT to explore possible relationships between the predictors and completing either of the tasks in an invalid manner. There were no relationships of any of the covariates or concussion predictors with completing either the EEfRT or PRT in an invalid manner (all ps > .10).

DISCUSSION

The hypotheses regarding the EEfRT were partially supported by the data. The presence of and number of concussions experienced across a lifetime did not relate to current motivational anhedonia in this sample, at least as measured by the EEfRT variables examined. However, the data suggests that motivational anhedonia may be more apparent in the period of time shortly following a concussion. Within participants who reported at least one lifetime concussion, effort expended when the probability of winning is high, as compared to low, tends to increase the further in time someone reports that their most recent concussion occurred (see Figure 3). These findings suggest that healthy pattern of expending more effort for reward when it is clear that one would likely win (e.g., 88% probability), increases with time since the most recent concussion for previously concussed individuals. A recent study on non-concussed healthy young adults found that better working memory performance on an n-back task was related to greater willingness to work for reward on the EEfRT when the probability of winning was moderate or high, but not low (Damme et al., 2019). Previous literature has shown that concussions often reduce working memory performance in rats (Hylin et al., 2013) and humans (Green et al., 2018, Tapper et al., 2017). Although recent correlational research has suggested that working memory deficits can persist for years post-concussion (Arciniega et al., 2019), longitudinal research suggests that working memory recovery may occur within one year following a concussion (Dall'Acqua et al., 2017). Although the present study did not assess working memory, the current results are broadly consistent with this finding and potentially extend it to include a task involving effort for reward. Theoretically, as working memory increases over time following a concussion, individuals might be better able to incorporate probability information in their

decisions on whether to expend effort for reward. As the current study design cannot directly test this theory, future research is needed to clarify this possibility.

Although discovered in exploratory analyses, for participants reporting at least one previous concussion, more concussions (range: 1 to 3) was linearly associated with expending more effort for rewards when the probability of winning was the lowest (i.e., 12%). Individuals with greater number of lifetime concussions may experience greater impulsivity and difficulty with planning behavior resulting in poor choices of when to expend more effort. Conversely, greater pre-existing trait impulsivity may put individuals at greater risk of engaging in risky behaviors that could result in a concussion (Mosti & Coccaro, 2018). Individuals with higher dopaminergic activity may engage in more risky behaviors which might increase their engagement in activities associated with increased concussion risk. Past research has found that increased dopaminergic sensitivity to amphetamines is positively associated with risky decision-making even in a non-clinical sample (Oswald et al., 2015). Other research has found that increased dopaminergic activity may increase impulsivity in situations when rewards are very close to attainment and the delay to reward is fixed and constant (i.e., as with the EEfRT; Dalley & Roiser, 2012; van Gaalen et al., 2006; Winstanley, Cocker, & Rogers, 2011). Importantly, research has extended this work to demonstrate that greater dopamine sensitivity in the corticostriatal network is associated with greater willingness to work for rewards in low-probability trials on the EEfRT (Treadway et al., 2012b). This may explain why having more concussions is associated with more effort exerted in low-probability conditions – the dopamine-related effects on risky and impulsive behavior that could increase the likelihood receiving a concussion may remain post-injury. While there does not appear to be any studies that have

found that individuals with concussions have higher dopamine activity, there may be an association between dopamine receptor genes and personality traits predicting concussion risk (Abrahams et al., 2019; but see Panenka et al., 2017).

The exploratory analyses also revealed that worse severity of most severe concussion was associated with decreased effort in the low probability condition. It is possible that concussions of higher severity are more likely to result in more substantial damage to dopaminergic pathways in this network. For example, a study on rats found a substantial decrease in nucleus accumbens dopamine release related to increased TBI severity (Chen et al., 2015). Severe concussions may result in decreased likelihood of working for low-probability rewards, as dopamine seems to be crucial for overcoming probability costs (Wardle et al., 2011). So, while more concussions might relate to greater effort for low-probability rewards, which may be mediated by trait impulsivity, having just one severe concussion might produce an opposite effect and reflect residual negative effects on motivational behavior.

Contrary to our hypothesis, there were no relationships between concussion predictors and PRT (i.e., reward learning) variables. This was unexpected given that both motivation for reward (i.e., EEfRT performance) and reward learning are thought to involve dopaminergic reward networks. Reward learning, however, is underpinned by a network that overlaps but involves distinct pathways from that of reward motivation (see Treadway & Zald, 2011 for review). It is possible that concussions have differential effects on the network that is relatively more specific to reward motivation versus reward learning.

Outside of the hypotheses, the results suggest that there is a relationship between consummatory anhedonia and concussion history. Participants reporting two or more lifetime

concussions had, as a group, significantly reduced hedonic slope on the STT than those reporting none (see Figure 4). Participants with none or more than one did not differ significantly from those reporting only one lifetime concussion. Previous literature suggests that post-concussion outcomes tend to be worse for head injuries received after an individual's first concussion (Oyegbile, Delasobera, & Zecavati, 2018) and the cumulative effects of multiple concussions are more deleterious on cognitive functioning than those of just one received across the lifetime (Koerte et al., 2017; Oyegbile et al., 2018; Vynorius et al., 2016). The current exploratory findings indicate that consummatory hedonic responses may also be reduced by receiving multiple concussions in a lifetime. Consummatory pleasure, unlike reward motivation and learning, primarily involves μ-opioid receptors in several brain structures and does not respond to manipulations of dopamine (Pecina, Smith, & Berridge, 2006). More concussions suffered over a lifetime regardless of severity or length of time since injury may disrupt opioid signaling in this part of the brain with the result of decreased hedonic response. A recent study on rats found that receiving a concussion reduced hedonic value of reinforcing stimuli, but only examined this effect for 52 days following the concussion (Avcu et al., 2019). There does not appear to be any existing research on past concussions in relation to any self-report or behavioral measures of consummatory pleasure in humans. Therefore, this exploratory finding is novel and future research and replication are needed to confirm and clarify the mechanisms and causality of this relationship.

This study has several limitations. First, the sample size is modest, particularly in groups reporting one or more concussions. Furthermore, the presence of invalid EEfRT and/or PRT data for a subset of participants resulted in an even smaller sample sizes used in analyses involving

those tasks. The sample used in this study is also relatively young and limited to undergraduate students. It is possible that lifetime concussion history may have different effects for older adults and other demographic subgroups that cannot be elucidated with the current sample. Another limitation is the lack of menstrual cycle predictors included in the STT analyses. Past research has found that women in the luteal menstrual cycle phase have lower hedonic slope on the STT (Bedwell et al., 2019). Given that we found a relationship between concussion history and consummatory anhedonia, menstrual cycle phase may be an important covariate. As explained above, however, the number of women in the luteal phase was too low in the present study to include this variable in analyses.

This study also relied on correlational data to make assumptions about time-related effects. Although relationships between concussion predictors and behavioral task outcomes were found, it cannot be claimed that changes in working memory or reward processing related to concussions were caused by concussions. A longitudinal study during which a subset of participants are likely to experience concussions (e.g., athletes) would need to be conducted to support such conclusions. Additionally, the results hint at differences in working memory and dopamine activity without true measurements of either. To support our conjecture, future studies would need to be conducted that examine concussion history, performance on the EEfRT and STT, executive functioning, and an index of dopamine functioning in the related networks. A further limitation is that concussion data was based entirely on participant self-report. Participants were asked to recall events that occurred at least six months prior to the interview, and in some cases, multiple years prior. Variables that involved duration of time (e.g., length of time unconscious/amnestic, length of time since most recent concussion) were dependent on

participants' best estimates and may not accurately reflect the actual length of time. However, this type of noise in the data would likely lead to Type II statistical error. The statistically significant result involving length of time since last concussion may show an even larger effect size if more precise measurement of time is available in future studies.

Along with the above limitations, this study also has multiple strengths. Concussion information was collected using a semi-structured interview with established psychometric properties that enabled researchers to use follow-up queries and gather better quality data that could have been missed or inaccurately reported using a self-report questionnaire. This appears to be the first study to examine the relationship between concussions and subtypes of anhedonia using validated behavioral measures. It provides initial evidence that concussions relate to effort expenditure for reward even if the mechanism and causal direction remains unclear. It appears to also be the first study to find that experiencing multiple concussions relates to increased consummatory anhedonia (i.e., reduced STT hedonic slope), regardless of concussion severity and length of time since most recently suffered concussion. In addition, regressions involving participants with at least one concussion used simultaneous entry of the concussion variables, which provides more confidence in the specificity of the variables that were found to be significant. Analyses were included to examine a wide range of potential confounding variables and controlled remaining analyses for the variable that demonstrated a statistical and theoretical confounding influence (i.e., time of day during testing). Finally, all regression results were examined for statistical outliers using two metrics and none were found, which helps bolster confidence that relationships found in the relatively small sample sizes were not driven by one or more extreme values (as can be seen in Figure 3).

If replicated with longitudinal research, information that a history of multiple concussions may cause a prolonged or permanent decrease in one's experience of pleasure in the moment has direct clinical implications. For examples, clinicians working with patients at heightened risk for concussions or reporting a history of multiple concussions could more routinely assess for consummatory anhedonia and depression. If such symptoms are then detected, the symptom(s) could be targeted in treatment and lead to improved functional outcome for these individuals. Additionally, information that severe concussions may increase motivational anhedonia for lower-probability rewards could have implication for clinicians working with patients reporting a history of head injuries with significant loss of consciousness and/or extended amnesia. Given preliminary evidence that dopamine agonists may be helpful in post-TBI treatment (Lan et al., 2019), these medications may yield improved treatment outcomes when targeting motivational anhedonia symptoms.

FIGURES

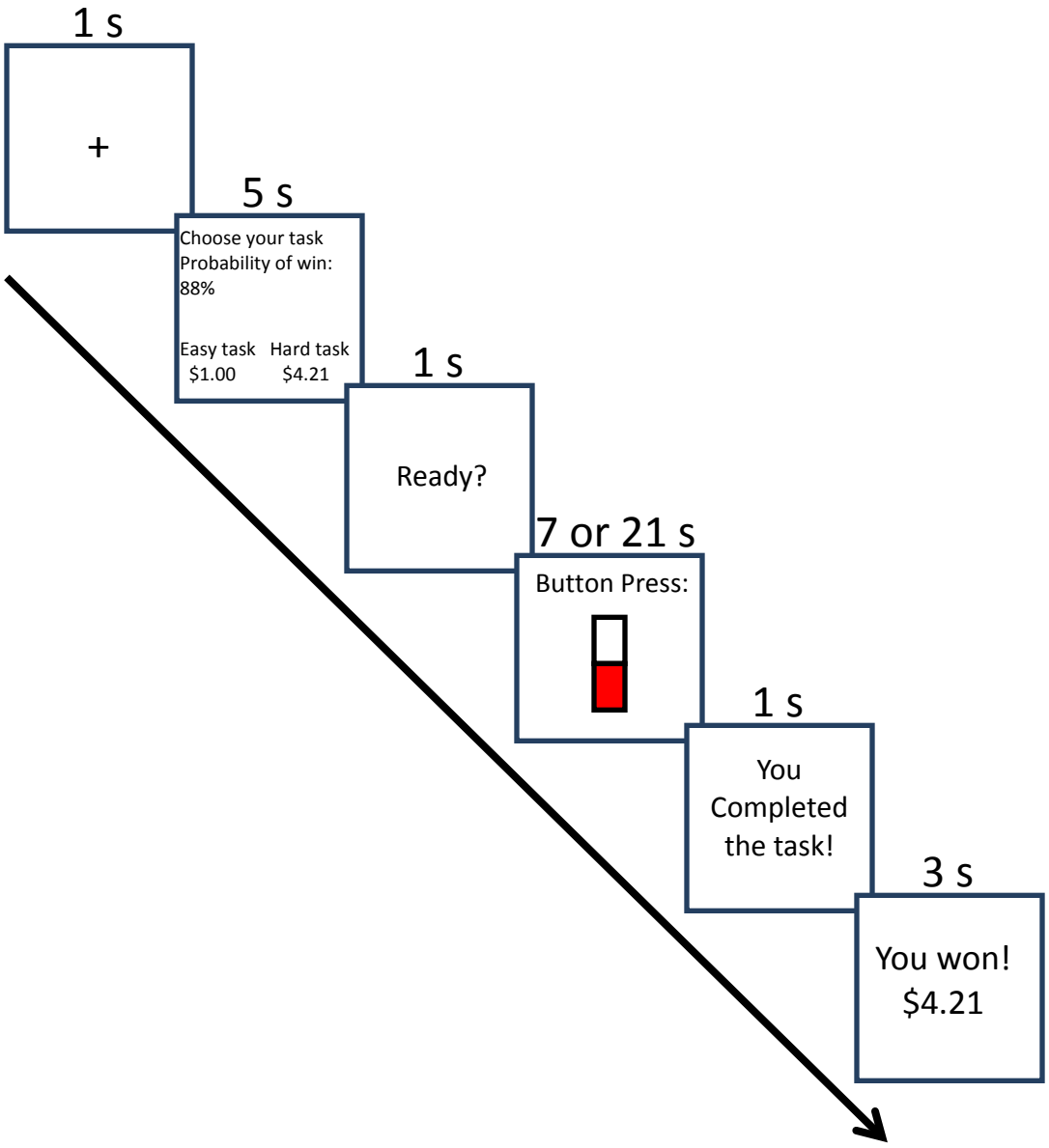

Figure 1. Schematic diagram of a single trial of the Effort Expenditure for Rewards Task (adapted from Treadway, et al., 2009).

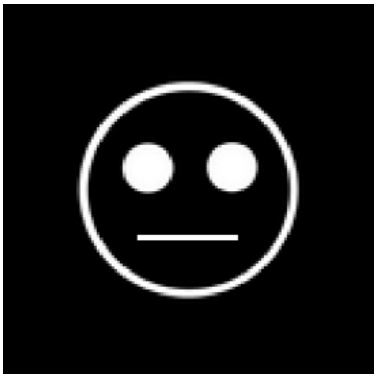

Figure 2. Example stimulus from the Probabilistic Reward Task.

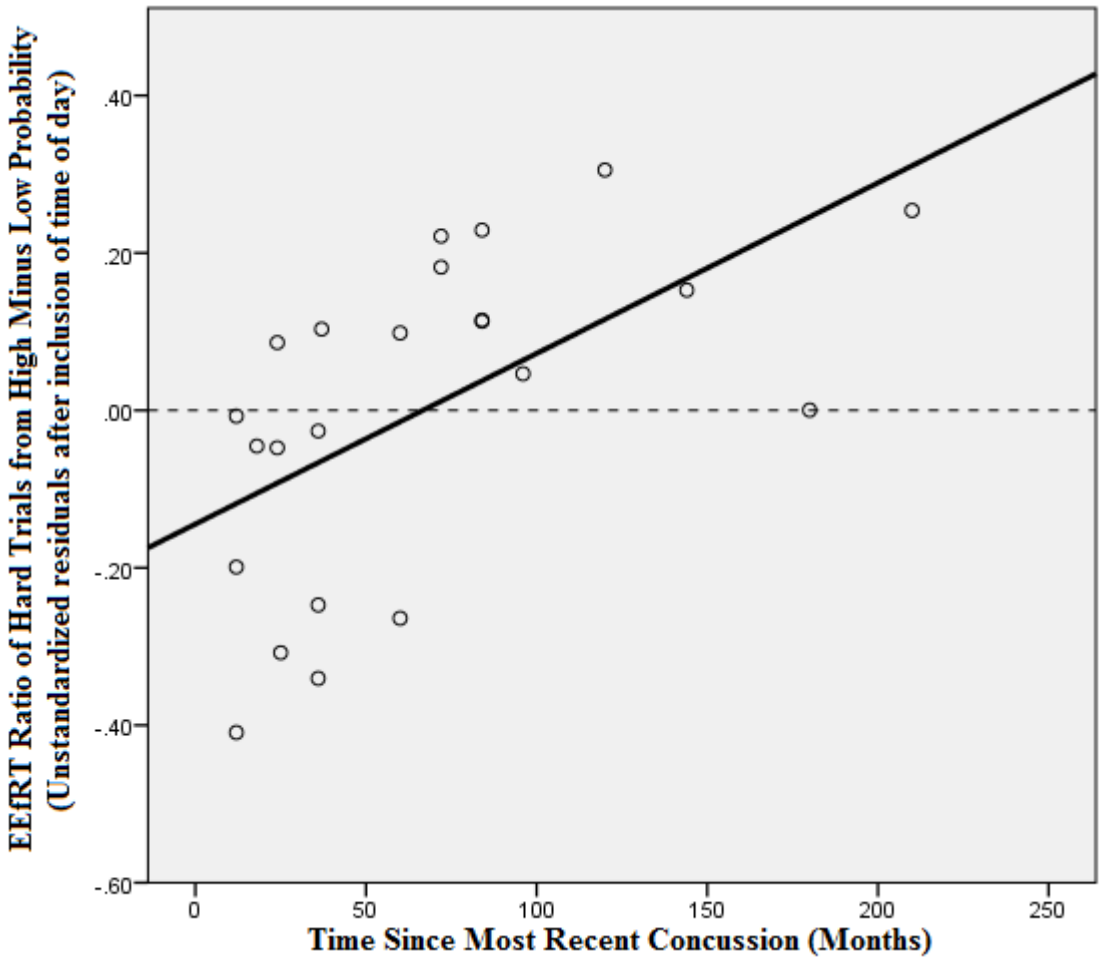

Figure 3. Scatterplot of time since most recent concussion by EEfRT ratio of hard trials chosen from high minus low probability conditions (unstandardized residuals after covarying for time of day).

EEfRT = Effort Expenditure for Rewards Task

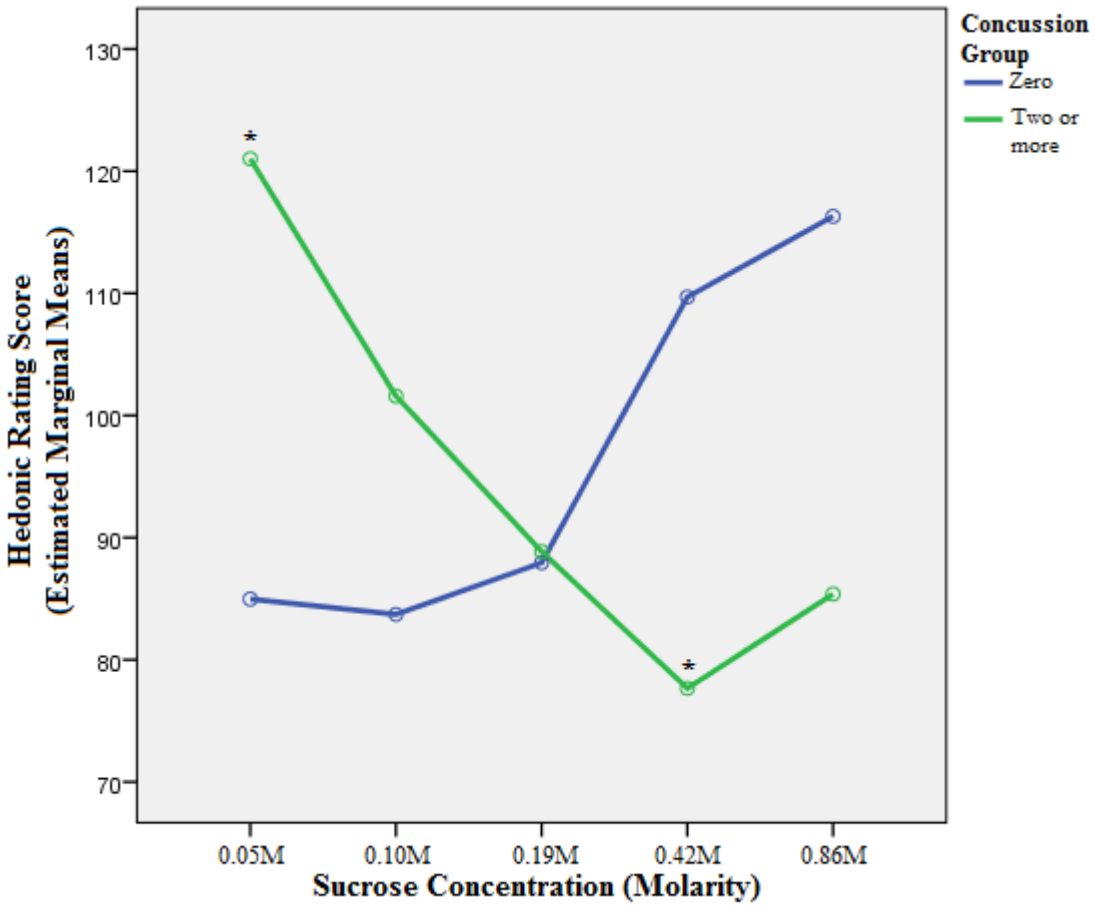

Figure 4. Hedonic slopes from Sweet Taste Test for participants reporting no lifetime concussions and those reporting two or more.

TABLES

Table 1. Descriptive statistics and zero-order correlations among Effort Expenditure for Rewards Task scores and predictor variables.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
1. High-Low Probability	0.50 (0.25)												
2. High-Low Value	.16 (n = 47)	0.36 (0.20)											
3. Average Effort	.49** (n = 47)	.06 (n = 47)	0.34 (0.15)										
4. Percent No Decision	-.18 (n = 47)	-.07 (n = 47)	-.08 (n = 47)	10.41 (26.24)									
5. Percent Completed	.16 (n = 47)	.10 (n = 47)	-.08 (n = 47)	-.29* (n = 61)	94.01 (9.35)								
6. Age	.03 (n = 47)	-.19 (n = 47)	.07 (n = 47)	.28* (n = 61)	.09 (n = 61)	19.19 (2.18)							
7. Sex	.12 (n = 47)	-.18 (n = 47)	-.14 (n = 47)	-.05 (n = 61)	-.08 (n = 61)	-.19 (n = 62)	1.53 (0.50)						
8. BDI	.05 (n = 46)	.11 (n = 46)	-.05 (n = 46)	-.13 (n = 59)	.13 (n = 59)	-.03 (n = 60)	.08 (n = 60)	9.67 (7.23)					
9. Time of Day	.16 (n = 47)	.29* (n = 47)	-.02 (n = 47)	-.23 (n = 61)	-.01 (n = 61)	-.14 (n = 62)	-.04 (n = 62)	-.19 (n = 60)	12.53 (2.07)				

10. Concussion Group	-.11 (*n* = 47)	.13 (*n* = 47)	-.03 (*n* = 47)	.09 (*n* = 61)	-.15 (*n* = 61)	.12 (*n* = 62)	.17 (*n* = 62)	.24 (*n* = 60)	-.08 (*n* = 62)	0.73 (0.79)			
11. Lifetime Number of Concussions (≥1)	-.19 (*n* = 47)	.09 (*n* = 47)	-.05 (*n* = 47)	.06 (*n* = 61)	-.21 (*n* = 61)	.11 (*n* = 62)	.18 (*n* = 62)	.18 (*n* = 60)	-.12 (*n* = 62)	.95** (*n* = 62)	0.81 (0.97)		
12. Worst Concussion Severity	-.30 (*n* = 23)	-.10 (*n* = 23)	-.36 (*n* = 23)	-.14 (*n* = 32)	.05 (*n* = 32)	-.14 (*n* = 32)	.26 (*n* = 32)	.00 (*n* = 31)	-.02 (*n* = 32)	.23 (*n* = 32)	.30 (*n* = 32)	0.00 (0.68)	
13. Time Since Most Recent Concussion	.59** (*n* = 23)	-.11 (*n* = 23)	.36 (*n* = 23)	-.18 (*n* = 32)	.27 (*n* = 32)	.12 (*n* = 32)	.06 (*n* = 32)	.00 (*n* = 31)	.14 (*n* = 32)	-.19 (*n* = 32)	-.19 (*n* = 32)	-.14 (*n* = 32)	58.56 (49.25)

Descriptive statistics on the outer diagonal in format: mean (standard deviation).
High-Low Probability – Ratio of hard trials from high minus low probability conditions
High-Low Value – Ratio of hard trials from high minus low value conditions
Average EEfRT – Average ratio of hard trials across all conditions
BDI – Beck Depression Inventory – 2nd Edition
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
* $p < .05$
** $p < .01$

Table 2. Descriptive statistics and zero-order correlations among Probabilistic Reward Task scores and predictor variables.

	1.	2.	3.
1. Change RB	0.66 (3.07)		
2. Average RB	.01 (n = 50)	0.57 (3.26)	
3. Change RB Direction	.47** (n = 50)	-.09 (n = 50)	0.70 (0.46)
4. Age	-.02 (n = 50)	.05 (n = 50)	.12 (n = 50)
5. Sex	.14 (n = 50)	-.21 (n = 50)	.16 (n = 50)
6. BDI	.04 (n = 49)	.01 (n = 49)	-.01 (n = 49)
7. Time of Day	-.35* (n = 50)	.05 (n = 50)	-.51* (n = 50)
8. Concussion Group	.07 (n = 50)	.04 (n = 50)	.12 (n = 50)
9. Lifetime Number of Concussions (≥1)	.04 (n = 50)	.01 (n = 50)	.16 (n = 50)
10. Worst Concussion Severity	-.13 (n = 27)	-.06 (n = 27)	-.08 (n = 27)
11. Time Since Most Recent Concussion	.21 (n = 27)	-.03 (n = 27)	.14 (n = 27)

Descriptive statistics on the outer diagonal in format: mean (standard deviation).
Change RB – Response bias of block 3 trials minus block 1 trials
Average RB – Average response bias across all blocks
Change RB Direction – categorical positive or negative Change RB (1 = Change RB > 0, 0 = Change RB ≤ 0)
BDI – Beck Depression Inventory – 2nd Edition
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
* $p < .05$
** $p < .01$

Table 3. Descriptive statistics and zero-order correlations among Sweet Taste Test scores and predictor variables.

	1.	2.	3.
1. Hedonic Slope	14.83 (119.46)		
2. Hedonic Rating for 0.86M	.93** (n = 61)	102.18 (57.22)	
3. Sweet Liker Status	.80** (n = 61)	.76** (n = 61)	0.46 (0.50)
4. Age	.07 (n = 61)	.01 (n = 61)	-.01 (n = 61)
5. Sex	-.08 (n = 61)	-.08 (n = 61)	-.01 (n = 61)
6. BDI	.01 (n = 59)	-.02 (n = 59)	-.02 (n = 59)
7. Time of Day	-.06 (n = 61)	-.04 (n = 61)	-.05 (n = 61)
8. Concussion Group	-.26* (n = 61)	-.23 (n = 61)	-.18 (n = 61)
9. Lifetime Number of Concussions (≥1)	-.22 (n = 61)	-.18 (n = 61)	-.10 (n = 61)
10. Worst Concussion Severity	-.07 (n = 32)	.11 (n = 32)	-.20 (n = 32)
11. Time Since Most Recent Concussion	-.11 (n = 32)	-.13 (n = 32)	-.08 (n = 32)

Descriptive statistics on the outer diagonal in format: mean (standard deviation).
Hedonic Slope – Linear slope of hedonic rating by molarity value.
Sweet Liker Status – Binary category 1 = highest average hedonic rating was for the sweetest (0.86M) concentration; 0 = highest average hedonic rating was for a different molarity.
BDI – Beck Depression Inventory – 2nd Edition
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
* $p < .05$
** $p < .0$

Table 4. Results of Effort Expenditure for Rewards Task linear regression analyses.

High-Low Probability	***n***	***B***	**SE**	***β***	***p***
Concussion Group	47	-.03	.05	-.09	.54
Number of Lifetime Concussions (≥1)	23	-.11	.05	-.37	.06
Worst concussion severity	23	-.03	.05	-.10	.57
Time since most recent concussion	23	<.01	<.01	.43*	.03*
High-Low Value					
Concussion Group	47	.04	.04	.18	.22
Number of Lifetime Concussions (≥1)	23	-.02	.06	-.08	.69
Worst concussion severity	23	.03	.05	-.14	.51
Time since most recent concussion	23	>-.01	<.01	-.28	.19
Average Effort					
Concussion Group	47	>-.01	.03	-.03	.83
Number of Lifetime Concussions (≥1)	23	.04	.03	.26	.23

Worst concussion severity	23	-.05	.03	-.36	.10
Time since most recent concussion	23	<.01	<.01	.31	.16

B = Unstandardized coefficient, SE = standard error for *B*, *β* = standardized coefficient
Covaried for Time of Day
High-Low Probability – Ratio of hard trials from high minus low probability conditions
High-Low Value – Ratio of hard trials from high minus low value conditions
Average EEfRT – Average ratio of hard trials across all conditions
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
* $p < .05$

Table 5. Results of Probabilistic Reward Task linear and binary logistic regression analyses.

Change RB	***n***	***B***	**SE**	***β***	***p***
Concussion Group	50	.06	.55	.02	.91
Number of Lifetime Concussions (≥1)	27	.58	.66	.18	.39
Worst concussion severity	27	-.73	.82	-.18	.39
Time since most recent concussion	27	.02	.01	.27	.18
Average RB					
Concussion Group	50	.19	.62	.04	.77
Number of Lifetime Concussions (≥1)	27	.02	.98	.01	.98
Worst concussion severity	27	-.32	1.21	-.06	.80
Time since most recent concussion	27	>-.01	.02	-.04	.87
Change RB Direction†	***n***	***B***	**SE**	***OR***	***p***
Concussion Group	50	.20	.48	1.22	.68
Number of Lifetime Concussions (≥1)	27	5.21	4.24	183.53	.22
Worst concussion severity	27	-2.40	5.80	.09	.68
Time since most recent concussion	27	.01	.02	1.01	.49

B = Unstandardized coefficient, SE = standard error for *B*, β = standardized coefficient
OR = Odds ratio
Change RB – Response bias of block 3 trials minus block 1 trials
Average RB – Average response bias across all blocks
Change RB Direction – categorical positive or negative Change RB (1 = Change RB > 0, 0 = Change RB ≤ 0)
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
† All values from binary logistic regressions

Table 6. Results of Sweet Taste Test linear and binary logistic regression analyses.

Hedonic Slope	***n***	***B***	**SE**	***β***	***p***
Concussion Group	61	-39.44	19.12	-.26*	.04*
Number of Lifetime Concussions (≥1)	32	-12.91	30.55	-.09	.68
Worst concussion severity	32	-11.74	35.41	-.07	.74
Time since most recent concussion	32	-.33	.48	-.13	.50
Hedonic Rating of 0.86M					
Concussion Group	61	-17.00	9.23	-.24	.07
Number of Lifetime Concussions (≥1)	32	-3.05	13.37	-.05	.82
Worst concussion severity	32	8.28	15.50	.11	.60
Time since most recent concussion	32	-.15	.21	-.14	.47
Sweet Liker†	***n***	***B***	**SE**	***OR***	***p***
Concussion Group	61	-.42	.34	.66	.22
Number of Lifetime Concussions (≥1)	32	.45	.51	1.56	.39
Worst	32	-1.10	.95	.33	.25

concussion severity					
Time since most recent concussion	32	>-.01	<.01	1.00	.65

B = Unstandardized coefficient, SE = standard error for *B, β* = standardized coefficient
OR = Odds ratio
Hedonic Slope – Linear slope of hedonic rating by molarity value.
Sweet Liker Status – Binary category 1 = highest average hedonic rating was for the sweetest (0.86M) concentration; 0 = highest average hedonic rating was for a different molarity
Concussion Group – Reporting zero, one, or more than one concussion (0 = no concussions, 1 = one concussion, 2 = two or more concussions)
* $p < .05$
† All values from binary logistic regressions

APPENDIX A: OHIO STATE UNIVERSITY TBI IDENTIFICATION METHOD

Name: _____ Current Age: _____ Interviewer Initials: _____ Date: _____

Ohio State University TBI Identification Method — Interview Form

Step 1

Ask questions 1-5 below. Record the cause of each reported injury and any details provided spontaneously in the chart at the bottom of this page. You do not need to ask further about loss of consciousness or other injury details during this step.

I am going to ask you about injuries to your head or neck that you may have had anytime in your life.

1. In your lifetime, have you ever been hospitalized or treated in an emergency room following an injury to your head or neck? Think about any childhood injuries you remember or were told about.
   ☐ No ☐ Yes—Record cause in chart
2. In your lifetime, have you ever injured your head or neck in a car accident or from crashing some other moving vehicle like a bicycle, motorcycle or ATV?
   ☐ No ☐ Yes—Record cause in chart
3. In your lifetime, have you ever injured your head or neck in a fall or from being hit by something (for example, falling from a bike or horse, rollerblading, falling on ice, being hit by a rock)? Have you ever injured your head or neck playing sports or on the playground?
   ☐ No ☐ Yes—Record cause in chart
4. In your lifetime, have you ever injured your head or neck in a fight, from being hit by someone, or from being shaken violently? Have you ever been shot in the head?
   ☐ No ☐ Yes—Record cause in chart
5. In your lifetime, have you ever been nearby when an explosion or a blast occurred? If you served in the military, think about any combat- or training-related incidents.
   ☐ No ☐ Yes—Record cause in chart

Interviewer instruction:
If the answers to any of the above questions are "yes," go to Step 2. If the answers to all of the above questions are "no," then proceed to Step 3.

Step 2

Interviewer instruction: If the answer is "yes" to any of the questions in Step 1 ask the following additional questions about each reported injury and add details to the chart below.

Were you knocked out or did you lose consciousness (LOC)?

If yes, how long?

If no, were you dazed or did you have a gap in your memory from the injury?

How old were you?

Step 3

Interviewer instruction: Ask the following questions to help identify a history that may include multiple mild TBIs and complete the chart below.

Have you ever had a period of time in which you experienced multiple, repeated impacts to your head (e.g. history of abuse, contact sports, military duty)?

If yes, what was the typical or usual effect—were you knocked out (Loss of Consciousness - LOC)?

If no, were you dazed or did you have a gap in your memory from the injury?

What was the most severe effect from one of the times you had an impact to the head?

How old were you when these repeated injuries began? Ended?

Step 1	Step 2						
	Loss of consciousness (LOC)/knocked out				Dazed/Mem Gap		Age
Cause	No LOC	< 30 min	30 min-24 hrs	> 24 hrs	Yes	No	

If more injuries with LOC: How many?_____ Longest knocked out?_____ How many ≥ 30 mins.?_____ Youngest age? _____

Step 3	Typical Effect		Most Severe Effect				Age	
Cause of repeated injury	Dazed/ memory gap, no LOC	LOC	Dazed/ memory gap, no LOC	LOC < 30 min	LOC 30 min - 24 hrs.	LOC > 24 hrs.	Began	Ended

Adapted with permission from the Ohio State University TBI Identification Method (Corrigan, J.D., Bogner, J.A. (2007). Initial reliability and validity of the OSU TBI Identification Method. J Head Trauma Rehabil, 22(6):318-329.

(Continuation from reverse side, if needed)

Name: _____ **Current Age:** _____ **Interviewer Initials:** _____ **Date:** _____

Step 1	Step 2						
	Loss of consciousness (LOC)/knocked out				Dazed/Mem Gap		Age
Cause	No LOC	< 30 min	30 min-24 hrs	> 24 hrs	Yes	No	

If more injuries with LOC: How many?_____ Longest knocked out?_____ How many ≥ 30 mins.?_____ Youngest age? _____

Step 3	Typical Effect		Most Severe Effect				Age	
Cause of repeated injury	Dazed/ memory gap, no LOC	LOC	Dazed/ memory gap, no LOC	LOC < 30 min	LOC 30 min - 24 hrs.	LOC > 24 hrs.	Began	Ended

Interpreting Findings

A person may be more likely to have ongoing problems if they have any of the following:

- **WORST**
  One moderate or severe TBI
- **FIRST**
  TBI with loss of consciousness before age 15
- **MULTIPLE**
  2 or more TBIs close together, including a period of time when they experienced multiple blows to the head
- **RECENT**
  A mild TBI in the last weeks or a more severe TBI in the last months
- **OTHER SOURCES**
  Any TBI combined with another way that their brain function has been impaired

For more information about TBI or the OSU TBI Identification Method visit:

- Ohio Valley Center at OSU
  www.ohiovalley.org/informationeducation
- BrainLine.org
  www.brainline.org

(Updated July 2013)

APPENDIX B: UCF IRB HUMAN SUBJECTS PERMISSION LETTER

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **John P O'Donnell** and Co-PI **Jeffrey S Bedwell**

Date: **August 14, 2018**

Dear Researcher:

On 08/14/2018 the IRB approved the following human participant research until 08/13/2019 inclusive:

Type of Review:	UCF Initial Review Submission Form Expedited Review Category #7; This approval includes a Waiver of Written Documentation of Consent
Project Title:	Concussion History and Reward Processing
Investigator:	John P O'Donnell
IRB Number:	SBE-18-13998
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 08/13/2019, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

This letter is signed by:

Signature applied by Renea C Carver on 08/14/2018 03:05:10 PM EDT
Designated Reviewer

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