A PSYCHONEUROMETRIC APPROACH TO INDEXING REWARD SENSITIVITY

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ABSTRACT

The National Institute of Mental Health has proposed the Research Domain Criteria (RDoC) framework as a dimensional approach to evaluating and defining components of psychopathology. The current RDoC matrix is comprised of several systems, including the positive valence system, which encompasses reward sensitivity, which can be further separated into temporal phases of reward anticipation and initial response to reward. The current RDoC matrix includes limited measures within reward sensitivity. As such, reward sensitivity is an ideal variable for the psychoneurometric approach, which aims to integrate multiple units of analysis to operationalize latent variables. An exploratory factor analysis (EFA) was used to integrate four electroencephalographic variables (SPN, P300, RewP amplitudes and delta power), a behavioral measure (reaction time), and self-report measures of personality traits and mood symptoms often associated with reward processing like impulsivity, anhedonia, and valuation. Although hypotheses included a two-factor solution of reward anticipation and reward response, results revealed a six-factor solution, explaining 66.031% of the variance. Factors seemed to reflect: the P-factor/Questionnaire Methods Variance, Trait-Level Approach Motivation/Task Disengagement, General Reward Sensitivity, Excitement Seeking, Impulsivity, and State-Dependent Response to Reward. The separation of hypomanic symptoms (motivation, excitement seeking, and impulsivity) from a broader reward sensitivity factor demonstrate that motivation, excitement seeking, and impulsivity may be candidates for separate subconstructs of Reward Responsiveness in the RDoC matrix. Most factors were comprised of either self-report or neurophysiological indices rather than integrating across units of analysis. Results highlight the need for future studies to include fewer variables coming from a variety of methods rather than oversaturating models with questionnaire data, potentially even developing new scales to index latent constructs or calculate composite scores before conducting factor analyses.

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Introduction

Understanding mechanisms involved in different domains of psychological functioning is imperative for accurate diagnosis and effective intervention of psychopathology. Currently, the fifth iteration of the Diagnostic and Statistical Manual of Mental Disorders (DSM; American Psychological Association, 2013) focuses on presenting symptoms, impeding research efforts and leading to heterogeneous categories that may not reflect distinct diseases (Cuthbert, 2022). To address some of the shortcomings of the current DSM diagnostic categories, the National Institute of Mental Health (NIMH) has proposed the Research Domain Criteria (RDoC) project as a way to redefine psychopathology and mental health problems using a dimensional framework focused on neurobehavioral mechanisms involved in individual differences in psychological functioning (Cuthbert, 2022). The initiative organizes symptomatology on continuous process-oriented spectra (Yancey et al., 2016). Although the RDoC framework is designed to challenge the DSM, it has considerable limitations, including an excessive focus on behavioral mechanisms and insufficient psychometric validity (Lilienfeld, 2014). To address both limitations, the psychoneurometric approach has been proposed to integrate physiological and self-report measures to index dispositional (i.e., individual differences) constructs of psychopathology like those found in the RDoC matrix (Venables et al., 2017; Yancey et al., 2016).

Within the RDoC matrix are five broad systems (negative valence, positive valence, cognitive, social processes, arousal and regulatory, and sensorimotor) intended to reflect processes involved in particular contexts like, in the case of the positive valence system, rewarding situations (*About RDoC*, n.d.). The positive valence system consists of three general reward dimensions: reward responsiveness or sensitivity (hereon referred to as reward sensitivity), reward learning, and reward valuation (*About RDoC*, n.d.). Since dysfunction in reward sensitivity is characteristic of several kinds of psychopathology, particularly mood disorders like Major Depressive Disorder (MDD) and Bipolar Disorder (BD), the current project focused on reward sensitivity. The RDoC matrix defines reward sensitivity as the processes underlying hedonic response to upcoming or anticipated reward (reward anticipation), the initial response to reward, and reward satiation following repeated exposure to rewarding stimuli (*About RDoC*, n.d.). Notably, the current RDoC matrix is lacking in units of analysis to index reward sensitivity. Although RDoC frames reward sensitivity as three subprocesses, the current

project focused on addressing the two temporal phases of reward sensitivity: reward anticipation and the initial response to reward.

One prominent theory of the etiology of mood disorders is the Reward Sensitivity Model, which proposes that mood disorders manifest predominantly as dysregulations of reward responses. It posits that reward hypersensitivity (i.e., excessive motivation towards rewarding stimuli) can lead to hypomanic/manic symptoms in BD, whereas reward hyposensitivity (i.e., blunted response to rewarding stimuli) can lead to depressive symptoms in both MDD and BD (Alloy et al., 2016). Integrating the neural, personality, and psychological processes related to reward sensitivity is critical to operationalizing reward sensitivity as a dispositional construct (i.e., through a psychoneurometric lens), which will inform both the RDoC matrix and the Reward Sensitivity Model. Therefore, the goal of the current project was to integrate measures of reward sensitivity from a psychoneurometric perspective, including several self-report measures of reward sensitivity as well as associated mood symptoms (e.g., anhedonia) and personality traits (e.g., boldness, impulsivity), a behavioral measure of reward choice reaction time, and four electroencephalographic (EEG) indices of reward processing derived from a randomized guessing task: the Stimulus-Preceding Negativity (SPN), the Reward Positivity (RewP), the P300 (following rewarding and loss feedback), and delta power.

EEG markers of reward processing can be indexed using event-related potentials (ERPs; e.g., SPN, RewP, P300) or time-frequency analysis (e.g., delta power). ERPs are time-locked neurophysiological markers, meaning they quantify activity following a response to a stimulus. Whereas ERPs provide millisecond (ms) precision, some valuable information is lost when averaging stimulus and trial-related information. This information is still accessible through time-frequency analysis, which reveals additional task-relevant dynamics and mechanisms. By pairing ERP and frequency data, researchers can assess highly precise temporal information about responses to specific stimuli and information regarding neural networks during task performance, respectively (Cohen, 2014). Indexing reward sensitivity by pairing ERPs and time-frequency analysis with self-report measures will be instrumental given the temporal nature of reward processing that is thought to be comprised of several subprocesses.

Reward Anticipation

RDoC defines reward anticipation as mechanisms related to anticipating or representing future rewarding stimuli through language, behavior, and neural responses to future incentives

(*About RDoC*, n.d.). In the current matrix, no molecules, circuits, behavior, self-report measures, or paradigms are associated with reward anticipation, making it an ideal subconstruct to operationalize through the psychoneurometric approach. The current study integrates self-report measures assessing reward processing and associated mood symptoms (through loss of interest and low energy as well as other depressive symptoms), impulsivity (through fun-seeking, boldness, and externalizing symptoms), and reward hypersensitivity (through hypomania, drive, and reward responsiveness) with a behavioral measure (i.e., reaction time) and an EEG index of anticipatory and preparatory processes (the Stimulus-Preceding Negativity) to operationalize reward anticipation.

Anhedonia, a key symptom of depression, is a decrease in motivation, interest, or pleasure related to a stimulus the individual once found rewarding (Treadway & Zald, 2011). Anhedonia is characterized by deficits in both anticipatory (i.e., motivation to pursue) and outcome (i.e., interest, liking) aspects of reward, meaning anhedonia could act as an index of both reward anticipation and response (Treadway & Zald, 2011; Chen et al., 2018; Bowyer et al., 2022). The lack of motivation to pursue rewarding stimuli can serve as an index of anticipatory reward processes. In contrast, the consummatory aspects (i.e., losing interest in previously pleasurable stimuli) could reflect an initial response to reward. Therefore, anhedonia could be related to both reward anticipation and response. Particularly, low energy (i.e., motivation to pursue) could be related to reward anticipation while loss of interest (i.e., consummatory aspect) could be related to initial response to reward.

In contrast to depressive symptoms, impulsivity, a defining feature of mania and hypomania, is maladaptive over-engagement in pleasurable activities (i.e., hypersensitivity to reward), which are often unsafe (Giovanelli et al., 2013). Impulsivity represents a maladaptive increase in motivation to pursue future rewarding stimuli, acting as an approximation to reward hypersensitivity and, thus, reward anticipation. An individual's level of impulsivity can be considered a personality trait as well as a state; however, the current study will focus on trait-level impulsivity. Trait-level impulsivity has been demonstrated to be associated with suicidal behaviors, substance abuse, eating disorders, anti-social personality disorder, and borderline personality disorder (McHugh et al., 2019; Acton, 2003; Claes et al., 2005; Swann et al., 2009; Mortensen et al., 2010). These findings highlight the necessity of characterizing the role of impulsivity in reward sensitivity as it relates to internalizing mood disorders (e.g., MDD and

BD) and correlated externalizing coping strategies and symptoms (e.g., excitement seeking, boldness). As impulsivity can be considered an excessive motivation to pursue rewarding stimuli (in contrast to anhedonia), impulsivity will likely be a marker of exaggerated reward anticipation.

Behavioral measures are an integral part of a psychoneurometric approach, as they provide insight into the functional outcomes associated with dispositional traits. Reaction time could serve as an indicator of reward anticipation by quantifying an individual's impulsivity or cautiousness when responding in a monetary reward task (Li et al., 2020). If an individual responds faster, it may indicate impulsivity, a trait-level indicator for reward anticipation. However, if an individual demonstrates slower reaction times, it may indicate more cautiousness or less sensitivity to the prospect of reward. Thus, incorporating reaction time into the psychoneurometric operationalization of reward sensitivity will demonstrate how these personality traits and neural markers implicate consequential behavior during cognitive tasks.

The Stimulus Preceding Negativity (SPN) serves as a direct neurophysiological measure of reward anticipation, particularly the substage of feedback anticipation, which will be imperative to incorporate into the psychoneurometric operationalization of reward anticipation. The SPN occurs within a 200 ms interval prior to feedback receipt and has been demonstrated to be related to anticipatory attention, such that it is elevated (i.e., more negative) prior to positive feedback (Kotani et al., 2001). The SPN is especially valuable in assessing passive anticipation of monetary incentives, making it an ideal anticipation index during a randomized guessing task resulting in monetary gains (Glazer et al., 2018; Knutson & Greer, 2008). Since the task used in the current study is a randomized guessing task, the SPN will serve as an indicator of the extent to which individuals anticipate outcomes.

Initial Response to Reward

RDoC describes the initial response to reward as processes caused by the initial presentation of rewarding stimuli, demonstrated through language, behavior, and neurophysiological activity (*About RDoC*, n.d.). Unlike reward anticipation, RDoC has laid out several underlying mechanisms of the initial response to reward, including molecules like endocannabinoids, circuits involving the nucleus accumbens, behaviors like taste reactivity, self-report measures including the Positive and Negative Affect Schedule, and simple guessing task paradigms such as the one used in the current project (*About RDoC*, n.d.). Beyond self-report

measures of affect, measures of valuation, the process of assigning salience to rewarding stimuli, is a crucial indicator of the initial hedonic response to reward. Reward valuation is its own subconstruct in the RDoC positive valence systems; however, it is highly related to reward response as it indicates how individuals make meaning of rewarding stimuli upon initial receipt, assessed through measures of what kinds of rewards individuals attend to and find attractive. Including valuation in the operationalization of reward response will capture hedonic response to specific stimuli, whereas the current RDoC matrix conceptualizes valuation solely in terms of decision-making. In addition to a self-report measure of valuation (i.e., reward preference), I utilized three EEG components to define initial response to reward: the reward positivity (RewP) ERP, the P300 ERP, and delta frequency power.

Valuation, or assigning importance based on representations of the environment before receiving feedback, can be assessed by evaluating what kinds of stimuli are rewarding to individuals (Hélie et al., 2017). When faced with multiple decisions, individuals use valuation to make selections based on available information regarding what they expect will be most rewarding (Montague & Berns, 2002). These valuation decisions are specific to individuals and their context. Although valuation can be used for reward learning and future decision-making, it is rooted in the initial response to reward by appraising hedonic response to specific rewarding stimuli. For instance, valuation represents whether an individual finds a stimulus rewarding and, if so, how rewarding. Explicitly assessing valuation will provide insight into the kinds of rewards eliciting more positive responses in individuals. Integrating self-report valuation measures with EEG reward response markers allowed me to index both the type of stimuli and the extent to which stimuli are rewarding to individuals.

The Reward Positivity, or RewP, is an ERP occurring at approximately 250 to 350 ms at frontocentral locations following feedback and tends to be larger following rewards than losses (Mackin et al., 2023; Moser et al., 2018; Holroyd et al., 2008). The RewP has been demonstrated to be related to individual differences in reward evaluation, reward salience, reward learning and anhedonia such that blunted reward responses are associated with blunted RewP amplitude (Glazer et al., 2018; Whitton et al., 2016; Liu et al., 2014; Bress et al., 2013; Hager et al., 2022). Given these findings linking RewP amplitude with several facets of reward appraisal (e.g., salience, learning, evaluation), using the RewP as a measure of the initial response to reward receipt will be valuable. Regarding the task utilized in the current project, RewP amplitude

should be, on average, larger following reward trials than loss trials. Still, it should also track with individual differences in personality traits and mood symptoms.

The P300 is an ERP occurring approximately 300 ms following the presentation of task-relevant stimuli (Sara et al., 1994). Previously, the RewP and the P300 have been used together to study reward magnitude, demonstrating that P300 amplitude is positively associated with reward magnitude (Sato et al., 2005). The P300's relationship with reward magnitude exemplifies its relevance to the initial response to reward. Further, individuals who report increased trait levels of anhedonia tend to demonstrate blunted P300 amplitude (Santopetro et al., 2022). Including the RewP and the P300 will further our understanding of individual differences in reward sensitivity, as each component reflects somewhat different aspects of reward processing. The feedback-related P300 has previously been implicated in reward processes reflecting motivational salience and affective processes of reward (Donchin, 1981; San Martín, 2012). Outside of reward tasks, the P300 is used to indicate attention and learning (Polich, 1986). Thus, the RewP seems to be clearly reflective of reward response and individual differences in reward sensitivity, whereas the P300 may demonstrate a more nuanced relationship to individual differences in reward sensitivity. The current study will enable a closer look at how these different neurophysiological mechanisms reflect individual differences in reward appraisal and sensitivity. However, given evidence that the P300 is modulated by rewarding feedback and is associated with individual differences in reward sensitivity, I expect it to reflect the initial response to reward.

The delta frequency (<3 Hz), which modulates RewP and P300 amplitude, has been implicated in several aspects of reward processing in both the anticipatory and response phases (Bernat et al., 2007). Regarding initial response to reward, delta power has been positively associated with reward learning and performance evaluation as well as monetary rewards, and it has been negatively associated with depressive symptoms (Cavanagh, 2015; Foti et al., 2015). Delta has been shown to modulate P300 activity, particularly following monetary gains (Bernat et al., 2015; Bernat et al., 2011). Like the P300, delta power has been associated with the appraisal of reward magnitude following receipt, demonstrating its relevance to the initial response to reward (Bernat et al., 2015). Further, blunted delta response elicited by the same randomized guessing task used in the current project has been demonstrated to predict the onset of MDD (a disorder characterized by decreased reward response), and delta-modulated RewP

activity following reward (Nelson et al., 2018). Due to delta power's established relationship with reward outcome and response as well as its relationship to ERPs representing reward response (RewP and P300), it will be critical to include delta power in a psychoneurometric model of the initial response to reward.

Aims and Hypothesis

The primary aim of the current project was to operationalize reward sensitivity as a psychoneurometric composite by integrating self-report, behavioral, and neurophysiological data using the approach described in Yancey et al. (2016). See Figure 1 for an outline of the proposed psychoneurometric operationalization of reward sensitivity.

I hypothesized that once all self-report, behavioral, and neurophysiological data were integrated, two subfactors of reward sensitivity would emerge representing phases of reward: reward anticipation and the initial response to reward. Reward anticipation would be indexed by self-report measures of anhedonia and impulsivity, reaction time, and the SPN ERP. A valuation self-report measure (e.g., the reward sensitivity subscale of the Sensitivity to Punishment and Sensitivity to Reward Questionnaire, which assesses the types of experiences an individual finds rewarding), and several EEG components (the RewP ERP, the P300 ERP, and delta power) would index initial response to reward. Anhedonia would be cross-loaded between both subfactors of reward sensitivity.

Methods

Participants

Participants were recruited from Lansing, Michigan to participate in an investigation of familial transmission of neurobehavioral liabilities for internalizing and externalizing pathways to substance use problems (see Moser et al., 2018). The current study focused on the adult parents who participated in the more extensive study. Participants were recruited through the Michigan Longitudinal Study (MLS), a longitudinal study assessing the familial risk of neurobehavioral liabilities associated with risk for substance use disorders (SUDs), and Craigslist. Participants received $75 cash. A subset of participants with useable data for the current purposes represented the final sample (N = 110 adults, 63.64 % female, 39.09% MLS Sample). See Table 1 for demographic information including age and racial background.

Guessing Task Procedure

While undergoing electroencephalography (EEG) recording, participants completed a guessing task, also referred to as the Doors Task, in which they were presented with an image of two doors on a computer screen. Participants were asked to select which door they believed hid a monetary reward, using keyboard buttons "C" to choose the left door and "N" to choose the right door. The doors remained on the screen either until the participant selected a door or 4000 ms had passed. After making a choice, participants were presented with a fixation cross (+) in the center of the screen for 1000 ms, with feedback following for 2000 ms. Participants were told they would either gain $0.50 (which was indicated by a green "↑") or lose $0.25 (which was indicated by a red "↓"). Following feedback, participants were instructed to press the spacebar to begin the next trial. The likelihood of winning a trial was 50%, regardless of the actual choice made by the participant, and the participants were naïve to the random nature of the task. First, there was a practice block of 10 trials (5 gain trials, 5 loss trials) to ensure participants understood the task. After the practice block, participants completed 6 blocks of 10 trials each. At the end of each block, participants received information about the money earned in the game up until that point.

Electroencephalography Recording and Data Processing

EEG recording was collected continuously by the ActiveTwo system (BioSemi, Amsterdam, The Netherlands) from 64 Ag-AgCl electrodes embedded in a stretch-lycra cap according to the 10/20 system. Two electrodes were placed on the left and right mastoids as

reference electrodes. Electrooculogram activity (i.e., eyeblink and movements) was recorded with three electrodes placed inferior to the left pupil and on the left and right outer canthi and at FP1. The Common Mode Sense active electrode and Driven Right Leg passive electrode formed the ground during acquisition. All signals were digitized at 1024 Hz via BioSemi's ActiView software. EEG processing and analysis were performed using BrainVision Analyzer 2 (BrainProducts, Gilching, Germany). Scalp electrodes were re-referenced to the numeric mean of the mastoids and bandpass filtered with cutoffs of 0.1 and 30 Hz (12 dB/oct roll-off). Ocular artifacts were corrected using the method developed by Gratton et al. (1983). Physiologic artifacts were rejected if they met the following criteria (detected by a computer-based algorithm): a voltage step exceeding 50 μV between contiguous sampling points, a voltage difference of >200 μV within a trial, or a maximum voltage difference of <0.5 μV within a trial.

Reaction Time

Reaction time was recorded in milliseconds and was locked to when participants chose between the two doors.

Reward Anticipation Questionnaires

Before the guessing task, participants completed a battery of self-report measures related to several aspects of risk for psychopathology. Participants' data was considered useable if they responded to at least 80% of items. For each measure, mean imputation was used for missing items.

Global Behavior Inventory (GBI)

The GBI is a 73-item inventory of behaviors contributing to the risk for depressive and bipolar disorders (Depue et al., 1981). Each item is scored on a four-point Likert scale from *1 (Never or Hardly Ever)* to *4 (Very Often or Almost Constantly)*. An example item is: *Have there been periods lasting several days or more when you lost almost all interest in people close to you and spent long times by yourself?* Per Pendergast et al. (2015), there are three mood factors evaluated on the measure: total depressive symptoms, total hypomanic symptoms, total biphasic (cross-loaded) symptoms. Depressive symptoms include feeling sad, hopelessness, loss of interest, low energy/anhedonia, sleep disturbance, cognitive disturbance (down), depressive irritable mood, guilt, somatic symptoms, atypical features, and sad appearance. Hypomanic symptoms include increased energy, elevated mood, high drive, rage, cognitive disturbance (up), and grandiosity. Biphasic symptoms include mood never in the middle and extremes of mood

and energy. Loss of interest, low energy/anhedonia, and high drive were included in the current analysis to proxy anhedonia and increased drive.

BAS-BIS

The BAS-BIS is a 24-item measure with two subscales assessing the Behavioral Activation System (BAS) and the Behavioral Inhibition System (BIS). BAS items, which will be used in the proposed study, have three subscales for drive, fun-seeking, and reward responsiveness (Carver & White, 1994). Each item is measured on a four-point Likert scale from *1 (Very true for me)* to *4 (Very false for me)*. An example item is: *When I'm doing well at something I love to keep at it*. Scores from each subscale – drive, fun-seeking, and reward responsiveness – were used in the current study to index motivation and traits associated with trait impulsivity like fun-seeking and reward responsiveness.

Boldness Inventory

The Boldness Inventory is a 19-item excerpt from the Triarchic Psychopathy Measure, measuring boldness in interpersonal behavior, emotional experience, and venturesomeness (Patrick et al., 2009). Each item is scored on a four-point Likert scale from *1 (False)* to *4 (True)*. An example item is: *I never worry about making a fool of myself with others*. Total boldness was used to index boldness, a personality trait similar to fearlessness, which is associated with trait impulsivity (Patrick et al., 2009).

Externalizing Spectrum Inventory Brief From (ESI-bf)

The ESI-bf is a 160-item inventory of experiences characteristic of dysfunctional impulse control (Patrick et al., 2013). Each item is scored on a four-point Likert scale from *1 (True)* to *4 (False*). An example item is: *I get in trouble for not considering the consequences of my actions*. Subscales include problematic impulsivity, irresponsibility, theft, fraud, impatient urgency, lacks planful control, lacks dependability, alienation, boredom proneness, blaming external factors, lacks honesty, rebelliousness, physical aggression, destructive aggression, relational aggression, lacks empathy, excitement seeking, cannabis use, cannabis problems, alcohol use, and alcohol problems. These subscales load onto general disinhibition, callous aggression, substance abuse, and total externalizing symptoms. Problematic impulsivity, impatient urgency, lacks planful control, excitement seeking, and boredom proneness were used in the current study to measure impulsivity.

Hypomanic Personality Scale (HPS). The HPS is a 45-item measure with three subscales for social vitality, mood volatility, and excitement. The measure intends to identify personality traits often associated with hypomanic symptoms and individuals at-risk for bipolar disorders (Eckblad & Chapman, 1986). All items are scored as either *True* or *False*. An example is: *I often feel excited and happy for no apparent reason*. The excitement subscale was used in the current study as an index of hypomanic drive or trait-level impulsivity.

Reward Anticipation Neurophysiology

SPN. The stimulus-locked SPN is time-locked to the onset of feedback regardless of gain or loss feedback at midline occipital location Oz (Moser et al., 2009; Bowyer et al., 2022). The SPN has several subcomponents, but this project uses the late SPN, which indexes anticipation of imperative stimuli. To capture anticipation, the SPN was baseline corrected from -1200 to -1000 ms. Then, the SPN was calculated as the average amplitude of the waveform in the 200 ms window preceding the feedback presentation, as defined in (Glazer et al., 2018), to reflect anticipation of feedback following the selection of the door.

Initial Response to Reward Questionnaires

Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ). The SPSRQ is a 39-item measure with two subscales: sensitivity to punishment, which is based on the BIS system, and sensitivity to reward, which is based on the BAS system (Torrubia et al., 2001). The original version of the SPSRQ has 48 items, but this project used a short form with 39 items. Because there is no published work on the validity of this short form, response averages were used for the SPSRQ score rather than totals. All items are scored as either *Yes (1)* or *No (0)*. An example item is: *Do you often do things to be praised?* The sensitivity to reward subscale was used to measure valuation.

Initial Response to Reward Neurophysiology

All three neurophysiological indices of reward response (RewP amplitude, P300 amplitude, delta power) were baseline corrected from -200 to 800 ms, locked to the onset of feedback.

RewP

As per previous literature, the stimulus-locked RewP is defined as the average amplitude between 215-315 ms at the midfrontal electrode FCz following the onset of the green or red arrow feedback stimuli (Moser et al., 2018; Mackin et al., 2023; Santopetro et al., 2021). Reward

and loss feedback waveforms were averaged separately, and the RewP was calculated by subtracting loss amplitude from reward amplitude (i.e., gain trials average waveform – loss trials average waveform) (Holroyd et al., 2008; Mackin et al., 2023; Santopetro et al., 2021).

P300

The gain-related P300 was used in this study as an indicator of the initial response to reward. Thus, the P300 will be calculated following procedures for the feedback-P300 described in Santopetro et al. (2021). The P300 will be calculated as the average activity from 300 ms to 500 ms following the onset of gain feedback (the green arrow) at central-parietal electrode location CPz.

Delta Power

Similar to the procedure outlined in Nelson et al. (2018), the feedback-locked ERP at FCz was averaged separately for trials presenting gain feedback and loss feedback were decomposed into a time-frequency metric using Morlet wavelets (with a Morlet Parameter equal to 5) which increased 20 logarithmic steps from .05 to 20 Hz to capture low-frequency delta activity. To estimate frequency band-specific power at each time point, the absolute value of the signal was squared (Nelson et al., 2018). Like the feedback-related ERPs, power was baseline corrected from -200 to 800 ms, locked to the onset of feedback. Then, the difference was calculated between gain and loss trials. Delta was captured as activity within the 1.6-4.13 Hz range from 50 to 250 ms. This time window was selected as the maximum gain-loss delta power difference following the onset of feedback.

Analyses

All analyses were completed in IBM SPSS Statistics (Version 28; IBM Corp., 2023) and R (R Foundation for Statistical Computing, Vienna, Austria., 2022). Statistical analysis followed the approach outlined in (Yancey et al., 2016). First, bivariate correlation analyses were calculated to assess relationships between all variables. Then, an exploratory factor analysis, using principal components analysis, with a promax rotation was used to test the proposed psychoneurometric reward sensitivity dimensions. Promax rotation was used to account for any potential correlations between factors. Specifically, I hypothesized there would be a two-factor solution: one factor representing reward anticipation metrics and the other representing the initial response to reward metrics (see Figure 1 for hypothesized organization of measures). Anhedonia

would cross-load between the two factors such that there is an equivalent loading score for anhedonia metrics on both reward anticipation and response to reward dimensions.

Results

Descriptive Statistics

See Figure 2 for the SPN average amplitude waveform at Oz and headmap. As previously discussed, the late SPN does not capture the entire negativity leading up to the onset of feedback, but rather, the 200 ms immediately preceding feedback to reflect the later stages of anticipation. This negativity was most predominant at occipital location Oz (similar to Bowyer et al., 2022). Average SPN amplitude was -2.810 μV (*SD* = 3.303). A one-sample t-test indicated SPN amplitude was significantly less than 0, validating the enhancement of the negative-going ERP just prior to feedback, $t(109) = -8.921$, $p < .001$.

See Figure 3 for the RewP average amplitude waveform at FCz and headmap. As demonstrated in the figure, the difference between gain and loss trials was maximal from 215-315 ms at the midfrontal electrode FCz. Average RewP amplitude (the difference between gain and loss trials) was 1.804 μV (*SD* = 2.921). A one-sample t-test demonstrated RewP amplitude was significantly greater than 0, validating larger positivity following gains than losses, $t(109) = 6.479$, $p < .001$.

See Figure 4 for the gain-related P300 average amplitude waveform at CPz and headmap. The P300 peaked around 300 to 500 ms following the onset of gain feedback with an average amplitude of 11.855 μV (*SD* = 5.231). A one-sample t-test demonstrated the P300 amplitude was significantly greater than 0, validating the prominent positive going wave following gain feedback, $t(109) = 23.768$, $p < .001$.

See Figure 5for the time-frequency plot depicting the difference between gain and loss trials in the delta frequency at FCz. The average difference between the two trial types was .854 $\mu V^2/Hz$ but there was a large amount of variance in this difference (*SD* = 16.947). A one-sample t-test indicated the difference between trial types was not significantly different from 0 ($t(109) = .529$, $p = .598$). Although these findings indicate the difference between gain and loss delta power may not be the optimal indicator for delta power, further analyses were run with and without delta power. There were no meaningful differences between the two EFAs and, as such, delta power remained in the model.

See Table 2 for mean values and standard deviations for each neurophysiological, self-report, and behavioral index.

Bivariate Correlations

See Table 2 for the bivariate correlations between the neurophysiological and behavioral indices with self-report measures.

Although the neurophysiological and behavioral indices were not related to any of the self-report measures, there were notable correlations amongst the neurophysiological and behavioral variables themselves. SPN amplitude was significantly negatively correlated with RewP (r = -.216, p < .05) and P300 (r = -.280, p < .05) amplitudes. Since the SPN is a negatively deflecting ERP, and the RewP and P300 are positively deflecting ERPs, these relationships indicate that increased anticipation (i.e., more negative SPN amplitude) was related to increased reward response (i.e., more positive RewP and P300 amplitudes). SPN amplitude was also significantly positively correlated with reaction time (r = .260, p < .05), such that increased anticipation to feedback was related to slower selection between the doors.

In addition to its relationship with SPN amplitude, RewP amplitude was significantly positively correlated with P300 amplitude (r = .448, p < .05), such that as RewP amplitude increased, P300 amplitude increased. These relationships amongst the P300, RewP, and SPN align with prior studies given the sensitivity of these ERPs to rewarding and arousing stimuli leading them to trend together (Bowyer et al., 2022; Santopetro et al., 2021). RewP amplitude was also significantly negatively related to reaction time (r = -.229, p < .05), such that faster reaction times to the doors were related to increased response to feedback. Delta power did not demonstrate any statistically significant relationships with any variables.

See Table 3 for the bivariate correlations between all self-report measures. Generally, most of the self-report measures were positively related with each other (with the exception of Boldness Inventory – Boldness Total demonstrating negative relationships with other self-report measures). The largest correlations tended to be amongst variables from the same measures. For example, the correlation between ESI Problematic Impulsivity and ESI Impatient Urgency was .615 (p < .05). Interestingly, the items from the depression subscale of the GBI (Low Energy/Anhedonia and Loss of Interest) were positively related to many variables associated with hypomanic symptoms. For example, the relationship between GBI Loss of Interest and GBI High Drive was .452 (p < .05), and the relationship between GBI Low Energy/Anhedonia and ESI Problematic Impulsivity was .391 (p < .05).

Exploratory Factor Analysis (EFA)

The EFA supported a six-factor solution such that each factor had an eigenvalue greater than 1. See Figure 6 for the scree plot of eigenvalues and Table 4 for the total variance explained by each of the six components. These six components accounted for 66.031% of the total variance in the data.

Table 5 describes how each variable loaded onto the different components, and Table 7 presents the pattern matrix, explaining how each variable uniquely contributes to the variance of each component. Only correlations at or above .300 in the components matrix (Table 5) were considered meaningful and were retained for the current analysis. Figure 7 presents a path figure of the six-factor solution along with bivariate correlations between factors and variables. The factors have a Cronbach's alpha reliability coefficient of 0.620, suggesting acceptable reliability of the model.

Component 1: P-factor/Questionnaire Methods Variance

Given that the first component, which explained 24.008% of the variance, contains only questionnaire data, most of which pull for psychopathology (i.e., all questionnaires except for BAS – Reward Responsiveness and Boldness Inventory – Total Boldness), it appears this first factor can be considered to represent the p-factor. This is supported by all questionnaires within this factor being positively loaded, suggesting endorsing some psychopathology is related to endorsing other kinds of psychopathology. Further, this factor may represent methods variance due to the inclusion of most self-report variables.

Component 2: Trait-Level Approach Motivation/Task Disengagement

As the second component, which explained 12.065% of the total variance, included positively loaded self-report measures of drive [BAS – Drive (r = .511), BAS – Fun Seeking (r = .592), BAS – Reward Responsiveness (r = .535)] but negatively loaded measures of anhedonia [GBI – Low Energy/Anhedonia (r = -.526), GBI – Loss of Interest (r = -.591)], this factor appears to represent trait-level approach motivation. This is further supported by the neurophysiological loadings. SPN amplitude (r = .526) positively loads onto this component. Given the SPN is a negatively deflecting ERP, this positive relationship reflects decreased anticipation to feedback during the randomized guess task. Further, RewP amplitude (r = -.313) and P300 amplitude (r = -.393) both negatively load onto this component. Since these are both positively deflecting ERPs, these negative relationships indicate decreased response to feedback

during the randomized guessing task. As such, there is a discrepancy within this factor between trait-level approach motivation (as indexed by BAS subscales and GBI anhedonia measures) and state-level indices of reward sensitivity during the randomized guessing task (ERP amplitudes). The second factor may be differentiating individual differences between trait-level motivation and disengagement with the behavioral task.

Component 3: General Reward Sensitivity

The third component explains 9.545% of the variance and included positively loaded measures of boldness [Boldness Inventory – Total Boldness (r = .322)], RewP amplitude (r = .679), and P300 amplitude (r = .623). Since a measure of reward anticipation (Boldness Inventory – Total Boldness) and two neurophysiological measures of reward response, RewP and P300 amplitudes, positively load onto this factor, it includes variables from both the predicted reward anticipation and reward response factors, indicating the third component represents general reward sensitivity processes rather than specific temporal phases of reward sensitivity.

Component 4: Excitement Seeking

The fourth component, which explains 7.808% of the variance, includes a negatively loaded measure of drive [BAS – Reward Responsiveness (r = -.491)] and positively loaded measures of reward anticipation including boldness [Boldness Inventory – Total Boldness (r = .751)] and impulsivity [ESI – Excitement Seeking (r = .525)]. Since BAS – Reward Responsiveness is a measure of drive and both Boldness and ESI – Excitement seeking include items about recklessness and stimulation seeking behaviors, the factor seems to represent excitement seeking more broadly.

Component 5: Impulsivity

The fifth component explains 6.672% of the variance. This component includes negatively loaded measures of anhedonia [GBI – Low Energy/Anhedonia (r = -.371] and valuation [SPSRQ – Sensitivity to Reward (r = -.362)] and positively loaded measures of impulsivity [ESI – Problematic Impulsivity (r = .329) and ESI – Lacks Planful Control (r = .595)]. Considering the opposing relationships with anhedonia/reward response and impulsivity, the fifth factor indexes impulsivity.

Component 6: State-Dependent Response to Reward

The sixth component explains 5.933% of the variance and contains positively loaded neurophysiological and behavioral indices [SPN amplitude (r = .343), RewP amplitude (r = .329), reaction time (r = .411)] and negatively loaded delta power (r = -.725). The positively loaded SPN amplitude and reaction time (i.e., slower reaction time) indicate decreased anticipation towards reward. In contrast, one of the neurophysiological indices of response to reward (RewP amplitude) is positively loaded onto the component. Given the t-test previously described regarding delta power, this may not be the most reliable calculation of delta power. Since there are discrepancies between the loadings of anticipation and response variables, with response variables positively loaded, this factor may describe individual differences in reward response as a related, but distinct, process from preparing for rewards. Further, since P300 amplitude, which is often associated with attention, does not load onto this factor, the factor may represent something unique about hedonic response rather than attentional control, differentiating the roles of P300 and RewP amplitude in reward response (Polich, 1986). Considering this factor only contains measures from the randomized guessing task, it is important to note this factor may represent state differences rather than more stable personality traits. It likely also captures method variance for indices from the Doors Task.

Relationships Amongst Variables and Components.

See Table 6 for bivariate correlations amongst the components. All factors were positively related, besides State-Dependent Response to Reward (Component 6), which demonstrated significant negative relationships with all factors besides the P-factor (Component 1), distinguishing state-depending reward response as a unique factor distinct from other personality trait factors. Table 7 presents the pattern coefficients which index how much each variable uniquely contributes to each component. Table 8 presents the communalities, how much variance within each variable can be explained by the components. At least 50% of each variable's variance could be explained by the six factors that emerged.

Discussion

The aim of the current study was to use a psychoneurometric approach to index reward sensitivity, a facet of the positive valence system in RDoC, by integrating self-report, neurophysiological, and behavioral data. I hypothesized that there would be a two-factor solution with components representing reward anticipation and initial response to reward. Instead, the EFA suggested a six-factor solution, with components representing: the P-factor/Questionnaire Methods Variance, Trait-Level Approach Motivation/Task Disengagement, General Reward Sensitivity, Excitement Seeking, Impulsivity, and State-Dependent Response to Reward.

Interestingly, the general reward sensitivity factor which emerged did not include any self-report measures of hypomanic/depressive symptoms (e.g., impulsivity, anhedonia) or valuation. Instead, the factor consisted of boldness, a reward anticipation personality trait associated with hypomanic symptoms, and neurophysiological indices of initial response to reward (i.e., P300 and RewP amplitudes). Increased RewP and P300 amplitudes following the onset of positive feedback suggest increased response reward (Glazer & Nusslock, 2022). Given the integration of self-report and EEG variables from both reward anticipation and response to reward, this factor broadly represents reward sensitivity. Even though these variables were not predicted to load onto the same factor, the contributions of each of these variables theoretically aligns with prior studies of reward sensitivity. This can be seen in prior literature through positive relationships between each neurophysiological index (P300 and RewP) and reward processing (Bowyer et al., 2021; Sato et al., 2005; for a review: Glazer et al., 2018). Additionally, past studies have linked neurophysiological indices of reward with hypomanic symptoms and associated personality traits (Glazer et al., 2019).

Although it contrasts with hypotheses, having separate components for Trait-Level Approach Motivation, Excitement Seeking, and Impulsivity align with other conceptualizations of reward sensitivity. Given the Reward Sensitivity Model of mood disorders, hypomanic symptoms (e.g., impulsivity, reckless behavior, increased drive) can be considered a result of hypersensitivity to reward (Alloy et al., 2016). High drive and impulsivity are two characteristic traits of hypomania (Stange et al., 2012; Benazzi, 2007). These three distinct, but theoretically related, constructs may represent two facets of hypomanic tendencies within the current study.

Although the current study failed to produce a two-factor psychoneurometric index of reward sensitivity based on the temporal phases of reward anticipation and initial response to

reward, the six-factor solution identified multiple traits which, in excess, can result in hypomanic symptoms (Trait-Level Approach Motivation, Excitement Seeking, and Impulsivity) as separate constructs contributing to the latent construct. As such, future iterations of the RDoC matrix might consider adding more specific subconstructs – such as specific symptoms and risk factors for hypomania like motivation, excitement seeking, and impulsivity – to its Reward Responsiveness construct. Currently, the Reward Responsiveness construct (and even the Positive Valence System as a whole) does not include any explicit self-report or behavioral measures of these traits (*About RDoC*, n.d.).

In addition to the systems and their subconstructs provided in the RDoC matrix, the units of analysis portions of the matrix provide guidance on measures and paradigms to evaluate these systems and subconstructs in empirical research. Currently, a simple random guessing task is included in the RDoC matrix, within the reward anticipation subconstruct of reward responsiveness (*About RDoC*, n.d.). RDoC is likely referring to the Doors Task used in this study; however, they should specify the kinds and quantities of rewarding stimuli involved in the paradigm. Prior literature has demonstrated that the kind of rewarding stimuli presented in these paradigms impacts the resulting relationships between personality traits and states with reward response (Banica et al., 2022). There may be something unique about monetary rewards impacting state-dependent motivation, which should be considered in future studies. Additionally, considering indices collected during the Doors Task cross-loaded between factors representing trait-level approach motivation/task disengagement, general reward sensitivity, and state-dependent response to reward, the Doors Task could be cross-listed in the matrix within reward anticipation and initial response to reward.

Limitations and Future Directions

These findings highlight key methodological issues with the psychoneurometric approach. Within each of the factors, generally, variables were either self-report or neurophysiological (except for the Trait-Level Approach Motivation/Task Disengagement and Reward Sensitivity factors). Thus, it seems the type of methodology explained a significant portion of the variance, rather than variance being explained by theoretically linked variables. Even further, the self-report measures which loaded together in the first factor representing the p-factor were all measures used to explicitly evaluate psychopathology. If the goal of the psychoneurometric approach, and, more broadly, dimensional models of psychopathology, is to

integrate multiple sources of data to index a continuum of latent variables from healthy to pathology, saturating the models with a multitude of self-report questionnaire measures may lend itself to identifying singular general factors (e.g., the p-factor). Although general factors do have merit, they do not describe causal mechanisms or how latent variables differentially contribute to these general factors (Watts et al., 2024).

In the original implementation of the psychoneurometric approach, factor analyses contained few variables from different sources. For example, in Yancey et al. (2016), the authors only used one self-report measure alongside three psychophysiological variables coming from different sources (i.e., heart rate, electromyography, and startle blink response). In the current study, there were twelve self-report measures alongside one behavioral measure and four EEG measures. The increased number of variables and decreased variability in the type of variables may have contributed to the large impact of methodology on variance explained in the current project. As such, future studies attempting to implement a psychoneurometric approach to index latent variables should consider using fewer, but more specific, variables in their operationalization.

Further, most self-report measures included in the current study pull for psychopathology (e.g., the GBI tracks mood disorder symptoms) and other negative associated personality traits (e.g., the ESI tracks many externalizing symptoms including callous aggression). The BAS and Boldness Inventory were the only two measures which measure more positive traits like drive, motivation, confidence, fearlessness, and self-esteem. If dimensional models aim to represent the spectrum of healthy to pathological levels of traits, including only negatively valanced scales can lead to issues like response bias, malingering, and impression management. These psychometric issues can contribute to general psychopathology factors emerging. As researchers develop dimensional models of psychopathology, they should consider constructing new scales tracking individual differences in latent variables rather than DSM-5 diagnostic criteria.

A final limitation of the current study is sample size. Despite the study including 110 participants, it may have been underpowered with the number of heterogeneous included variables. Within factor analysis, less than 150 participants is considered a small sample size (Kyriazos, 2018). Future studies implementing a psychoneurometric approach to EFA should aim to include at least 150 participants, and ideally 300 to 400, to ensure reliability of correlations amongst variables (Kyriazos, 2018).

Concluding Remarks

Overall, the current study aimed to use a psychoneurometric approach to operationalize reward sensitivity comprising two factors representing temporal phases of reward processing, anticipation and initial response. Although the EFA revealed six factors, including three factors which cut across methodologies (Trait-Level Approach Motivation/Task Disengagement and General Reward Sensitivity), the current study highlights challenges to using multiple units of measurement in dimensional models. Future studies should consider developing their own self-report scales of latent constructs rather than depending on currently available measurement tools which often are based on DSM-5 categorical symptoms.

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APPENDIX

Figures and Tables

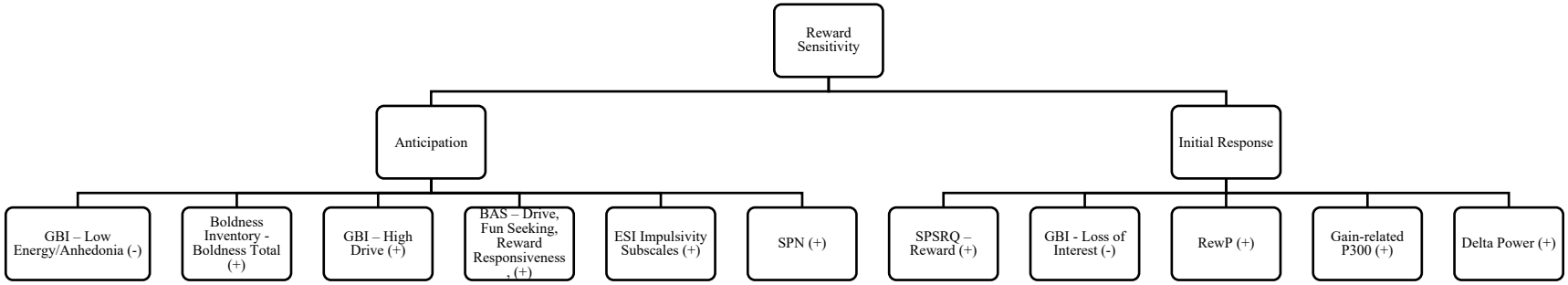

Figure 1. Proposed psychoneurometric model of reward sensitivity using self-report and EEG indices.

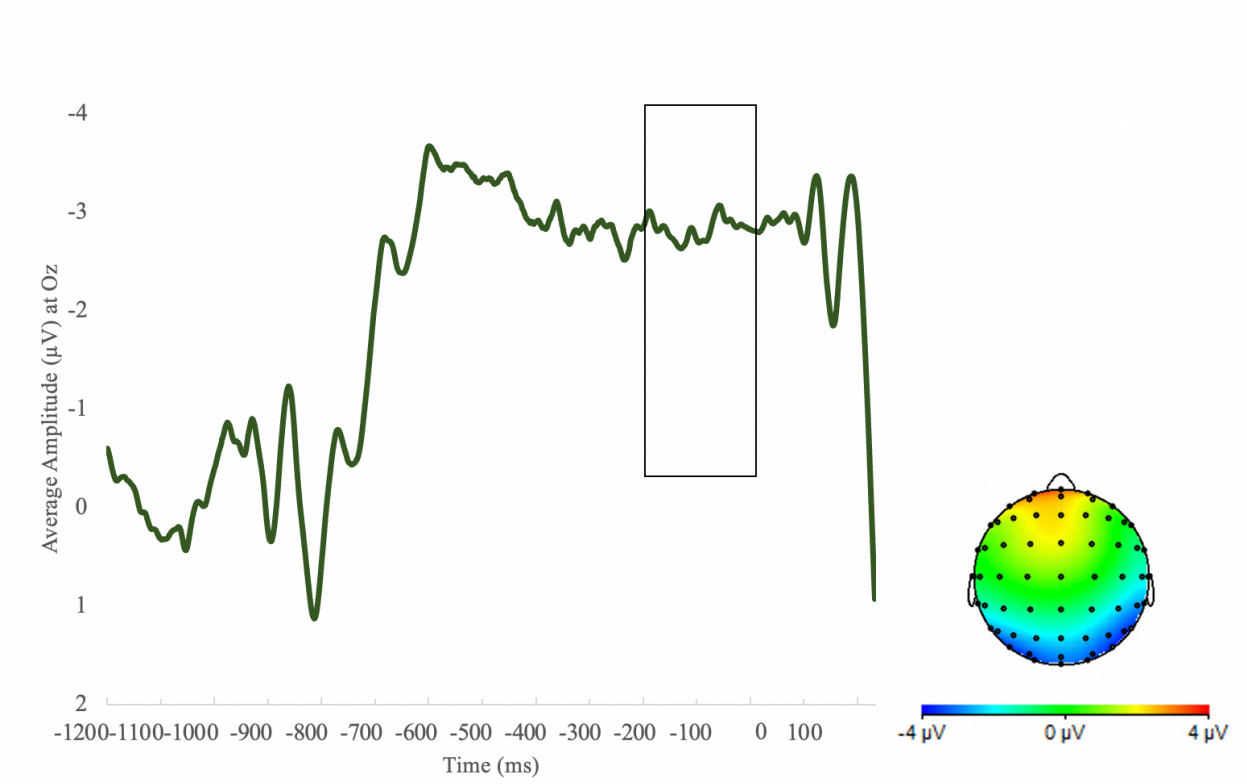

Figure 2. SPN waveform and headmap. The SPN is the average amplitude at occipital location Oz during the 200 ms immediately preceding the receipt of feedback (i.e., the green or red arrow), regardless of win or loss. 0 ms indicates the onset of feedback (i.e., the green or red arrow). The headmap depicts decreased activity (blue) at occipital locations during this time window.

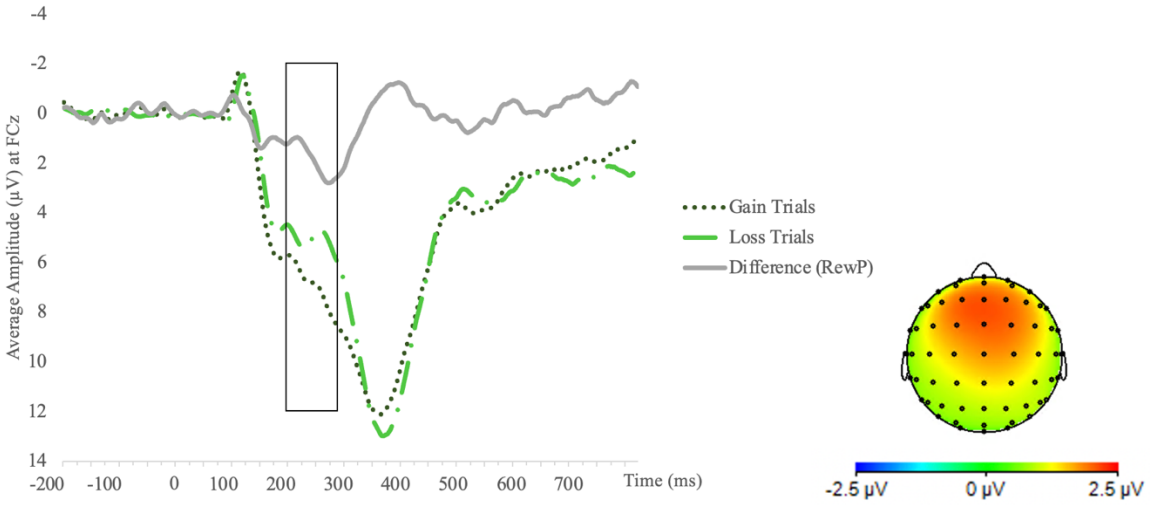

Figure 3. RewP waveform and headmap. The RewP is the difference between gain and loss trials from 215 to 315 ms following the onset of feedback at frontal-central location FCz. 0 ms indicates the onset of feedback (i.e., the green or red arrow). The headmap depicts increased activation (red) at frontal central locations during this time window.

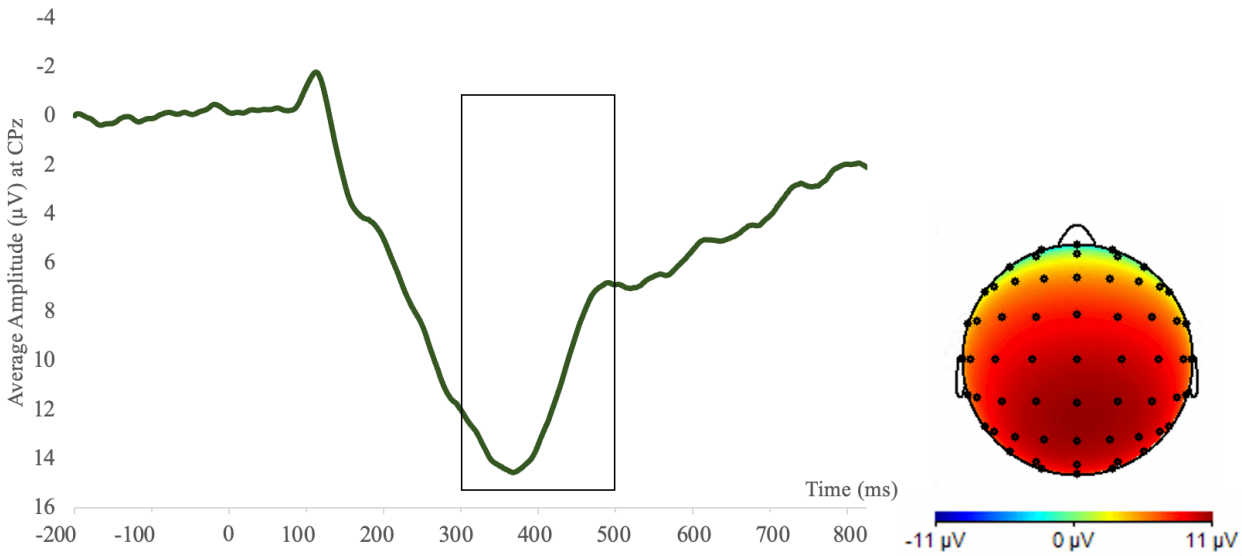

Figure 4. P300 waveform – gain trials. The gain-related P300 is the average amplitude 300-500 ms following the onset of feedback (i.e., the green arrow) at central-parietal location CPz. 0 ms represents the onset of the feedback. The headmap depicts increased activity (red) at central-parietal locations during this time window.

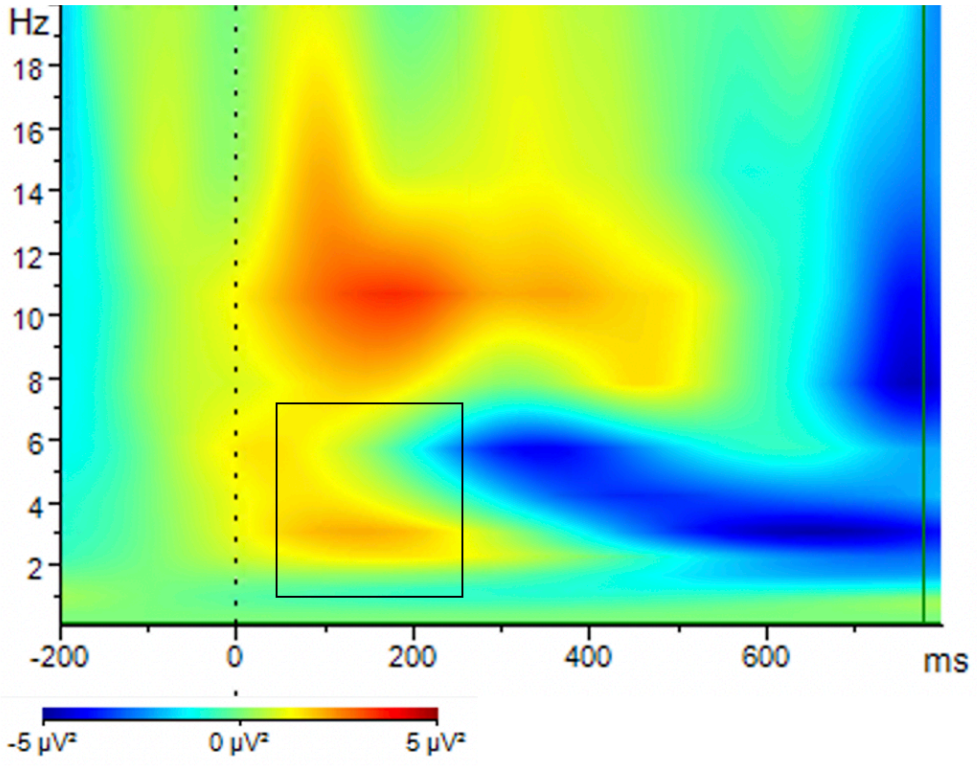

Figure 5. Delta power difference for gains minus losses. Delta was extracted using a Morlet wavelet transformation with 20 logarithmic steps ranging from .05 to 20 Hz. Delta power was calculated as the average delta frequency occurring from 50 to 250 ms following losses subtracted from the average delta frequency occurring from 50 to 250 ms following gains. Delta frequency was more sensitive to gain trials compared to losses, as depicted in the warmer tones of the figure.

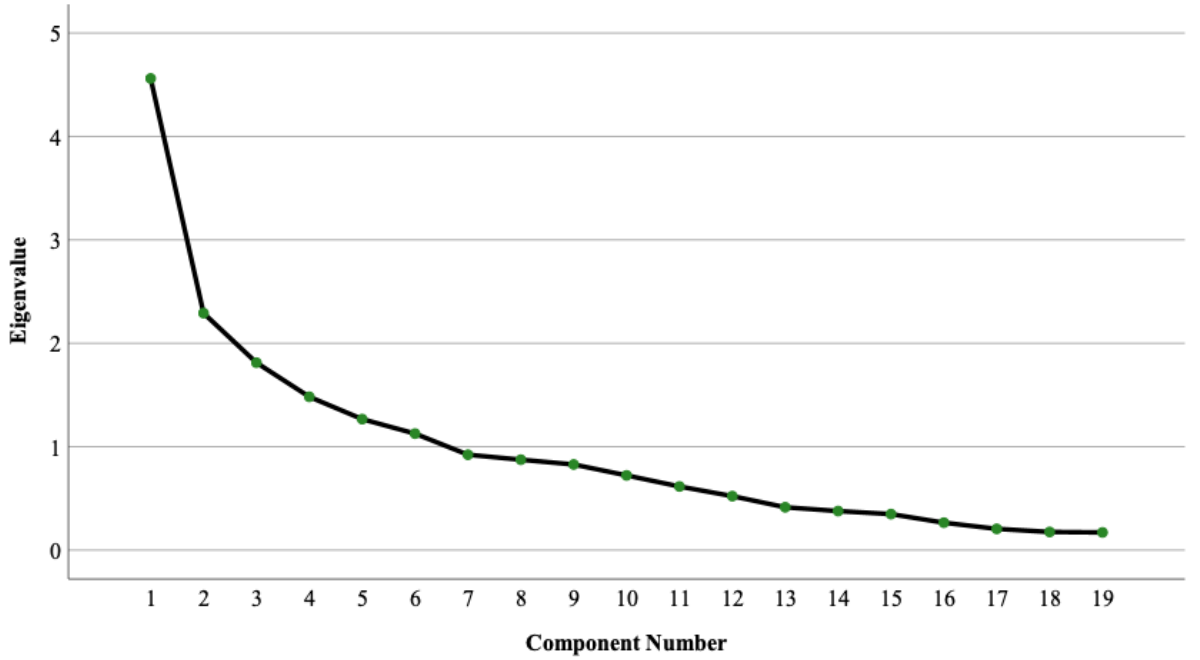

Figure 6. Scree plot. Six components with eigenvalues greater than 1 were interpreted in the current study.

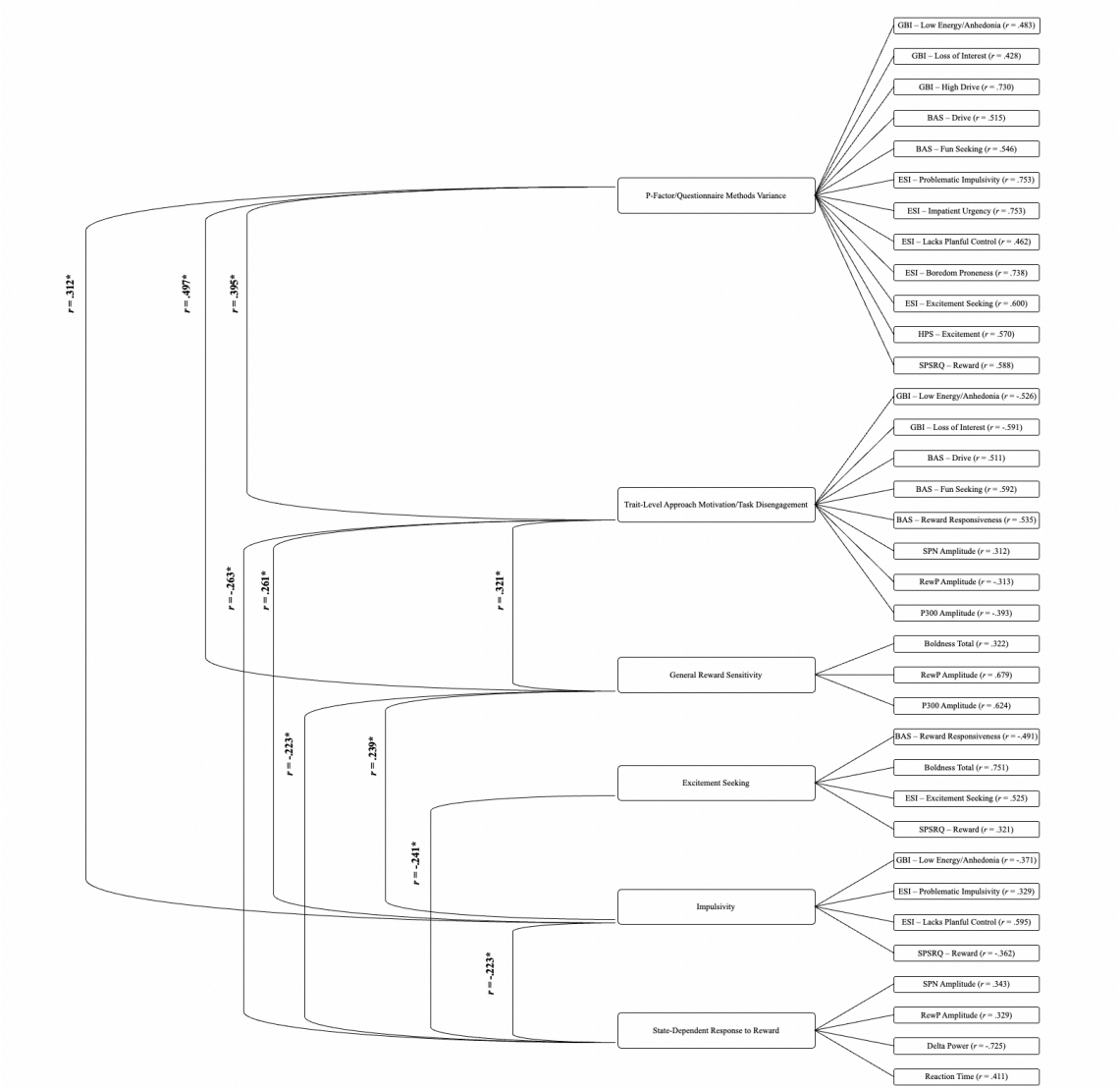

Figure 7. Path diagram of each component along with each variable loading and bivariate correlations between components. Only loadings $r > .30$ are depicted.

Table 1. Demographic information for the sample.

Total Sample	MLS Sample	Sex	Age (*Mean (Standard Deviation)*)
N = 110	39.091% original MLS sample	63.637% Female	34.593 (6.374)
Race/Ethnicity			
White/Caucasian		60.910% (*n* = 67)	
African American/Black		4.545% (*n* = 5)	
Asian		1.818% (*n* = 2)	
Latine		0% (*n* = 0)	
Middle Eastern/North African		0% (*n* = 0)	
Pacific Islander/Native Hawaiian		0% (*n* = 0)	
Multiracial		2.727% (*n* = 3)	
Did not specify		30.0% (*n* = 33)	

Table 2. Means and standard deviations for each variable included in the EFA.

Measure	*Mean (Standard Deviation)*
EEG and Behavioral Measures	
RewP Amplitude	1.804 (2.921) μV
P300 Amplitude	11.855 (5.231) μV
SPN Amplitude	-2.810 (3.303) μV
Delta Power – Gain/Loss Difference	.854 (16.947) $\mu V^2/Hz$
Reaction Time	542.00 (197.252) ms
Anhedonia Measures	
GBI – Loss of Interest	6.510 (2.325)
GBI – Low Energy/Anhedonia	5.600 (2.010)
Impulsivity and Drive Measures	
GBI – High Drive	4.845 (1.110)
ESI – Problematic Impulsivity	2.472 (3.697)
ESI – Impatient Urgency	5.248 (3.919)
ESI – Lacks Planful Control	2.895 (3.628)
ESI – Boredom Proneness	3.781 (3.470)
ESI – Excitement Seeking	3.098 (3.644)
BAS – Drive	11.981 (3.744)
BAS – Fun Seeking	9.691 (2.695)
BAS – Reward Responsiveness	15.354 (3.170)
HPS – Excitement	1.277 (1.658)
Boldness Inventory – Boldness Total	49.684 (7.733)

Table 2 (cont'd)

Valuation Measure	
SPSRQ – Sensitivity to Reward	0.330 (0.201)

Table 3. Bivariate correlations between neurophysiological and behavioral indices and self-report measures.

	SPN Amplitude (μV)	RewP Amplitude (μV)	P300 Amplitude (μV)	Delta Power (μV^2/Hz)	Reaction Time (ms)
GBI – *Low Energy/Anhedonia*	-.050	-.086	.044	-.095	.086
GBI – *Loss of Interest*	-.058	.038	-.020	-.137	-.044
GBI – *High Drive*	-.065	-.063	-.025	.034	.184
BAS – *Drive*	.070	.024	-.127	.039	-.050
BAS – *Fun Seeking*	.078	-.117	-.134	.184	.102
BAS – *Reward Responsiveness*	.070	-.048	-.064	.040	.112
Boldness Inventory – *Boldness Total*	-.102	.066	.122	.027	-.007
ESI – *Problematic Impulsivity*	-.017	.008	.072	-.026	.098
ESI – *Impatient Urgency*	-.072	.067	.102	.001	.068
ESI – *Lacks Planful Control*	.020	.092	.035	-.030	.024
ESI – *Boredom Proneness*	-.035	-.084	-.051	.021	-.041
ESI – *Excitement Seeking*	.065	-.105	-.087	.043	.162
HPS – *Excitement*	-.104	-.125	.006	.056	.074

Table 3 (cont'd)

SPSRQ – *Sensitivity to Reward*	.051	.003	-.116	.026	.105
SPN Amplitude		**-.216***	**-.280***	-.002	**.260***
RewP Amplitude	**-.216***		**.448***	-.182	**-.229***
P300 Amplitude	**-.280***	**.448***		.040	-.180
Delta Power	-.002	-.182	-.068		-.027
Reaction Time	**.260***	**-.229***	-.180	-.027	

*$p < .05$

Table 4. Bivariate correlations between self-report measures.

	GBI – *Low Energy/Anhedonia*	GBI – *Loss of Interest*	GBI – *High Drive*	BAS – *Drive*	BAS – *Fun Seeking*	BAS – *Reward Responsiveness*	Boldness Inventory – *Boldness Total*
GBI – *Low Energy/Anhedonia*		**.684***	**.445***	.037	-.021	-.067	**-.189***
GBI – *Loss of Interest*	**.684***		**.452***	.008	-.052	-.072	**-.287***
GBI – *High Drive*	**.445***	**.452***		**.246***	**.260***	.123	.067
BAS – *Drive*	.037	.008	**.246***		**.645***	**.469***	.081
BAS – *Fun Seeking*	-.021	-.052	**.260***	**.645***		**.496***	.040
BAS – *Reward Responsiveness*	-.067	-.072	.123	**.469***	**.496***		-.108
Boldness Inventory – *Boldness Total*	**-.189***	**-.287***	.067	.081	.040	-.108	
ESI – *Problematic Impulsivity*	**.391***	**.326***	**.546***	.174	.174	.040	-.111
ESI – *Impatient Urgency*	**.252***	**.238***	**.424***	**.350***	**.302***	**.265***	**-.236***

Table 4 (cont'd)

ESI – *Lacks Planful Control*	.087	.154	**.228***	.186	**.233***	-.028	-.080
ESI – *Boredom Proneness*	**.294***	**.283***	**.439***	**.265***	**.360***	.098	**-.203***
ESI – *Excitement Seeking*	.179	.136	**.387***	.123	**.313***	-.068	**.202***
HPS – *Excitement*	**.299***	.079	**.357***	**.347***	**.338***	.123	-.019
SPSRQ – *Sensitivity to Reward*	.110	.117	**.444***	**.351***	**.274***	**.209***	**.319***

	ESI – *Problematic Impulsivity*	ESI – *Impatient Urgency*	ESI – *Lacks Planful Control*	ESI – *Boredom Proneness*	ESI – *Excitement Seeking*	HPS – *Excitement*	SPSRQ – *Sensitivity to Reward*
GBI – *Low Energy/Anhedonia*	**.391***	**.252***	.087	**.294***	.179	**.299***	.110
GBI – *Loss of Interest*	**.326***	**.238***	.154	**.283***	.136	.079	.117
GBI – *High Drive*	**.546***	**.424***	**.228***	**.439***	**.387***	**.357***	**.444***
BAS – *Drive*	.174	**.350***	.186	**.265***	.123	**.347***	**.351***
BAS – *Fun Seeking*	.174	**.302***	**.233***	**.360***	**.313***	**.338***	**.274***
BAS – *Reward Responsiveness*	.040	**.265***	-.028	.098	-.068	.123	**.209***

Table 4 (cont'd)

Boldness Inventory – *Boldness Total*	-.111	**-.236***	-.080	**-.203***	**.202***	-.019	**.319***
ESI – *Problematic Impulsivity*		**.615***	**.547***	**.485***	**.558***	**.314***	**.262***
ESI – *Impatient Urgency*	**.615***		**.306***	**.600***	**.389***	**.318***	**.426***
ESI – *Lacks Planful Control*	**.547***	**.306***		**.240***	**.298***	**.219***	.056
ESI – *Boredom Proneness*	**.485***	**.600***	**.240***		**.478***	**.374***	**.399***
ESI – *Excitement Seeking*	**.558***	**.389***	**.298***	**.478***		.118	**.338***
HPS – *Excitement*	**.314***	**.318***	**.219***	**.374***	.118		**.412***
SPSRQ – *Sensitivity to Reward*	**.262***	**.426***	.056	**.399***	**.338***	**.412***	

*$p < .05$

Table 5. Total variance explained by each component of the EFA.

Component	Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %
1	4.562	24.008	24.008
2	2.292	12.065	36.073
3	1.814	9.545	45.618
4	1.483	7.808	53.426
5	1.268	6.672	60.098
6	1.127	5.933	66.031

Table 6. Components matrix of how each variable correlates to each component. Only correlations above .300 are presented.

Component	1	2	3	4	5	6
GBI – *Low Energy/Anhedonia*	.483	-.526			-.371	
GBI – *Loss of Interest*	.428	-.591				
GBI – *High Drive*	.730					
BAS – *Drive*	.515	.511				
BAS – *Fun Seeking*	.546	.592				
BAS – *Reward Responsiveness*		.535		-.491		
Boldness Inventory – *Boldness Total*			.322	.751		
ESI – *Problematic Impulsivity*	.753				.329	
ESI – *Impatient Urgency*	.753					
ESI – *Lacks Planful Control*	.462				.595	
ESI – *Boredom Proneness*	.738					
ESI – *Excitement Seeking*	.600			.525		
HPS – *Excitement*	.570					

Table 6 (cont'd)

SPSRQ – *Sensitivity to Reward*	.588			.321	-.362	
SPN Amplitude		.312				.343
RewP Amplitude		-.313	.679			.329
P300 Amplitude		-.393	.624			
Delta Power						-.725
Reaction Time						.411

Table 7. Bivariate correlations between factor scores.

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
Component 1		**.395***	**.497***	-.040	**.312***	-.159
Component 2	**.395***		**.321***	.027	**.261***	**-.263***
Component 3	**.497***	**.321***		.041	**.239***	**-.223***
Component 4	-.040	.027	.041		.042	**-.241***
Component 5	**.312***	**.261***	**.239***	.042		**-.223***
Component 6	-.159	**-.263***	**-.223***	**-.241***	**-.223***	

*$p < .05$

Table 8. Pattern coefficients, which index the unique contribution of each variable to each component.

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
GBI – *Low Energy/ Anhedonia*	-.088	-.159	.965	-.007	-.104	-.075
GBI – *Loss of Interest*	-.032	-.155	.928	-.026	-.221	.163
GBI – *High Drive*	.171	.063	.565	.037	.281	.035
BAS – *Drive*	-.021	.861	-.096	-.019	.070	.054
BAS – *Fun Seeking*	.183	.751	-.255	.069	.015	-.175
BAS – *Reward Responsiveness*	-.225	.932	-.078	.124	-.144	.168
Boldness Inventory – *Boldness Total*	-.153	-.139	-.308	-.068	.961	.068
ESI – *Problematic Impulsivity*	.838	-.098	.187	.027	-.057	.057
ESI – *Impatient Urgency*	.554	.336	.172	-.092	-.130	.079
ESI – *Lacks Planful Control*	.913	-.034	-.250	.023	-.210	.065
ESI – *Boredom Proneness*	.467	.165	.266	-.099	-.089	-.211
ESI – *Excitement Seeking*	.755	-.227	-.096	.193	.327	-.111
HPS – *Excitement*	-.021	.335	.319	-.170	.147	-.201
SPSRQ – *Sensitivity to Reward*	-.038	.319	.205	.054	.631	.079
SPN Amplitude	.145	.104	-.173	.753	-.135	.153
RewP Amplitude	.140	.091	-.133	-.442	.101	.601
P300 Amplitude	.145	.074	-.048	-.571	.072	.335
Delta Power	.043	-.038	-.256	-.245	-.057	-.838
Reaction Time	.084	.008	.059	.710	.154	.230

Table 9. Communalities for each variable. Communalities represent the proportion of the variance in each variable which can be explained by the six factors.

	Initial	Extraction
GBI – *Low Energy/Anhedonia*	1.000	.755
GBI – *Loss of Interest*	1.000	.733
GBI – *High Drive*	1.000	.662
BAS – *Drive*	1.000	.697
BAS – *Fun Seeking*	1.000	.710
BAS – *Reward Responsiveness*	1.000	.693
Boldness Inventory – *Boldness Total*	1.000	.845
ESI – *Problematic Impulsivity*	1.000	.783
ESI – *Impatient Urgency*	1.000	.657
ESI – *Lacks Planful Control*	1.000	.602
ESI – *Boredom Proneness*	1.000	.603
ESI – *Excitement Seeking*	1.000	.719
HPS – *Excitement*	1.000	.457
SPSRQ – *Sensitivity to Reward*	1.000	.690
SPN Amplitude	1.000	.564
RewP Amplitude	1.000	.689
P300 Amplitude	1.000	.555
Delta Power	1.000	.622
Reaction Time	1.000	.510