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Extraversion and Reward-Processing:

Consolidating Evidence from an Electroencephalographic Index of Reward-Prediction-Error

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ABSTRACT

Trait extraversion has been theorized to emerge from functioning of the dopaminergic reward system. Recent evidence for this view shows that extraversion modulates the scalp-recorded Reward Positivity, a putative marker of dopaminergic signaling of reward-prediction-error. We attempt to replicate this association amid several improvements on previous studies in this area, including an adequately-powered sample ($N = 100$) and thorough examination of convergent-divergent validity. Participants completed a passive associative learning task presenting rewards and non-rewards that were either predictable or unexpected. Frequentist and Bayesian analyses confirmed that the scalp recorded Reward Positivity (i.e. the Feedback-Related-Negativity contrasting unpredicted rewards and unpredicted non-rewards) was significantly associated with three measures of extraversion and unrelated to other basic traits from the Big Five personality model. Narrower sub-traits of extraversion showed similar, though weaker associations with the Reward Positivity. These findings consolidate previous evidence linking extraversion with a putative marker of dopaminergic reward-processing.

Key words: Extraversion; Reward Prediction Error; Reward-Positivity; Feedback Related Negativity; Dopamine.

Extraversion and Reward-Processing:

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The goal of Personality Neuroscience is to understand the neural processes that give rise to stable patterns in behavior and experience—which is to say, personality (DeYoung, 2010). One sign of progress toward this goal is the development and growing influence of a general reward processing theory of extraverted personality (Depue & Collins, 1999; DeYoung, 2013; Pickering & Gray, 2001; Rammsayer, 1998). This theory suggests that individual differences along the extraversion-introversion dimension may be partially grounded in differential processing of rewards within the mesocorticolimbic dopamine system (see Wacker & Smillie, 2015, for a review). In the present study, we attempt to consolidate one strand of evidence favoring the reward processing theory of extraversion, based on an electroencephalographic (EEG) marker of reward-prediction-error (RPE) signaling, the Reward Positivity. Our first aim is to provide an adequately-powered direct replication of previous underpowered studies that reported an association between extraversion and the Reward Positivity (e.g. Smillie, Cooper, & Pickering, 2011). Our second aim is to evaluate the evidence for this association in terms of both convergent validity (i.e. does this relation hold for multiple measures of extraversion?) and divergent validity (i.e. is this relation specific to extraversion, versus other personality traits?). Finally, we aim to compare the strength of relation that lower-order traits within the broad extraversion “*domain*” (i.e. separable “*aspects*” of extraversion) have with RPE signaling.

Extraversion and Reward-Processing

Like all of the “Big Five” personality domains (i.e. extraversion, neuroticism, agreeableness, conscientiousness, and openness/intellect; John, Naumann & Soto, 2008), *extraversion* is a broad trait construct describing a cluster of more specific correlated tendencies

—boldness, talkativeness, gregariousness, assertiveness, and positive emotionality (Wilt & Revelle, 2016). The reward-processing theory of extraversion holds that the existence and coherence of this trait cluster can be partly attributed to differential sensitivity to the motivational impact of rewarding stimuli, and motivational drive to obtain such stimuli. This suggests that boldness and talkativeness may be viewed as instances of reward-directed behavior, that positive emotionality can be understood in terms of affective responses to reward pursuit and attainment, and that the coherence of these various traits within the extraversion domain can be understood in terms of their shared links with an underlying reward-processing system (DeYoung, 2010; Smillie, 2013; Wilt, Bleidorn, & Revelle, 2017). Depue and Collins (1999) based the reward-processing theory of extraversion on an apparent similarity of features of this trait to incentive motivation processes described in non-human animals, within which activity of the mesolimbic dopamine system plays a central role (see also Gray, 1973; Pickering & Gray, 2001; Rammsayer, 1998, for convergent theorizing). It is important to note, however, that the specification of this theory has not developed far beyond the considerably broad (and thus vague) prediction that extraversion will relate (in some way) to indices of (some aspect of) dopaminergic reward-processing. Nevertheless, the accumulated evidence for associations between extraversion and several such indices is encouraging (see Wacker & Smillie, 2015), and there have been recent attempts to specify the theory more thoroughly and precisely (e.g. Pickering & Pesola, 2014), and to derive novel predictions (e.g. Pickering, Hunt, & Siljebrat, 2017).

Dopamine plays a number of complex roles in reward-processing and related behaviors, and influences behavioral activation, exertion of effort, approach behavior, sustained task engagement, plus both Pavlovian and instrumental learning processes (Salamone & Correa, 2012; Wise, 2004). One influential perspective is that phasic activity of dopamine neurons concentrated in the midbrain (projecting from the ventral tegmental area and substantia nigra to limbic and

prefrontal regions) codes for reward-prediction-errors (RPEs), thereby signaling events that are better or worse than expected (Schultz, 1998; Schultz, Stauffer, & Lak, 2017). Evidence for this view comes primarily from single unit recordings in both rodents and non-human primates, in which the delivery of an unexpected or larger-than-expected reward results in increased dopamine cell firing and an omitted or smaller-than-expected reward results in decreased dopamine cell firing (e.g. Bayer & Glimcher, 2005; Matsumoto & Hikosaka, 2009; Mirenowicz & Schultz, 1994). These dopaminergic neuron firing changes are thought to instantiate the reinforcement signal specified in classic models of reinforcement learning, suggesting that dopamine plays a crucial role in the learning of reward contingencies (Glimcher, 2011). Within the present, loose constraints of the reward-processing theory of extraversion, it is reasonable to predict that this RPE reinforcement signal will be more pronounced in highly extraverted versus introverted individuals. Of course, as there are considerable barriers to conducting single unit recordings in human participants, indirect markers of dopaminergic RPE signaling are required.

One potential proxy for RPE signaling is the Reward Positivity (Proudfit, 2015), which can be derived from the event-related potential (ERP) known as the Feedback-Related Negativity (FRN). The FRN is a negative deflection occurring approximately 200-300ms after various events and outcomes. It is typically most negative following the omission of expected reward, and least negative (or even positive) following the delivery of an unexpected reward (Holroyd, Pakzad-Vaezi, & Krigolson, 2008; Potts, Martin, Burton, & Montague, 2006). Thus, the FRN waveform mirrors patterns of phasic dopamine activity obtained from single unit recordings in experimental animals (described above). It has been argued that RPE-producing midbrain dopamine neurons may travel to the anterior cingulate cortex via the corticostriatal pathway, with activation of cortical pyramidal neurons then detectable using EEG (Hauser et al., 2014; Holroyd & Coles, 2002). Some have questioned the ability of dopamine to travel to and be released from

the anterior cingulate at such speed (Ullsperger, Fischer, Nigbur, & Endrass, 2014), and others suggest that indirect links between dopamine activity and the FRN may be more biologically plausible (e.g. via co-release of a faster-acting neurotransmitter such as glutamate; Pickering & Pesola, 2014). Nevertheless—and regardless of the neurochemical mechanisms involved—there is strong meta-analytic evidence that the FRN reliably codes RPE (Sambrook & Goslin, 2015; Walsh & Anderson, 2012). In turn, the difference waveform contrasting FRN following positive and negative reward-prediction errors—recently termed the Reward Positivity—reflects the overall magnitude of RPE signaling, and has been argued to provide a neural indicator of reward sensitivity (Proudfit, 2015). There is also a growing literature suggesting linking the Reward Positivity with reward motivation states (e.g., Threadgill & Gable, 2016). The Reward Positivity is therefore a promising index for evaluating the association between extraversion and reward-processing.

Extraversion and the Reward Positivity

We have now identified a relation between extraversion and the Reward Positivity in three empirical studies (Mueller, et al., 2014; Cooper, Duke, Pickering, & Smillie, 2014; Smillie et al., 2011). Two of these studies employed an associative learning paradigm devised by Potts et al. (2006), in which participants passively view trials comprising reward or non-reward events that are each either expected or unexpected. Specifically, rewards are signaled by the appearance of a visual cue (gold bar), which on 80% of such trials is followed by a repeat presentation of the cue and then a financial reward (i.e. reward cue → reward cue → reward delivery). On the remaining 20% of trials, however, the first reward cue is followed by a non-reward cue (lemons) and a non-reward outcome (i.e. reward cue → non-reward cue → no reward delivery). Similarly, non-rewards are signaled by the appearance of the non-reward cue, which on 80% of such trials leads to an expected non-reward (i.e. non-reward cue → non-reward cue → no

reward delivery) and on the remaining 20% of trials to an unexpected reward (i.e. non-reward cue → reward cue → reward delivery). There are thus four trial types: predicted non-reward, predicted reward, unpredicted non-reward, and unpredicted reward. Employing this task, Smillie et al. (2011) found that the Reward Positivity was larger in a group of high-extraverts (> +1SD from mean) relative to a group of low-extraverts (< -1SD from mean), drawn from a large sample who had completed a standard extraversion questionnaire. Cooper et al. (2014) provided a close replication of this finding, comprising a positive correlation ($r = .36$) between extraversion scores and the size of the Reward Positivity. Using a similar paradigm, Mueller et al. (2014) then showed that this correlation was abolished by the D2 dopamine receptor antagonist sulpiride. Related findings have also been reported using somewhat similar tasks, and extraversion-related personality scales (e.g. Bress & Hajcak, 2013; Boksem, Tops, Wester, Meijman, & Lorist, 2006; Lange, Leue, & Beauducel, 2012).

The accumulating evidence linking trait extraversion with the Reward Positivity supports the hypothesized relation between extraversion and RPE signaling, and corroborates the more general reward-processing view of this trait. Moreover, the finding that this association is sensitive to pharmacologic manipulation of dopamine levels potentially confirms the involvement of dopamine in this process. However, there are at least three limitations to this research that necessitate a further replication and extension. First, studies in this area have almost always relied on small samples, with most recruiting fewer than 50 participants (e.g. Bress & Hajcak, 2013; Boksem et al., 2006; Cooper et al., 2014; Smillie et al., 2011). As discussed by Mar, Spreng, and DeYoung (2013), small sample sizes are a problematic feature of studies in personality neuroscience (as they are in neuroscience more generally; Button et al., 2013), owing to the burden of recruitment and testing costs. Even allowing for a one-tailed test, a sample of 50 participants provides only 55% power to detect a typical correlation in personality psychology

(i.e. $r \sim .25$; Fraley & Marks, 2007). Concerns about statistical power may seem minor given that an association between extraversion and the Reward Positivity has already been observed in multiple studies, but low power increases the likelihood of type 1 errors (or false positives; Ioannidis, 2005). To bolster confidence in this association, our first aim in this paper was to provide a further replication of our initial studies (i.e. Smillie et al., 2011; Cooper et al., 2014), using a well-powered sample.

A second limitation of research in this area concerns the lack of convergent-divergent validation of the extraversion-Reward Positivity association. That is, studies have tended not to examine whether this association is generalizable to multiple measures of extraversion, nor whether it is specific to the extraversion domain. Instead, researchers tend to employ a single preferred scale—such as the Positive Emotionality scale from the Multidimensional Personality Questionnaire (Mueller et al., 2014; Wacker, Chavanon, & Stemmler, 2006), or the Extraversion scale from the Eysenck Personality Questionnaire (Smillie et al., 2011)—and focus only on that scale. This limits the extent to which conclusions from these studies extend beyond any one questionnaire. With regard to divergent validity, it was noted by Wacker and Smillie (2015) that the Reward Positivity has previously been found to relate to at least one other trait domain (i.e. neuroticism; Hirsh & Inzlicht, 2008), which raises questions about the specificity of the relation between extraversion and reward-processing. To address these ambiguities, we included multiple measures of all five domains of personality in order to comprehensively evaluate the convergent-divergent validity evidence for the relation between extraversion and RPE signaling.

Finally, there is a general tendency in this area, and in the broader literature linking extraversion and reward processing, to focus only on broad domain-level measures of extraversion (e.g. Depue & Fu, 2013; Smillie et al., 2011; Wu et al., 2014). However, narrower traits within the extraversion domain may have diverging relations with reward-processing

indices, as originally suggested by Depue and Collins (1999). It is therefore interesting to assess the extent to which previously observed relations between extraversion and the Reward Positivity generalize across the lower-order traits that comprise extraversion. Although structural models of extraversion differ with regard to the number and nature of such traits, most identify one component of extraversion reflecting boldness and dominance, and another reflecting the experience and/or expression of positive emotion (DeYoung et al., 2007; Quilty et al., 2014; Soto & John, 2017; Tellegen, 1982). This is reflected in the two major trait “aspects” of the extraversion domain, known as *assertiveness* and *enthusiasm* (DeYoung et al., 2007). Assertiveness appears to correspond to the trait that Depue and Collins (1999) termed “agentic extraversion”, and linked most closely with the reward-processing functions of the mesocorticolimbic dopamine system. It is less clear whether or not enthusiasm will have a similarly close relation to reward processing, although DeYoung (2013) has suggested that the “eager, vigorous emotional responses” described by this trait may “suggest dopaminergic activation in response to the promise or delivery of reward” (p. 10)¹. To clarify this issue in the present study, we included two measures of extraversion that could each be clearly divided into its assertiveness and enthusiasm aspects.

Summary

In this experiment we attempt to replicate the previously observed association between extraversion and the Reward Positivity, a putative marker of dopaminergic RPE signaling. Improvements on previous studies include the recruitment of an adequately powered sample, and

¹ The reader should note that the distinction between assertiveness and enthusiasm is not equivalent to the distinction between “agentic extraversion” (social boldness and dominance) and “affiliative extraversion” (social closeness and interpersonal warmth) originally described by Depue and Collins (1999). Indeed, recent research shows that trait affiliation falls directly between the extraversion and agreeableness domains, whereas enthusiasm falls more clearly within the extraversion domain (DeYoung, 2013).

an examination of convergent and divergent validity across multiple trait measures and multiple levels of the extraversion trait hierarchy (i.e. both broader domains and narrower aspects). This will enable us to assess whether the extraversion-Reward Positivity association is (a) replicable, (b) specific to extraversion, (c) robust across multiple measures of extraversion, and (d) generalizable across major aspects (or “sub-traits”) of the broader extraversion domain. More formally, we predict that (H1) extraversion will be positively related to the Reward Positivity (i.e., FRN difference contrasting unexpected reward versus unexpected non-reward), that (H2) this relation will generalize across multiple measures of extraversion, and that (H3) when all of the ‘Big Five’ personality domains are entered into a single regression model predicting the Reward Positivity, a significant unique relation will emerge only for extraversion. We will also explore the relation between Reward Positivity and aspect-level measures of extraversion, viz., assertiveness and enthusiasm. Regrettably, we did not pre-register any of these hypotheses, but we note that H1 at least comprises a very close replication of Cooper and colleagues (2014), and that the methods described below are based directly on this existing publication.

Method

Participants

The final sample comprised 100 members of the community recruited from flyers placed around the University of Melbourne campus (58% female; aged 18-47, $M = 23.69$, $SD = 5.82$). Our sample size was predetermined based on a power analysis. Given that this is a replication study, we had a clear directional prediction and indications of effect size from previous studies (e.g. Cooper et al., 2014) that we could expect an effect size of at least $d \sim .50 / r \sim .25$, which is the approximate average effect size in personality psychology in particular and psychology as a whole (Fraley & Marks, 2007; Hemphill, 2001). A sample of 98 participants provides 80% power to detect an effect size of $r = .25$ using a 1-tailed test. We therefore determined that data

collection would cease after obtaining usable data for a minimum of 98 participants. In all, 111 participants were recruited and tested, however usable data could not be obtained for 11 individuals (detailed below). All participants were compensated with AUD\$30 (~US\$23), half of which was paid up front as a “show up” fee, the remaining half of which was won during the experimental task described below. All study procedures received ethical approval via the relevant committees within The University of Melbourne.

Personality Measures

Participants completed domain-level measures of extraversion from three questionnaires: The Big Five Aspects Scales (BFAS; DeYoung, Quilty, & Peterson, 2007), the Big Five Mini Markers (MM; Saucier, 1994), and the Multidimensional Personality Questionnaire (MPQ; Tellegen, 1982). The BFAS Extraversion scale consists of 20 statements (e.g. *Am the first to act*) to which participants respond by indicating the extent to which they agree that each statement describes them well (on a scale from 1 = *Strongly Disagree* to 5 = *Strongly Agree*). The MM Extraversion scale consists of 8 adjectives (e.g. *bold*) to which participants respond by indicating the extent to which they agree that each statement describes them accurately (on a scale from 1 = *Extremely Inaccurate* to 9 = *Extremely Accurate*). The MPQ Positive Emotionality scale provides a measure of extraversion developed outside the Big Five tradition. It consists of 30 statements (e.g. *I often liven up a dull party*) with which participants indicate their agreement (on a scale from 1 = *Strongly Disagree* to 4 = *Strongly Agree*). These three domain-level measures enabled us to assess whether the relation between extraversion and RPE generalizes across multiple scales.

Two of our domain-level measures of extraversion could also be divided into narrower sub-scales measuring the assertiveness and enthusiasm aspects of extraversion. This is explicitly the case for BFAS extraversion, which divides into Assertiveness (10 items, e.g. *Can talk others*

into doing things) and Enthusiasm (10 items, e.g. *Laugh a lot*), while MPQ Positive Emotionality subsumes two conceptually similar scales called Social Potency (10 items, e.g. *I am dominant, self-confident, and assertive*) and Wellbeing (10 items, e.g. *I am naturally cheerful*). (Participants completed a third 10-item subscale of MPQ Positive Emotionality, Achievement, which was unrelated to our predictions and thus excluded from analyses, whereas a fourth subscale, Social Closeness, was not administered in this study.) These four intermediate-level scales (assertiveness, enthusiasm, social potency, and wellbeing) enabled us to assess whether the relation between extraversion and RPE generalizes across the major aspects of the extraversion domain.

Finally, as we included the full BFAS and MM questionnaires, our data included two measures of each of the remaining Big Five domains (i.e. neuroticism, conscientiousness, agreeableness, and openness/intellect). These enabled us to assess whether the relation between extraversion and RPE is indeed unique to the extraversion domain, and holds when controlling for other major trait domains.

Associative Learning Paradigm

Our focal task was developed by Potts and colleagues (2006), and used in our previous research to establish a relation between extraversion and RPE signaling (Cooper et al., 2014; Smillie et al., 2011). Each trial of the task (programmed in *Eprime*TM by the first author) consisted of a S1-S2 stimulus pairing that culminated either in the delivery of a financial reward (\$1) or no reward (\$0), which was either predicted or unpredicted. More specifically, each trial sequence comprised a fixation cross (300ms), followed by the presentation of S1 (500ms), a second fixation cross (300ms), the presentation of S2 (500ms), and finally a financial outcome and running total of cumulative winnings (600ms). Trials were separated by a variable inter-trial interval (2000-3600ms), during which the message “blink now” was presented in order to

minimize ocular artifacts (discussed further, below). On half of trials S1 comprised an image of a gold bar, and on the other half of trials an image of a lemon. Stimuli were 3×3cm in size and viewed from 50cm (distance from eyes to center of monitor). On 80% of trials for which S1 was a gold bar, S2 was also a gold bar and a reward was delivered (predicted reward, 144 trials). Similarly, on 80% of trials for which S1 was a lemon, S2 was also a lemon and no reward was delivered (predicted non-reward, 144 trials). For the remaining minority of trials these contingencies were reversed, such that the gold bar was unexpectedly followed by a lemon and no reward (unpredicted non-reward, 36 trials) and the lemon was unexpectedly followed by a gold bar and a reward (unpredicted reward, 36 trials). A total of 360 such trials were delivered in a randomized order, divided into six blocks of 60 trials, with each block separated by a brief rest period. An additional block of 30 familiarization trials was completed before the main task. Winnings reset at the beginning of each block, and participants were informed that they would be paid the full winnings from the highest paying block (fixed at \$15 for all participants). No behavioral responses were collected from participants during the task².

EEG Acquisition and Analysis

All acquisition and analysis procedures were identical to those reported by Cooper et al. (2014), unless specifically noted, and made use of the same hardware and software. EEG was recorded continuously from 64 Ag/AgCl electrodes embedded in an elasticized Easy-Cap[®] and aligned with the extended 10-20 system. Four additional electrodes were placed on the outer canthi of both eyes, and above and below the right eye, to record electroculogram (EOG) to assist with artifact rejection (described below). EEG signals were sampled at 512hz and amplified using

² All details of this task are identical to that we have described previously (Cooper et al., 2014; Smillie et al., 2011), except that in these previous studies a total of 480 trials across eight blocks were delivered, and participants (located in the UK) were paid £15 (~ US\$20).

a low noise, DC-coupled BioSemi ActiveTwo® amplifier, and digitized using Biosemi's Actiview acquisition software. Recording sessions for six participants were terminated as a result of technical problems including faulty electrodes.

EEG data was pre-processed using Brainvision Analyser v.2.1.1. (Brain Products GmbH, 2015). A 0.5 – 50hz band-pass filter plus 50hz notch filter was applied to the data, which was re-referenced to a global average, omitting any excessively noisy channels from this average³. Five participants' data were discarded at this point due to excessively noisy or otherwise unusable data from target medial frontal channels. An initial manual inspection of each remaining participant's data was then conducted to mark obvious muscle artifacts and excessively noisy sections of EEG. The EEG was then segmented into 600ms epochs beginning 100ms before the onset of S2, after which a 200ms baseline correction was applied. A semi-automated artifact rejection routine was then conducted, whereby voltage changes exceeding $\pm 50 \mu\text{V/s}$ on target frontal channels and EOG channels were automatically marked, and then manually inspected and either retained or removed⁴. A small number of segments were also omitted due to trigger coding errors. In total, ~86% of the data was retained for analysis, with an average of 31.01 ($SD = 5.02$) and 31.11 ($SD = 5.04$) retained segments for the unpredicted reward and unpredicted non-reward trials, respectively, and 122.58 ($SD = 19.23$) and 123.30 ($SD = 17.32$) retained segments for the predicted reward and predicted non-reward trial types, respectively. As in previous studies (Cooper et al., 2014; Smillie et al., 2014), we operationalized the FRN as the mean amplitude from 200-300ms over medial frontal sites (viz., F1, F2, Fz, FC1, FC2, and FCz). The Reward Positivity was then calculated as the UNR-UR difference wave.

³ We acknowledge that slight differences in the number of electrodes used to compute the average reference may result in slight differences to the obtained FRN waveform (see Luck, 2014, p.162).

⁴ This was slightly more stringent than the $\pm 70 \mu\text{V/s}$ criterion adopted by Cooper et al. (2014).

Data Analyses and Availability of data

Hypotheses were tested using traditional frequentist analyses within SPSS (version 24), and one-tailed tests were adopted for the directional hypotheses stated explicitly above (otherwise, all analyses are two-tailed). Bayesian analyses—particularly relevant to testing H3—were deployed within JASP (version 0.8.3.1). Internal consistency estimates of reliability were estimated with omega (ω_t), computed using Psych package (Revelle, 2017) within RStudio (RStudio Team, 2016). Omega is analogous to but superior than Cronbach's alpha (see Revelle & Zinbarg, 2009). Data upon which our results are based have been placed onto an OSF repository to be released on publication. Included are all de-identified survey data and supplementary analyses not reported below. We also include selected EEG data consisting of the -200 to 500ms S2 ERP wave averaged over medial frontal sites, and individual channel grand average of S2 for the four outcome types (predicted non-reward, predicted reward unpredicted reward, and unpredicted non-reward).

Results

Does Feedback Related Negativity Code a Reward-Prediction-Error?

Our six-channel composite had very high internal consistency for each trial type (i.e. UR, UNR, PR, PNR; all ω_t s $\geq .98$). To confirm the validity of our index of RPE, we ran a 2 (reward, non-reward) \times 2 (predicted, unpredicted) repeated-measures ANOVA with the six channel composite as the dependent variable. As in previous studies, we obtained significant main effects of reward, $F(1,99) = 82.32, p < .001, \eta_p^2 = .45$, and prediction, $F(1,99) = 34.97, p < .001, \eta_p^2 = .26$, which were qualified by a significant 2-way interaction, $F(1,99) = 36.85, p < .001, \eta_p^2 = .27$. The pattern of this interaction confirmed that FRN differed most sharply between the two unpredicted trial types, $F(1,99) = 89.42, p < .001, \eta_p^2 = .48$, with unpredicted non-reward ($M = -1.51, SD = 2.24$) eliciting a more negative deflection than unpredicted reward ($M = -.29, SD = 2.03$).

Conversely, the difference between the two predicted trial types was far smaller, $F(1,99) = 13.46$, $p < .001$, $\eta_p^2 = .12$, though the FRN was still more negative following predicted non-reward ($M = -.36$, $SD = 1.28$) relative to predicted reward ($M = -.02$, $SD = 1.59$). The FRN waveforms for the four trial-types are depicted in Figure 1. Importantly, the critical reward \times prediction interaction was significant for each of the individual electrodes contributing to our six-channel composite (all $ps \leq .001$; see supplementary Table S2), as mirrored by the highly similar FRN waveforms at each of these sites (see Figure 2). In contrast, the same repeated-measures ANOVA conducted on both vertical and horizontal electrooculogram revealed no significant effects of reward, prediction, or their interaction (all $ps > .085$; see supplementary Table S2 and Figure 3), confirming that the components depicted in Figure 1 and Figure 2 cannot be attributed to ocular activity retained from our artifact rejection procedure.

Table 1

Means, standard deviations, omega total internal consistencies (on diagonal), and intercorrelations for all measures of extraversion.

	<i>M</i>	<i>SD</i>	1	2	3	4	5	6	7
1. BFAS Extraversion	3.36	0.48	.88						
2. MM Extraversion	5.40	1.33	.81	.88					
3. MPQ Pos-Emotion	2.70	0.30	.76	.75	.84				
4. Assertiveness	3.21	0.57	.80	.66	.66	.86			
5. Social Potency	2.45	0.45	.64	.70	.69	.76	.87		
6. Enthusiasm	3.51	0.61	.83	.65	.58	.33	.29	.87	
7. Wellbeing	2.82	0.48	.54	.49	.68	.20	.13	.68	.89

Note: All $rs > .33$ are significant at $p < .001$.

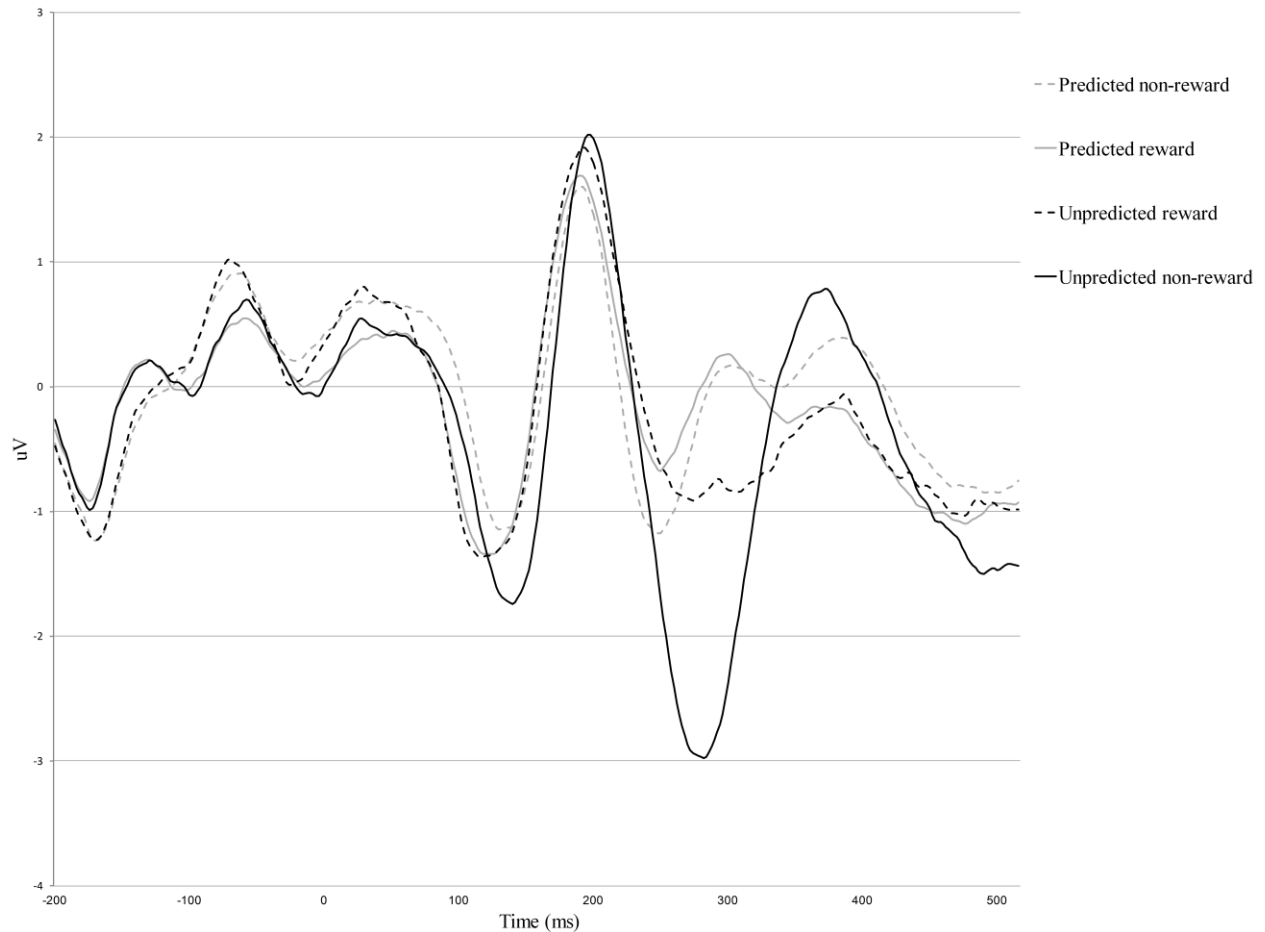


Figure 1. Waveform averaged across the medial frontal electrodes (F1, F2, Fz, FC1, FC2, and FCz), as in previous work (e.g. Cooper et al., 2014) showing neural response to rewards (dashed lines) and non-rewards (solid lines) that were either predicted (light/grey lines) or unpredicted (heavy/black lines). The FRN occurs over the 200-300ms time window.

Extraversion and the Reward Positivity

Means, standard-deviations, omega internal consistencies, and intercorrelations among all questionnaire measures are depicted in Table 1. As our three domain-level measures were all very highly intercorrelated, we subjected these to dimension reduction via Principal Axis Factoring. An unambiguous single-factor solution was obtained (eigenvalues = 2.54, 0.27, 0.20), with 77% of variance accounted for, and all three scales loading at .80 or higher. Standardized scores for this extraversion factor were then saved (regression method) and entered into a one-way

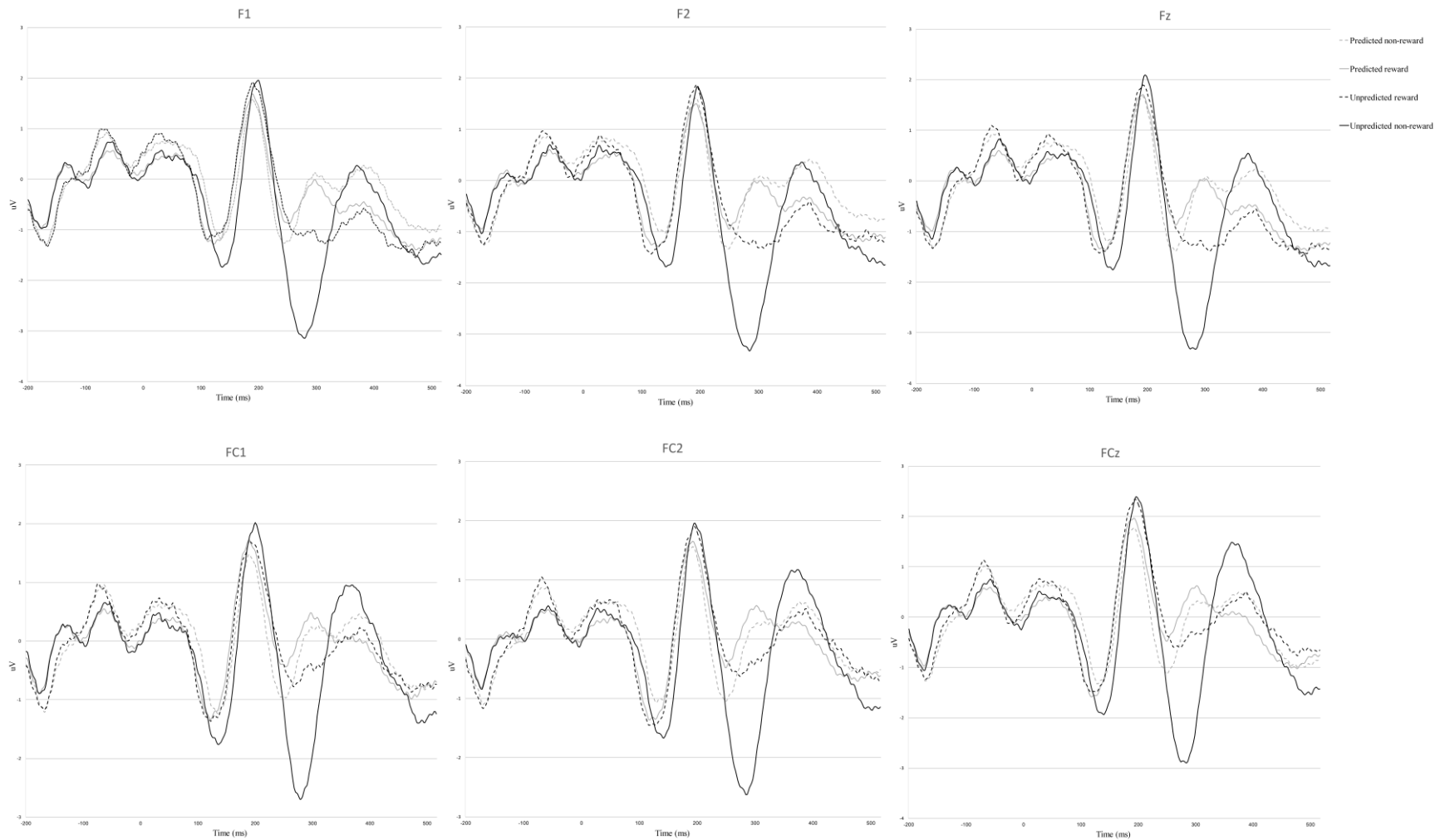


Figure 2. Neural response to rewards (dashed lines) and non-rewards (solid lines) that were either predicted (light/grey lines) or unpredicted (heavy/black lines) shown *separately* for medial frontal electrodes (F1, F2, Fz, FC1, FC2, and FCz). The FRN occurs over the 200-300ms time window.

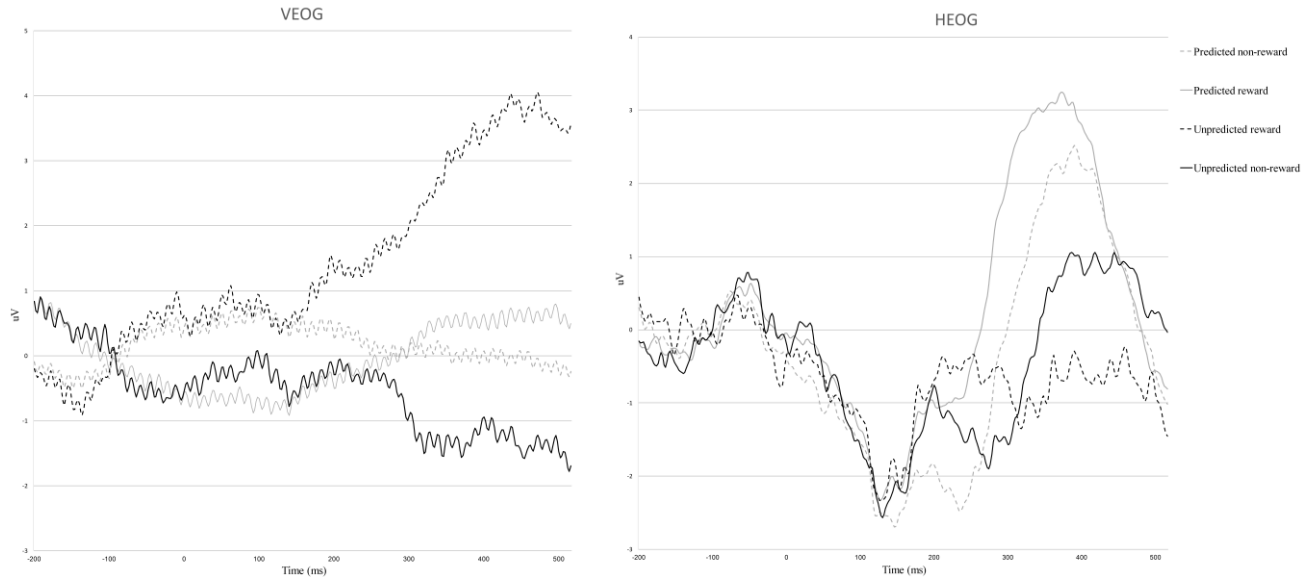


Figure 3. Vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) averaged across the four trial types, i.e., rewards (dashed lines) and non-rewards (solid lines) that were either predicted (light/grey lines) or unpredicted (heavy/black lines). There were no significant effects of trial type on either electrooculogram (see supplementary Table S2).

ANCOVA contrasting FRN following unpredicted reward versus unpredicted non-reward. There was a significant main effect corresponding to the Reward Positivity, $F(1,98) = 94.80, p < .001, \eta_p^2 = .49$, no main effect of extraversion, $F(1,98) = 1.12, p = .29, \eta_p^2 = .01$, and a significant interaction between these factors, $F(1,98) = 6.95, p = .005, \eta_p^2 = .07$. This interaction is equivalent to the bivariate correlation between extraversion and the Reward Positivity (i.e. the difference wave contrasting UR and UNR), which was positive and significant, $r = .26, p = .005$, supporting our first hypothesis (H1). A Bayesian analysis of this Pearson correlation coefficient revealed a Bayes Factor of 6.7 in favor of H1 relative to the corresponding null hypothesis, offering substantial evidence against the null. (Bayes factors in the range between 2.3 and 10 are interpreted as providing “substantial evidence” in favor of one hypothesis over another; see Kass & Raftery, 1995, Table 1.) This correlation was also significant (though slightly smaller) for each of our extraversion scales independently ($r_s = .21 - .26$, all $p_s < .05$, see supplementary Table

S3). That is, higher scores on all three of our domain-level measures of extraversion were positively associated with the Reward Positivity. This replicates previous findings and confirms that these findings generalize across multiple measures of extraversion, supporting our second hypothesis (H2). For illustrative purpose, the Reward Positivity is depicted in Figure 4 for three tertials of extraversion (i.e. high, middling, and low scores).

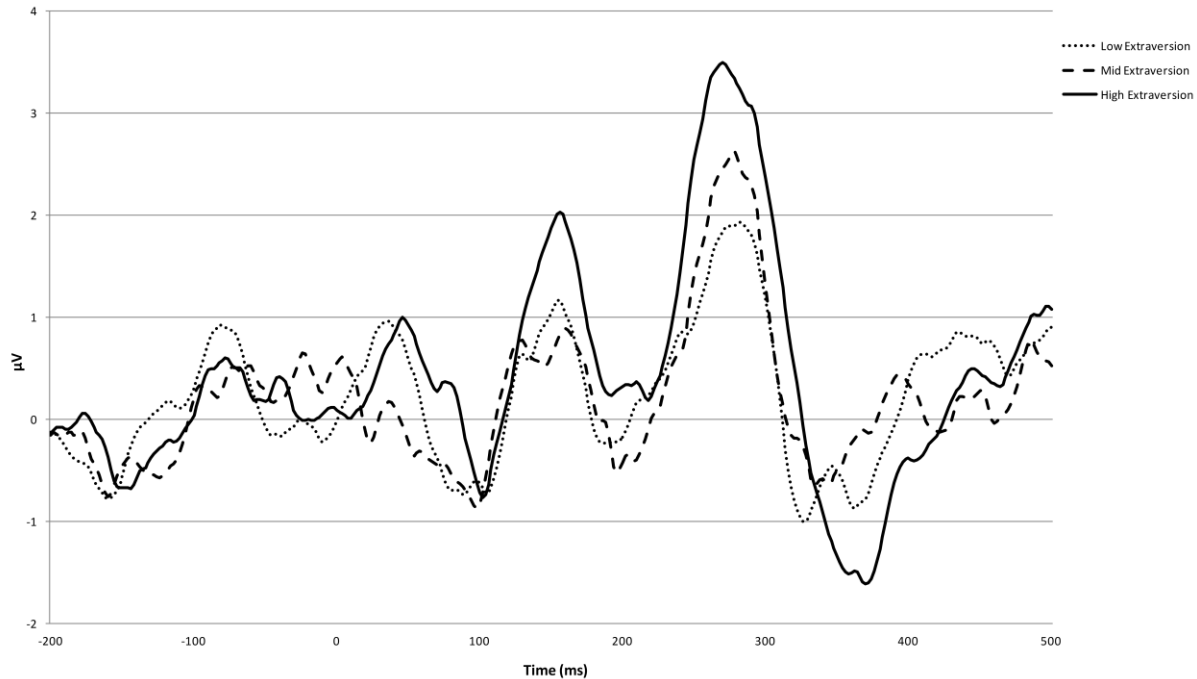


Figure 4. Reward Positivity waveform (occurring over the 200-300ms time window, and computed as the unpredicted-reward—unpredicted-non-reward difference wave) shown for three tertials of extraversion (i.e. high, middling, and low scores).

We then assessed the incremental validity of our extraversion finding while controlling for the remaining Big Five domains. When entering all domains from the BFAS into a linear regression predicting the Reward Positivity, the only significant unique predictor was extraversion, $\beta = .23$, $p = .015$. We then conducted the equivalent Bayesian linear regression, following the methods described by Rouder and Morey (2012). Against a null model (with none of the BFAS domain scores entered) the best-fitting model was one in which extraversion was

entered as a single predictor (Bayes factor = 4.9). The next best single predictor model was for openness/intellect, with a Bayes factor of 2.0. If the probability of inclusion of each of the predictors was set at 0.5 prior to gathering the data, the probability of including extraversion and openness/intellect both increased after gathering the data (to 0.763 and 0.514, respectively), whereas the probability of including the other three BFAS trait domains all decreased. Finally, in comparison to a model containing the other four trait domains, a model that additionally included extraversion had a Bayes factor of 2.7, again offering substantial evidence in favor of its inclusion. For openness/intellect the equivalent Bayes factor for its inclusion as a fifth predictor was a more modest 1.1. In contrast, equivalent analyses of the other three predictors revealed Bayes factors in favor of *excluding* the fifth predictor (Bayes factors between 1.3 and 2.5).

Next, when entering all of the MM domains into a regression predicting the Reward Positivity, the only significant unique predictor was again extraversion, $\beta = .22$, $p = .02$ (see Table 2 for full results of both models). An equivalent Bayesian linear regression analysis revealed very similar findings to the analyses using the BFAS domains reported above: the best model included extraversion as a single predictor (Bayes factor = 2.3 compared with a null model), whereas the next best single predictor model was for intellect, with a modest Bayes factor of 1.3. The probability of inclusion for extraversion rose from prior of 0.5 to posterior of 0.68—and for intellect, to 0.51—but fell for all other MM domains. Finally, adding extraversion as a fifth predictor to a model comprised of the other four trait domains was supported by a Bayes factor of 2.3. For intellect the corresponding Bayes factor was 1.2, and for each of the other three predictors the model *without* the fifth predictor was favored (Bayes factors between 1.7 and 2.4).

In summary, extraversion appears to be the only Big Five domain to have a significant, unique association with this index of RPE signaling, thus supporting our third hypothesis (H3). Our Bayesian analyses offered substantial evidence in favor of this hypothesis relative to the null,

with Bayes factors ranging from 2.3 to 4.9 (see Kass & Raftery, 1995, Table 1). These values are consistent with the range of (significant) p -values reported in our frequentist regression analyses. The only other trait with any hint of a unique association with the reward positivity was openness/intellect (which had a significant zero-order association with the Reward Positivity, see Table S3), but these analyses revealed non-significant relationships in our frequentist regression analyses and more modest Bayes factors ranging from 1.1 to 2.0.

Table 2

Unique relations (β coefficients) between the Big Five trait domains and the Reward Positivity.

	Reward Positivity	
	Model 1 (BFAS)	Model 2 (MM)
Extraversion	.23*	.22*
Openness/Intellect	.17	.17
Neuroticism	.01	.01
Agreeableness	-.12	-.07
Conscientiousness	-.03	-.10
<i>Variance explained</i>	10%	9%

Note: * $p < .05$.

Aspects of Extraversion and Reward-Prediction-Error

Data reduction across our aspect-level measures of extraversion (assertiveness, social potency, enthusiasm, wellbeing) via Principal Axis Factoring (direct oblimin rotation) yielded a clear two-factor solution (eigenvalues = 2.20, 1.25, 0.31, 0.23). This was corroborated by results

of a parallel analysis test (99th percentile of eigenvalues from 1,000 random datasets = 1.42, 1.17, 1.02, 0.93; see O’Conner, 2000), and accounted for 73% of the variance. Based on the loadings presented in Table 3 we labeled Factor 1 “agentic extraversion” and Factor 2 “affective extraversion”, to avoid confusion between these factors and their constituent variables. There were no cross-loadings, and the two factors were moderately intercorrelated, $r = .31$.

Table 3

Pattern matrix from Principal Axis Factoring (with direct oblimin rotation) of aspects of extraversion.

	Agentic Extraversion	Affective Extraversion
Social Potency	.90	-.04
Assertiveness	.85	.05
Wellbeing	-.08	.84
Enthusiasm	.11	.80
<i>Variance explained</i>	49%	24%

Standardized scores for both factors were then saved (regression method) and entered into a one-way ANCOVA contrasting FRN following unpredicted reward versus unpredicted non-reward. This yielded a main effect corresponding to the Reward Positivity, $F(1,98) = 93.02$, $p < .001$, $\eta_p^2 = .49$, and no main effect of either agentic or affective extraversion, $F_s < 1$, ns . The interaction between agentic extraversion and the FRN contrast fell short of significance, $F(1,97) = 2.40$, $p = .12$, $\eta_p^2 = .02$, and corresponds to the correlation between this factor and the Reward Positivity when partialing out affective extraversion, $r = .16$, $p = .12$. The interaction involving

affective extraversion also fell short of significance, $F(1,97) = 1.47$, $p = .23$, $\eta_p^2 = .02$, and corresponds to the correlation between this factor and the Reward Positivity while partialing out agentic extraversion, $r = .12$, $p = .23$. Exploration of zero order correlations revealed that both agentic extraversion, $r = .21$, $p = .04$, and affective extraversion, $r = .19$, $p = .06$, had marginally significant positive associations with the Reward Positivity. This lack of divergent validity was also apparent in the zero order correlations that our four aspect-level scales had with the Reward Positivity (see supplementary Table S3).

Discussion

Research into the reward-processing theory of extraversion is often described as one of the more robust strands of Personality Neuroscience. However, this observation may reflect the fledgling state of Personality Neuroscience in general than the depth of our understanding of the neurobiology of extraversion in particular. In a recent review of this literature (Wacker & Smillie, 2015) we observed that many promising studies linking extraversion with neural indices of reward-processing were limited by low sample sizes and a dearth of replication studies. We therefore sought to provide a well-powered replication and extension of studies linking extraversion with the Reward Positivity. Our supportive findings engender confidence that there is indeed a reliable association between extraversion and this EEG-derived index of RPE signaling.

In support of our first hypothesis, extraversion was positively and significantly associated with the Reward Positivity (i.e. the difference wave contrasting the FRN for unpredicted reward with that for unpredicted non-reward). Because this event-related potential appears to code for RPE signaling (Sambrook & Goslin, 2015), and potentially originates from phasic midbrain dopamine cell firing (Holroyd & Coles, 2002; Potts et al., 2006), our finding lends support to the view that extraversion is underpinned by a more sensitive dopaminergic reward-processing

system (Depue & Collins, 1999). In support of our second and third hypotheses, the association with the Reward Positivity generalized across three separate measures of extraversion, and remained significant after controlling for the remaining Big Five personality domains (all of which had non-significant unique associations). Equivalent Bayesian analyses confirmed that measures of extraversion, but not other traits, produced substantially stronger models of variation in the Reward Positivity relative to the null. This provides the critical convergent-divergent evidence for the relation between extraversion and RPE that has been conspicuously absent in previous research. Specifically, our results as a whole provide evidence *against* the null when examining the relation between extraversion and the Reward Positivity, and evidence *in favor of* the null when examining this relation for other Big Five domains (with the exception of openness/intellect, discussed further below). This evidence provides a solid base from which to expand knowledge of the link between extraversion and reward-processing, as well as the putative role of dopamine in this link. Our own efforts along these lines include the use of pharmacological manipulations (Mueller et al., 2014) and biologically realistic computational models (Pickering et al., 2017; Pickering & Pesola, 2014) to probe whether, and in which ways, dopamine may underlie the link between extraversion and the Reward Positivity.

Although a secondary focus in the present study, one interesting finding was that the relation between extraversion and the Reward Positivity was not primarily driven by either of two narrower aspects of this domain. Specifically, we extracted two factors that we labeled “agentic extraversion” and “affective extraversion”, in alignment with models that distinguish boldness/dominance versus enthusiasm/positivity as core components of extraversion (e.g. DeYoung et al., 2007; Quilty et al., 2014; Soto & John, 2017). Consistent with DeYoung’s (2013) argument that both of these aspects of extraversion may relate to reward processing and dopamine function, our two factors had similar associations with the Reward Positivity, although

these were slightly weaker than those observed at the domain level. This may suggest that reward-processing has broad relevance to the extraversion domain, and that little is gained by descending the trait hierarchy to the narrower aspects of this domain. However, we offer this suggestion with some caution given that these analyses were novel in this literature and undertaken on a largely exploratory basis. In addition, the agentic/affective distinction we have drawn is not definitive. For instance, Depue and Collins (1999) originally theorized that their reward-processing theory applies most directly to the agentic component of extraversion, which they contrasted with “affiliative extraversion”. This latter trait comprises tendencies toward social closeness and interpersonal warmth, and was recently re-conceptualized as a blend of extraversion and agreeableness (DeYoung, 2013). Future research might also examine relations with the Reward Positivity at the more finely grained “facet” level of extraversion, which comprises six or more narrow bandwidth traits.

Another noteworthy finding in the present study was an unpredicted correlation between the Reward Positivity and two separate measures of openness/intellect. Although these correlations were statistically non-significant after controlling for extraversion, our Bayesian analyses of these associations did not yield clear evidence against the null. Indeed, these analyses showed that our models of the Reward Positivity were slightly improved through the inclusion of openness/intellect, albeit to a much more modest extent than for extraversion. These results are interesting in the context of a recent theory linking openness/intellect to a different aspect of prediction error signaling. Specifically, DeYoung (2013) has theorized that openness/intellect may also be related to dopamine function, and that this may be one explanation for the meta-trait *plasticity* (A.K.A. *beta*), which describes the shared variance between extraversion and openness/intellect (see DeYoung, 2006; Digman, 1997). DeYoung draws on animal studies that distinguish two classes of dopamine neurons with distinct firing patterns. One class of neurons

follows the traditional RPE effect, encoding motivational *value* (i.e. firing for unexpected positive stimuli; inhibited by unexpected negative stimuli), whereas the other appears to encode motivational *salience* (i.e. firing for unexpected stimuli, both positive and negative; Bromberg-Martin et al., 2010). DeYoung (2013) suggests that value-coding dopamine neurons may underpin individual differences in extraversion, whereas salience-coding dopamine neurons may underpin individual differences openness/intellect. If there is such a link between openness/intellect and dopamine, it is possible that the Reward Positivity partly taps into this relation. Of course, this suggestion is entirely speculative, and further confirmatory research would be necessary to address the possibility of openness/intellect consistently relating to this index of RPE signaling.

There are several possible improvements and extensions to our design and methodology that would be worthwhile to pursue in future research. For example, a recent study has suggested that there are potential confounds in designs such as ours that might obscure relevant variance (Sambrook & Goslin, 2014). First, the associative task we have used presents outcomes as either rewards (gold bar) or non-rewards (lemons), but there is no “punishment” condition in which participants directly lose money. As rewards have been found to be more salient than non-rewards (Esber & Haselgrove, 2011), it may be beneficial to adapt our associative task to allow for rewards, non-rewards, *and* punishments. However, given the theoretical correspondence between neuroticism and sensitivity to threatening or aversive stimuli (DeYoung, 2010; Corr, 2008), it is possible that any neural response to unexpected punishment would be driven by this personality trait. Thus, before adapting this task to incorporate punishments, it would be prudent to first test whether personality traits unrelated to extraversion (such as neuroticism) are in fact related to the strength of response to the loss of money (cf, Hirsh & Inzlicht, 2008).

Second, our task does not recognize the distinction between reward *likelihood* (i.e. receiving a reward or punishment that has only appeared very infrequently) and reward *magnitude* (i.e. receiving a reward or punishment that is presented equally often, but is different from the average reward or punishment). If the delivery of a reward is unexpected, then this could produce an “alerting” EEG signal that may not give an accurate representation of the Reward Positivity (Bromberg-Martin et al., 2010; DeYoung, 2013). One solution to this problem is to use a semi-continuous measure of rewards in the form of a range of monetary gain outcomes, thus varying the magnitude of reward independently of its predictability (see Sambrook & Goslin, 2014, for an example of this technique).

It is also important to note that, owing to our use of a purely associative paradigm, we are unable to interpret our findings with reference to the impact of rewards on behavior. That is, we can conclude that extraverts differ from introverts in terms of their neural response to rewards, but we cannot infer, for example, that extraverts *learn* more effectively from rewards, or that they are more strongly *motivated* by rewards. With some notable exceptions (e.g. Depue & Fu, 2013; Pickering, 2004), few studies in the literature have used behavioral paradigms to test the reward-processing theory of extraversion. This strikes us as a conspicuous gap in the evidence base that ought to be given close attention in future research.

To conclude, we have provided a well-powered replication of the association between extraversion and an EEG index of reward-prediction-error signaling, the Reward Positivity. Our findings closely match two previous (underpowered) studies (Cooper et al., 2014; Smillie et al., 2011), while also providing evidence for convergent and divergent validity through frequentist and Bayesian analyses. Our results reveal a significant association between multiple measures of extraversion and the Reward Positivity. When considered alongside similar studies elsewhere in the literature (e.g. Boksem et al., 2008; Bress & Hajcak, 2013; Mueller et al., 2014), these

findings provide strong support for an association between extraversion and RPE signaling, and encouragement for the reward-processing theory of this trait within personality neuroscience.

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Supplementary Analyses (to be made available online)

Table S1

Omega (hierarchical) reliabilities with 1,000 bootstrapped 95% CIs for extraversion scales.

Scale	Internal Consistency (ω_t)	95% CI
BFAS Extraversion	.85	[.78, .90]
Assertiveness	.82	[.74, .88]
Enthusiasm	.83	[.77, .88]
MPQ Positive Emotionality	.79	[.58, .88]
Social Potency	.84	[.79, .88]
Wellbeing	.86	[.80, .90]
MM Extraversion	.84	[.79, .88]

Table S2

Individual Chanel Analysis Confirming Reward-Prediction-Error Coding at Medial Frontal Channels but not Ocular Channels

	Reward vs. Non-Reward	Predicted vs. Unpredicted	Interaction (Reward Positivity)
F1	$F(1,99) = 44.76, p < .001, \eta_p^2 = .31$	$F(1,99) = 56.25, p < .001, \eta_p^2 = .24$	$F(1,99) = 33.88, p < .001, \eta_p^2 = .26$
F2	$F(1,99) = 61.21, p < .001, \eta_p^2 = .45$	$F(1,99) = 83.45, p < .001, \eta_p^2 = .28$	$F(1,99) = 82.32, p < .001, \eta_p^2 = .30$
Fz	$F(1,99) = 62.60, p < .001, \eta_p^2 = .39$	$F(1,99) = 82.51, p < .001, \eta_p^2 = .28$	$F(1,99) = 24.27, p < .001, \eta_p^2 = .25$
FC1	$F(1,99) = 47.40, p < .001, \eta_p^2 = .28$	$F(1,99) = 33.14, p < .001, \eta_p^2 = .18$	$F(1,99) = 11.88, p = .001, \eta_p^2 = .11$
FC2	$F(1,99) = 70.54, p < .001, \eta_p^2 = .44$	$F(1,99) = 34.60, p < .001, \eta_p^2 = .15$	$F(1,99) = 14.16, p < .001, \eta_p^2 = .16$
FCz	$F(1,99) = 82.25, p < .001, \eta_p^2 = .43$	$F(1,99) = 20.60, p < .001, \eta_p^2 = .17$	$F(1,99) = 20.25, p < .001, \eta_p^2 = .17$
VEOG	$F(1,95) = 0.52, p = .473, \eta_p^2 = .01$	$F(1,95) = 1.46, p = .230, \eta_p^2 = .02$	$F(1,95) = 0.39, p = .535, \eta_p^2 = .01$
HEOG	$F(1,93) = 2.62, p = .109, \eta_p^2 = .44$	$F(1,93) = 0.01, p = .954, \eta_p^2 = .00$	$F(1,93) = 3.02, p = .085, \eta_p^2 = .03$

Note: For all medial frontal electrode channels listed above (F1, F2, Fz, FC1, FC2, FCz) the FRN was more negative following reward vs. non-reward, and following unpredicted versus predicted events. However, in all cases these effects were qualified by a significant interaction, reflecting the fact that the effects of reward vs. non-reward was considerably more pronounced for unpredicted vs. predicted trials. Conversely, there were no significant main effects or interactions when these analyses were repeated for ocular channels (VEOG, HEOG). The lower degrees of freedom for the ocular analyses reflect unavailable or unusable VEOG data for 4 participants and HEOG data for 6 participants.

Table S3

Zero-order correlations between all trait measures and the Reward Positivity.

	Reward Positivity
BFAS Extraversion	.26**
Assertiveness	.21*
Enthusiasm	.22*
BFAS Openness/Intellect	.22*
Openness	.09
Intellect	.25*
BFAS Agreeableness	-.07
Politeness	-.14
Compassion	.03
BFAS Conscientiousness	.03
Industriousness	.08
Orderliness	-.04
BFAS Neuroticism	.02
Volatility	.06
Withdrawal	-.04
MM Extraversion	.23*
MM Intellect	.20*
MM Agreeableness	-.01
MM Conscientiousness	-.03
MM Neuroticism	.10
MPQ Positive Emotionality	.21*
Social Potency	.17^
Wellbeing	.10

Note: ^ $p < .10$; * $p < .05$; ** $p < .01$