Self-report and behavioral measures of reward sensitivity predict the feedback negativity

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Abstract

Rewards are integral to learning associations that aid in survival. The feedback negativity (FN), an event-related potential that differentiates outcomes indicating monetary losses versus gains, has recently emerged as a possible neural measure of reward processing. If this view is correct, then the FN should correlate with measures of reward sensitivity in other domains, although few studies have investigated this question. In the current study, 46 participants completed a self-report measure of reward responsiveness, a signal detection task that generated a behavioral measure of reward sensitivity, and a gambling task that elicited an FN. Consistent with the view that the FN reflects reward-related neural activity, a larger FN correlated with increased behavioral and self-report measures of sensitivity to reward.

Descriptors: EEG/ERP, Normal volunteers, Reward, Feedback negativity

Rewards play an integral role in learning (Thorndike, 1927). A rat will learn to press a lever if rewarded with an enticing food, and more desired rewards will lead to increased frequency of rewarded behaviors (Hodos, 1961). Humans are similarly motivated: we hunt for food in part because we enjoy eating, and we procreate because it is pleasurable to do so. Thus, reward shapes our behaviors and allows us to learn associations that aid in our survival.

Recent studies in humans have assessed reward sensitivity using behavioral measures, such as a progressive ratio task in which the number of responses required to earn a reward increases over time (Chelonis, Gravelin, & Paule, 2011). Reward sensitivity is assessed by measuring the "break point" at which the participant is no longer willing to continue pressing the lever to receive the reward. Pizzagalli and colleagues (Pizzagalli, Jahn, & O'Shea, 2005) have studied reward sensitivity using a signal detection task in which participants are asked to make a difficult perceptual decision between two similar stimuli on each trial; unbeknownst to the participant, one type of correct response is rewarded more frequently than the alternative, and reward sensitivity is measured as the extent to which the participant develops a bias to make the more frequently rewarded response.

Reward sensitivity, as measured behaviorally on the signal detection task, has been proposed as an objective marker of anhedonia: whereas healthy participants show a bias toward the more frequently rewarded response, those with clinical depression, and even subclinical anhedonia, show no response bias (Kunisato et al., 2012; Pizzagalli, Iosifescu, Hallett, Ratner, & Fava, 2008; Pizzagalli et al., 2005). Such findings are consistent with the

decreased self-reported reward responsiveness associated with depression (Kasch, Rottenberg, Arnow, & Gotlib, 2002).

Reward processing is associated with activity in midbrain dopamine areas and related regions (Schultz, 2002). Moreover, activation in the frontostriatal-amygdala-midbrain dopamine network correlates with self-reported reward responsiveness (Beaver et al., 2006; Simon et al., 2010). Consistent with the role of midbrain dopamine systems in reward sensitivity, decreasing phasic dopamine leads to a reduction in the behavioral bias toward reward in the signal detection task (Pizzagalli, Evins et al., 2008). Furthermore, both depression and anhedonia are associated with reduced striatal activity (Forbes et al., 2006; Keedwell, Andrew, Williams, Brammer, & Phillips, 2005; Pizzagalli et al., 2009; Smoski et al., 2009).

Increasing evidence suggests that reward sensitivity can also be measured using the feedback negativity (FN), an event-related potential (ERP) elicited by stimuli that indicate monetary gain versus loss. In gambling tasks, the FN appears as a relative negative deflection in the waveform approximately 300 ms following feedback that indicates monetary loss compared to gain (Hajcak, Moser, Holroyd, & Simons, 2006, 2007; Yeung, Holroyd, & Cohen, 2005; Yeung & Sanfey, 2004). Consistent with the role of dopamine in reward prediction error signaling, the FN is more pronounced for unpredicted than predicted outcomes (Hajcak et al., 2007).

Traditionally, the negative deflection in the ERP has been interpreted as an error signal in response to losses (Hajcak et al., 2006; Holroyd & Coles, 2002). Recent studies, however, have led to a contrasting conceptualization of the FN in terms of a positive deflection in response to monetary gains that is absent on loss trials (Baker & Holroyd, 2011; Bernat, Nelson, Steele, Gehring, & Patrick, 2011; Carlson, Foti, Mujica-Parodi, Harmon-Jones, & Hajcak, 2011; Foti, Weinberg, Dien, & Hajcak, 2011). Moreover, there is evidence that the FN is generated by neural regions

engaged in reward processing (Carlson et al., 2011; Foti, Weinberg et al., 2011). Consistent with this conceptualization of the FN, and the relationship between reward and depression, the amplitude of the FN is also modulated by depressive symptoms: more severe depressive symptoms are associated with a reduced FN (Bress, Smith, Foti, Klein, & Hajcak, 2012; Foti & Hajcak, 2009).

If the FN reflects individual differences in reward-related brain activity, then it should also relate to other measures of reward sensitivity across individuals. Yet, despite clear conceptual parallels with self-report and behavioral measures, only a few studies have directly investigated associations across these domains. One study found that the magnitude of the FN was associated with a change in behavioral bias toward rewards (Santesso et al., 2008). However, the task used to elicit the FN did not present feedback indicating monetary loss, making the results somewhat difficult to interpret. Results from studies examining relationships between the FN and self-reported reward responsiveness are mixed (Lange, Leue, & Beauducel, 2012; Van den Berg, Franken, & Muris, 2011). Van den Berg and colleagues (2011) measured responses to gains and losses separately in a gambling task and found no association between FN amplitude and reward responsiveness. In contrast, using an extinction learning task to elicit an FN, Lange and colleagues (2012) found that higher trait behavioral activation system (BAS) scores were associated with a more negative FN in response to unexpected nonrewards. Like Santesso and colleagues (2008), however, their task was not optimized to directly compare responses to gain and loss.

The purpose of the current study was to test the hypothesis that the FN is predicted both by a self-report measure of reward responsiveness and by a behavioral measure of reward sensitivity. It was hypothesized that individuals with a larger FN—measured as the difference between response to monetary losses and gains—would show greater sensitivity to rewards, as reflected both by self-report and a larger behavioral bias based on reward contingencies in the signal detection task.

Method

Participants

Fifty-one Stony Brook University undergraduate psychology students (mean age = 19.77, SD = 1.78) participated in the current study; all received course credit for their participation. Three subjects were excluded for poor quality data. Participants whose feedback negativity difference scores (ΔFN, i.e., response to losses minus response to gains), response bias, or self-report scores were more than three standard deviations from the mean were also excluded, resulting in the exclusion of two additional participants. In total, five participants were excluded, for a final sample of 46 participants (27 female). This study was formally approved by the Stony Brook Institutional Review Board.

Gambling Task

In order to elicit reward-related brain activity, participants completed a gambling task similar to those used in previous studies (Foti & Hajcak, 2009, 2010; Foti, Kotov, Klein, & Hajcak, 2011). The task consisted of two blocks of 20 trials each, separated by a break of a duration determined by the participant. During each trial, participants viewed an image of two doors side by side and were asked to choose one by clicking either the right or left mouse button. After participants chose a door, a feedback screen indicated that they had either won $0.50 or lost $0.25. These values were chosen in order to equalize the subjective value of gains and losses (Tversky & Kahneman, 1992) and so that participants could accrue earnings over the course of the experiment. No neutral condition (i.e., a condition in which the participant would neither lose nor gain money) was included, because previous work has found that ERPs to neutral feedback and loss feedback are equivalent in this type of task (Holroyd, Hajcak, & Larsen, 2006). In contrast to the signal detection task, it was not possible to learn associations between responses and outcomes in the gambling task. We have previously used similar tasks to assess reward-related brain activity using both ERP and fMRI (Carlson et al., 2011), and in relation to depressive symptoms (Bress et al., 2012; Foti & Hajcak, 2009, 2010).

On each trial, a fixation cross was presented for 1,000 ms, followed by the image of the doors, which remained on the screen until the participant made a response. Another fixation cross was presented for 1,000 ms, and feedback was presented for 2,000 ms. Finally, another fixation mark was presented for 1,500 ms, followed by the message "Click for the next round," which remained on the screen until the participant clicked a mouse button to begin the next trial. An equal number of gain and loss trials (20 of each) were presented to each participant in a random order.

Psychophysiological Recording and Data Reduction

During the gambling task, electroencephalographic (EEG) activity was recorded using a 34-channel ActiveTwo BioSemi System (BioSemi, Amsterdam, the Netherlands) and a custom cap with electrodes placed according to the International 10/20 system. Electrooculogram (EOG) and mastoid activity were also recorded. Data were digitized at a sampling rate of 1024 Hz with a 24-bit resolution and a low-pass fifth-order sinc filter with a half-power cutoff of 204.8 Hz.

Off-line analysis was conducted with BrainVision Analyzer (Brain Products, Munich, Germany). EEG channels were rereferenced to an average of the activity at the mastoids, and data were filtered at cutoffs of .1 and 30 Hz. EEG was segmented into 1,000-ms epochs, which began 200 ms before and ended 800 ms after feedback onset; signals were corrected using the segment from −200 ms to feedback onset as baseline. EOG artifacts were removed using the procedure from Gratton and colleagues (Gratton, Coles, & Donchin, 1983), and physiological artifacts were removed using a semiautomated procedure with a maximum allowed voltage step of 50 µV, a maximum absolute difference between any two points of 300 µV, and a minimum allowed activity of .50 µV in a 100-ms interval. Pooled stimulus-locked ERP data from the Fz and FCz electrodes—where the loss-gain difference was numerically maximal—were averaged separately for gains and losses in the 250–350 ms window after feedback onset; this pooling has also been used in previous studies (Foti & Hajcak, 2010; Foti, Kotov et al., 2011). The ΔFN was then measured as the difference between losses and gains (i.e., response to losses minus response to gains), as is typical in the field (Dunning & Hajcak, 2007; Gu, Huang, & Luo, 2010; Moser & Simons, 2009; Nieuwenhuis, Slagter, von Geusau, Heslenfeld, & Holroyd, 2005). Although the difference-wave approach has limitations, it is useful in that it lessens the risk of falsely identifying an ERP component and isolates valence-related variability in the ERP (Luck, 2005). In addition to the difference wave, ERP responses to gains and losses were also evaluated separately for secondary analyses.

Self-Reported Reward Responsiveness

The Reward Responsiveness Scale (RR; Van den Berg, Franken, & Muris, 2010) was used to quantify participants' self-reported tendency to engage in reward-related behavior. The RR scale was developed as a means of providing a purer and more reliable measure of reward responsiveness than other self-report scales. For instance, previous scales include multiple distinct components relating to approach behavior and have relatively low reliability (Van den Berg et al., 2010). The RR scale consists of eight items based in part on the BIS/BAS scale (Carver & White, 1994)—for example, "I would do anything to achieve my goals," "When I see an opportunity for something I like, I get excited right away"—and has been demonstrated to be internally consistent and to have excellent reliability and validity (Van den Berg et al., 2010). Items are rated on a scale from 1 (*very false for me*) to 4 (*very true for me*), with no items reverse-coded; the overall RR score is calculated by summing the scores of the eight items.

Behavioral Measure of Reward Sensitivity

A computerized signal detection task developed by Pizzagalli and colleagues (Pizzagalli et al., 2005) was used to assess bias toward frequently rewarded responses. On each trial, participants viewed an icon representing a simplified face with a straight line for a mouth; the length of the mouth could be long (13 mm) or short (11.5 mm) on each trial, and participants were asked to press either the "z" or the "/" key on the keyboard to indicate the mouth type. The task consisted of three blocks of 100 trials each (50 short and 50 long, pseudo-randomly distributed throughout the block with the restriction that neither stimulus occurred more than three times in a row). Blocks were separated by a rest of at least 30 s. On each trial, a fixation mark was presented for 1,400 ms; a face without a mouth was presented for 500 ms; a mouth (either short or long) then appeared on the face for 100 ms; finally, the face without a mouth remained on screen until the participant responded. The response was followed immediately either by a blank screen lasting 1,750 ms, or by feedback indicating a monetary reward of $0.05 ("Correct!! You won 5 cents") for 1,500 ms followed by a blank screen for 250 ms.

Feedback was given only for correct responses, and a total of 40 correct trials were rewarded throughout each block. Over the course of the task, one type of correct response (long or short) was more richly rewarded, such that the participant received a monetary reward three times more frequently for that type of response (i.e., on 30 trials per block) than for the other (10 trials per block). For half of the participants, the short-mouthed stimulus was assigned to the richly rewarded condition, and the long-mouthed stimulus was assigned to the leanly rewarded condition; for the other half, these mappings were reversed. Previous work indicates that participants develop a response bias (RB) toward the more richly rewarded response over the course of the task (Pizzagalli, Iosifescu et al., 2008; Pizzagalli et al., 2005). Response bias was calculated using the following formula:

$$\log b = \frac{1}{2}\log\left(\frac{\text{rich}_{correct} * \text{lean}_{incorrect}}{\text{rich}_{incorrect} * \text{lean}_{correct}}\right)$$

where "log *b*" represents the response bias, "rich$_{correct}$" represents the number of correct responses made toward the more frequently rewarded stimulus, "rich$_{incorrect}$" represents the number of incorrect responses toward the more frequently rewarded stimulus, "lean$_{correct}$" represents the number of correct responses toward the

less frequently rewarded stimulus, and "lean$_{incorrect}$" represents the number of incorrect responses toward the less frequently rewarded stimulus. A measure of discriminability was also calculated using the following formula:

$$\log d = \frac{1}{2}\log\left(\frac{\text{rich}_{correct} * \text{lean}_{correct}}{\text{rich}_{incorrect} * \text{lean}_{incorrect}}\right)$$

where "log *d*" represents the discriminability value. As described by Pizzagalli and colleagues (Pizzagalli et al., 2005), these measures are derived from classic behavioral signal detection literature (McCarthy & Davison, 1979; Tripp & Alsop, 1999) (for additional information, see Pizzagalli et al., 2005). EEG was not recorded during this task.

In the context of the current study, RB was used as a between-subjects measure of the degree to which individuals adjusted their performance to obtain rewards. Importantly, this response bias reflects the extent to which participants select the more richly rewarded response—independent of their ability to discriminate the two stimuli. Indeed, in the current study, RB and discriminability were not significantly correlated ($r = .12$, $p = .44$).

Procedures

After participants gave informed consent, the EEG cap was applied, and the gambling and signal detection tasks were administered in the context of other tasks. Task order was counterbalanced across participants, and the RR and other questionnaires were administered after participants completed the EEG tasks. In addition to receiving course credit, participants were told that they would be given the winnings from the gambling and signal detection tasks at the end of the session; this was done in order to increase motivation and to maximize the perceived value of the rewards. All participants were given $5 for the gambling task and $6 for the signal detection task.

Results

Descriptive Statistics

Feedback-locked ERPs at Fz/FCz and scalp distribution of the ΔFN are presented in Figure 1 (left and right, respectively). Consistent with previous studies, the difference between loss and gain outcomes was evident as a negative deflection around 280 ms and was largest at frontocentral sites. Electrocortical response to losses ($M = 11.79$ μV, $SD = 6.00$) was significantly less positive than response to gains ($M = 17.23$ μV, $SD = 7.47$; $t(45) = −6.33$, $p < .001$).

Mean RR was 27.07 ($SD = 3.31$), with a range of 20 to 32. These values are similar to those reported by Van den Berg et al. (2010), who found means of 26.1 ($SD = 3.2$), 27.2 ($SD = 2.7$), and 26.9 ($SD = 3.0$) in their studies.

Mean RB in the signal detection task was .16 ($SD = .12$) and was significantly greater than 0, $t(45) = 9.25$, $p < .001$; thus, over the course of the task, participants developed a behavioral bias toward making the more frequently rewarded response.

Correlations Among Measures

Among the overall sample, five participants had negative RB scores. Separate analyses of the negative- and positive-RB participants indicated that the two groups showed different patterns in their RB over the three blocks of the task. In the negative-RB
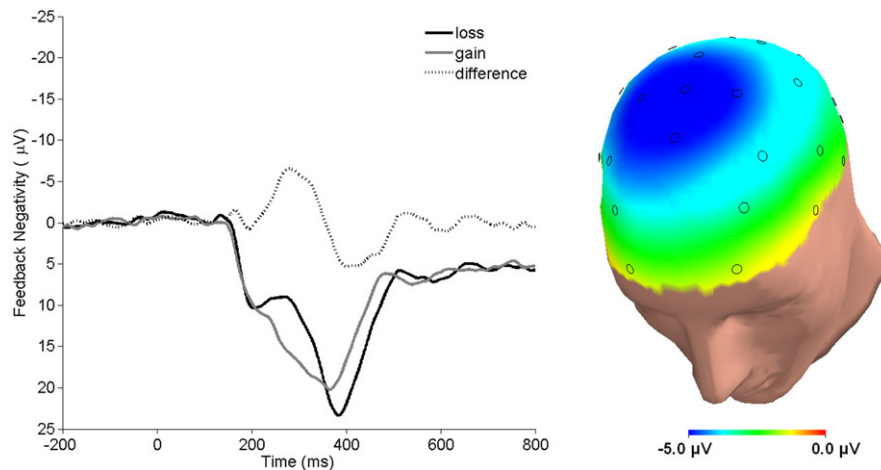
Figure 1. Left: Feedback-locked ERPs at pooled Fz and FCz electrodes for losses, gains, and loss-gain difference in the gambling task. Right: Scalp distribution of the difference between response to losses and gains from 250–350 ms in the gambling task. Negative-RB participants are excluded.

group, RB was negative in blocks 1 ($M = −.16$, $SD = .10$) and 2 ($M = −.08$, $SD = .06$) but became positive in block 3 ($M = .11$, $SD = .15$); RB in block 3 was significantly larger than in block 1, $t(4) = 3.03$, $p < .05$, and marginally significantly larger than in block 2, $t(4) = 2.34$, $p = .08$. In the positive-RB group, in contrast, a positive RB had developed by block 1 ($M = .12$, $SD = .11$) and remained positive in blocks 2 ($M = .21$, $SD = .15$) and 3 ($M = .23$, $SD = .18$). Only block 1 RB differed from block 2, $t(40) = 3.24$, $p < .01$, and block 3, $t(40) = 3.52$, $p < .01$. RB in blocks 2 and 3 did not differ significantly, $t(40) = .90$, $p = .38$, suggesting that these participants may have developed a response bias toward reward by the end of block 1, and reached maximal RB by the end of the task. Together, the different patterns in the negative- and positive-RB participants suggest that the negative-RB participants began the task with a negative bias, and may simply not have had time to fully correct this bias by the end of the task. Therefore, after conducting the correlational analyses with the full sample, these analyses were run again with only the positive-RB participants included.[1]

Figure 2 depicts the relationship between ΔFN and RR (top) and between ΔFN and RB (bottom); in both plots, participants with positive RBs are represented by filled circles, and participants with negative RBs are represented by open circles. In the overall sample, ΔFN correlated with RR ($r = −.33$, $p < .05$). An analysis of the ERP response to losses showed no significant correlations with RR ($r = −.11$, $p = .46$); likewise, the ERP response to gains was not correlated with RR ($r = .17$, $p = .27$).

In the overall sample, RB did not significantly correlate with ΔFN ($r = −.13$, $p = .39$), and ΔFN did not significantly correlate with discriminability ($r = −.09$, $p = .57$). RB did not significantly correlate with either ERP response to losses ($r = −.08$, $p = .60$) or to gains ($r = .04$, $p = .81$). RB was also not significantly correlated with RR ($r = .26$, $p = .08$).

When negative-RB participants were excluded from the analyses, the correlation between RB and ΔFN became significant
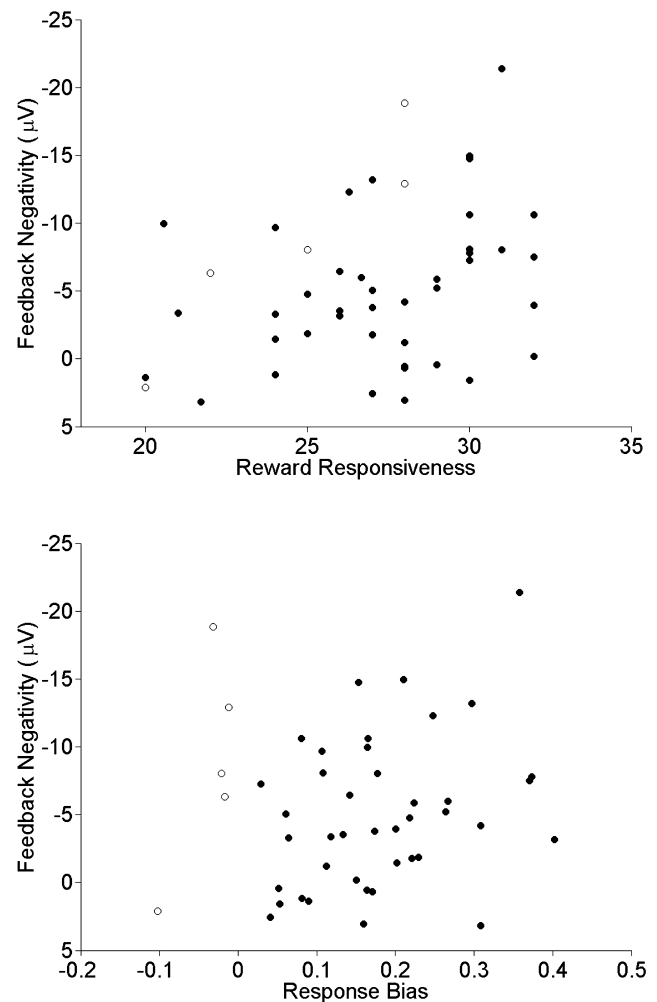
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1. With negative-RB participants excluded, mean electrocortical response to losses was 11.79 μV ($SD = 6.30$), and mean response to gains was 16.82 μV ($SD = 7.36$). Mean RR was 27.37 ($SD = 3.19$), and mean RB was .18 ($SD = .10$). Positive- and negative-RB participants did not differ significantly in terms of their ΔFN amplitudes, $t(44) = 1.38$, $p = .18$, or their RR values, $t(44) = 1.81$, $p = .08$.

Figure 2. Top: Scatter plot depicting ΔFN and RR values. ΔFN and RR were significantly correlated in both the overall sample ($r = −.33$, $p < .05$) and with negative-RB participants excluded ($r = −.32$, $p < .05$). Bottom: Scatter plot depicting ΔFN and RB values. ΔFN and RB were not correlated in the overall sample ($r = −.13$, $p = .39$), but a significant correlation emerged when negative-RB participants were excluded ($r = −.31$, $p < .05$). Negative-RB participants are denoted by open circles, and positive-RB participants are denoted by filled circles.

($r = -.31$, $p < .05$); on the other hand, the relationship between discriminability and ΔFN did not ($r = .04$, $p = .81$). RB did not correlate with either ERP response to losses ($r = -.11$, $p = .48$) or to gains ($r = .14$, $p = .39$) separately. Additionally, the relationship between RR and ΔFN remained significant ($r = -.32$, $p < .05$), and RR and RB remained uncorrelated ($r = .11$, $p = .48$).

Partial correlations were calculated in order to determine whether self-report and behavioral measures of reward sensitivity related to the ΔFN after controlling for the contribution of the other predictor. Both the partial correlation between RR and ΔFN controlling for RB (partial $r = -.30$, $p = .06$) and the partial correlation between RB and ΔFN controlling for RR (partial $r = -.29$, $p = .07$) were marginally significant. Because the ΔFN is a numerically negative component, the significant negative correlations indicate that participants with more negative (i.e., greater magnitude) ΔFNs had greater self-reported and behavioral sensitivity to reward.

Discussion

The aim of the current study was to test the association between a putative electrocortical measure of reward processing (i.e., the ΔFN) and both behavioral (i.e., RB in the signal detection task) and self-report (i.e., RR) measures of reward sensitivity. As expected, the gambling task elicited an FN, which was apparent as a negative deflection in the waveform at about 280 ms and was less positive in response to losses than gains. Consistent with our hypothesis, the amplitude of the ΔFN was significantly correlated with self-reported RR; that is, subjects with larger ΔFNs endorsed subjectively more interest in reward.

The current findings contrast with those of Van den Berg and colleagues (Van den Berg et al., 2011), who found no significant association between the FN and RR. However, there are a number of methodological differences in the way they evaluated the FN that may account for this discrepancy. In particular, Van den Berg and colleagues separately evaluated ERPs to loss and gain outcomes, rather than using a difference waveform. The current results, using a difference measure of the FN that isolates valence-related activity, are consistent with the emerging view that variation in the ΔFN is driven by reward-related brain activity (Carlson et al., 2011; Foti, Weinberg et al., 2011; Holroyd, Pakzad-Vaezi, & Krigolson, 2008).

The signal detection task produced the expected behavioral pattern: over the course of the task, participants developed a tendency to choose the more frequently rewarded response when they were unsure of the correct answer. However, a subset of the sample showed the opposite pattern—an overall negative response bias. In considering the scatter plots, it is evident that the five negative-RB participants had widely variable ΔFN scores; there does not appear to be any consistent relationship between ΔFN and RB in these participants. Although there is no single reason for a person to more often choose a less frequently rewarded response when the choice is unclear, some participants may have been testing out different scenarios, observing whether they might be able to change their luck by choosing a response that had not yet been rewarded.

The separate block-by-block analyses shed further light on this subset of participants. Although they began with negative RBs, the negative-RB participants developed a positive RB by the final block

of the signal detection task, indicating that they may simply have been slower to learn the reward contingencies. Some negative-RB participants may actually have been highly reward sensitive, but it would have required a longer task for this to become discernible. Thus, perhaps unsurprisingly, when negative-RB participants were included in analyses, the association between the ΔFN and the RB was not apparent.

In contrast, when negative-RB participants were excluded from analyses, the amplitude of the ΔFN was significantly correlated with RB on the signal detection task; that is, subjects with larger ΔFNs were more likely to choose a richly rewarded response when the correct choice was unclear. Thus, individuals with a larger ΔFN adapted their behavior more based on reward-related contingencies. The ΔFN was not associated with discriminability in the signal detection task, suggesting that the effects of the RB were not simply due to the extent to which participants were able to distinguish the stimuli. Moreover, both RR and RB continued to relate to the ΔFN at a trend level, even when the variability due to the other predictor was accounted for—suggesting that RR and RB explain somewhat unique variation in the ΔFN. Overall, these three measures reflect an overlapping, but nonredundant, construct of reward sensitivity.

It is important to note that self-reported (i.e., RR) and behavioral (i.e., RB) measures did not correlate with each other. Indeed, there are important differences between the self-report and behavioral measures. The RR questionnaire is composed of questions about participants' tendency to respond to reward in general—their trait level of reward responsiveness. Moreover, the RR scale relies on participants' evaluation of their own reward responsiveness, which makes it a relatively indirect measure. The response bias, on the other hand, is a measure of the tendency, when the correct choice is unclear, to choose an option that has resulted in a reward more often in the recent past. The RB can be seen as more of a reflection of implicit reward sensitivity in the moment—which might be sensitive to both trait and state levels of reward sensitivity. In line with this possibility, Bogdan and Pizzagalli (2006) found that the response bias is decreased when a stressor is introduced, suggesting that the response bias is modulated by state-related changes in stress reactivity. Thus, self-reported reward responsiveness and behavioral bias toward reward may represent different aspects of reward sensitivity that contribute separately to the ΔFN.

In accordance with this interpretation, previous studies have associated the FN with both state (Foti & Hajcak, 2009, 2010) and trait (Bress et al., 2012; Gu et al., 2010; Lange et al., 2012) variables. Thus, it is plausible that the FN indexes the contributions of state and trait factors, which might be reflected in behavioral and self-report measures, respectively. Additional research is needed in larger samples with multiple assessments to disambiguate state and trait effects (e.g., Cole, Nolen-Hoeksema, Girgus, & Paul, 2006).

The current study was limited by the fact that behavioral and EEG data were not available from the same task. Moreover, it would have been interesting to examine whether measures in the current study related to subjective responsiveness to the actual rewards received in these laboratory-based tasks; however, these data were not collected. Nevertheless, the current study provides evidence that the FN indexes individual differences in reward sensitivity, which might be affected by both state (i.e., response bias) and trait (i.e., self-report) variability.

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