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Cognitive Brain Research 25 (2005) 851 – 861
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Research Report

Individual differences in extraversion and dopamine genetics predict neural reward responses

Michael X. Cohen[a,b,*], Jennifer Young[b], Jong-Min Baek[c], Christopher Kessler[c], Charan Ranganath[b]

[a]Department of Epileptology, University of Bonn, 53115 Bonn, Germany
[b]Center for Neuroscience, University of California, Davis, CA 95616, USA
[c]Genomics Facility, University of California, Davis, CA 95616, USA

Accepted 20 September 2005
Available online 11 November 2005

Abstract

Psychologists have linked the personality trait extraversion both to differences in reward sensitivity and to dopamine functioning, but little is known about how these differences are reflected in the functioning of the brain's dopaminergic neural reward system. Here, we show that individual differences in extraversion and the presence of the A1 allele on the dopamine D2 receptor gene predict activation magnitudes in the brain's reward system during a gambling task. In two functional MRI experiments, participants probabilistically received rewards either immediately following a behavioral response (Study 1) or after a 7.5 s anticipation period (Study 2). Although group activation maps revealed anticipation- and reward-related activations in the reward system, individual differences in extraversion and the presence of the D2 Taq1A allele predicted a significant amount of inter-subject variability in the magnitudes of reward-related, but not anticipation-related, activations. These results demonstrate a link between stable differences in personality, genetics, and brain functioning.

Theme: Neural basis of behavior
Topic: Motivation and emotion

Keywords: Extraversion; Personality; fMRI; Dopamine; Genetics; Reward

1. Introduction

Although much is known about the neural substrates of reward processing, a complete understanding of the neural mechanisms of reward must take into account how psychological and biological individual differences affect these processes [46]. Several lines of evidence show that rewards and reward motivation are processed by the nucleus accumbens, amygdala, and orbitofrontal cortex, an interconnected network of dopaminergic brain regions termed the neural reward system [6,9,20,58,59,68]. Although individual differences in reward processing have been linked to clinical disorders such as depression and addictions [14,30,45], little is known about how individual differences in psychological and biological variables affect the functioning of this system.

Extraversion, one of the most extensively researched constructs in personality psychology, has been linked to both normal and abnormal reward processes. Extraversion is characterized by individual differences in positive emotion, social engagement, and life satisfaction [5,36]. Several researchers have hypothesized that these characteristics arise from underlying differences in sensitivity to cues of rewards and motivation to obtain future rewards [21,22,25,31,49]. Some researchers have additionally proposed that individual differences in the sensitivity of the brain's reward system lead to differences in reward sensitivity, and this in turn may be a neural mechanism of individual differences in

* Corresponding author. Center for Neuroscience, University of California, Davis, CA 95616, USA.
E-mail address: mcohen@ucdavis.edu (M.X. Cohen).

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doi:10.1016/j.cogbrainres.2005.09.018

extraversion [22,50]. In particular, the dopamine D2 receptor (DRD2) has been heavily implicated in reward processes [7,8,56,57], is found in highest concentrations in the reward system [57], and thus the functioning of this system may be related to extraversion [22,23]. Having the A1 minor allele on the Taq1A DRD2 gene site is associated with fewer DRD2 receptors [38,56,65,71], and clinical research has linked this polymorphism with addictive disorders, reward insensitivity, alcoholism, and personality [8,35,56]. Although this polymorphism has been associated with reduced levels of D2 receptors in several studies using diverse methodologies including post-mortem analyses and PET, the precise mechanism by which the A1 allele leads to lower levels of this receptor remains debated [4,40]. Given that it is located at the 3′ untranslated region, this polymorphism may have regulatory functions during gene expression.

Here, we used functional magnetic resonance imaging (fMRI) to examine whether individual differences in extraversion predict the reactivity of the brain's dopaminergic neural reward system and whether these differences are related to the A1 allele on the DRD2 gene. In 2 experiments, participants were probabilistically rewarded after choosing uncertain gambles. In the first experiment, we examined the relationship between individual differences in self-reported extraversion and variability in neural responses to rewards. In the second experiment, we replicated these findings in a new sample of participants and extended them by (1) experimentally separating two processes engaged by the reward system–reward anticipation, a state of waiting to learn whether a reward would be received, and reward evaluation, the indication that a reward is received–and (2) testing whether neural responses to reward were additionally related to the presence of the DRD2 allele.

2. Methods

2.1. Experimental design and protocol

2.1.1. Study 1

Seventeen participants completed 520 trials of our decision-making task while in the MRI scanner. The task involved making rapid behavioral responses in order to win money. On each trial (see Fig. 1a), participants first saw a visual cue for 400 ms and were required to choose one of two economically equivalent (i.e., equal in expected value) gambles: a low-risk gamble, in which they were very likely to win a small reward (80% chance of $1.25 and 20% chance of $0.00), or a high-risk gamble, in which they were less likely to win a large reward (40% chance of $2.50 and 60% chance of $0.00). Three hundred milliseconds after the offset of the cue, the amount of money participants won in that trial appeared on the screen (for example, "+$2.50"). A variable inter-trial interval (range: 2–8 s) separated trials. Participants indicated each decision by either responding or withholding a response, depending on the shape of the cue. For example, a white circle meant that participants would press the button to indicate a low risk gamble or withhold a response to indicate a high risk gamble, whereas a white square would indicate the opposite. The purpose of having participants press a button during half of the trials and withhold responses during the other half of trials was to counterbalance any effects of response selection and inhibition. The reported effects did not vary as a function of whether a response was made or withheld, so we collapsed across this factor. Additional control trials were included in which participants were 100% likely to receive a reward ($2.50) if they responded appropriately to the cue. Appropriate responses were made on 92% (SEM = 3%) of trials in Study 1 and 89% (SEM = 2%) of trials in Study 2.

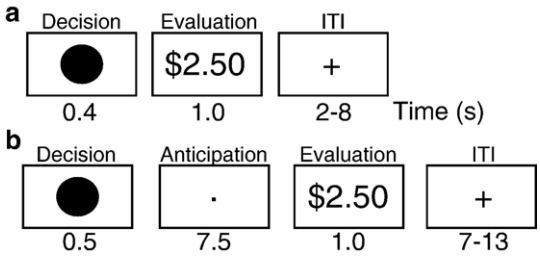

Fig. 1. Depiction of trial events. (a) Study 1. On each trial, participants decided whether to choose a high- or low-risk gamble. Soon after the offset of the cue, participants learned whether they won money on that trial. Following each trial was a variable 2–8 s inter-trial interval (ITI). (b) Study 2. The design was similar to that of Study 1 except for the inclusion of a 7.5 s anticipation period, which allowed separation of hemodynamic responses to reward anticipation from reward evaluation.

Participants were trained extensively on a behavioral version of this task prior to the experiment and were fully informed of the probabilities and outcomes associated with each cue type and response. This training minimized any learning effects over the course of the experiment. Additionally, because the two decision options (high vs. low risk) yielded the same amount of reward in the long run (the expected value of each option was $1.00), there were no optimal decision strategies participants could learn. We tested for sex differences in all of the reported analyses, and none was significant (all F's < 1).

2.1.2. Study 2

Study 2 was identical to Study 1 with the following exceptions. First, the cue remained on screen for 500 instead of 400 ms. Second, an anticipatory delay of 7.5 s was added after participants made their decision and before they learned whether they won money on that trial. Third, a longer inter-trial interval (7–13 s) was added to allow the BOLD response from the evaluation period to return to baseline before the start of the next trial. Fourth, there were no withhold-response conditions, and participants instead indicated their decision using one of two buttons on a response box.

2.2. Personality questionnaire

To measure individual differences in extraversion, participants completed a paper-and-pencil version of the Big 5 Personality Inventory [36], a validated and commonly used self-report measure of 5 personality traits, including extraversion, after the scanning session. This measure of extraversion has been shown to be both reliable and stable over time [36]. In our own samples, the reliability estimates were 0.89 in Study 1 and 0.86 in Study 2.

2.3. Genetic collection and analyses

Genetic assays were performed at the Genomics Facility at the University of California, Davis. DNA samples were obtained from participants in Study 2 using the MasterAmp Buccal Swab kit (Epicentre Inc.). DNA was extracted according to the protocol provided by the company. Polymerase chain reaction (PCR) was used to amplify the DNA sequences of interest. PCR primers used to test for the presence of the A1 allele at the DRD2 *Taq*1A site were designed based on previous studies [40]. The primer sequences are 5′-CCGTCGACGGCTGGCCAAGTTG-TCTA-3′ and 5′-CCGTCGACCCTTCCTGAGTGTCA-TCA-3′. These primers amplify a 294 base-pair region of the DRD2 gene that contains a *Taq*1 recognition site, and the allele was detected by digesting the PCR products with *Taq*1 restriction enzyme followed by separation on agarose gel electrophoresis.

2.4. fMRI acquisition

MRI data were collected on a 1.5 T GE Signa scanner at the UC Davis Research Imaging Center. Functional imaging was done with a gradient echo EPI sequence (TR = 2000, TE = 40, FOV = 220, 64 × 64 Matrix, voxel size = 3.475 × 3.475 × 5 mm), with each volume consisting of 22 (24 in Study 2) oblique axial slices (tilt angle: ∼−15° from ac–pc line). In pilot studies, we determined that this set of parameters maximized signal-to-noise ratios and blood oxygenation level dependent (BOLD) contrast in the orbitofrontal cortex and amygdala. Co-planar and high-resolution T1-weighted images were also acquired from each participant. EPI data were realigned to the first volume, corrected for slice-timing differences, co-registered with the anatomical scan, spatially normalized to MNI template brain, resampled to 3.5 mm isotropic voxels, and spatially smoothed with an 8 mm FWHM kernel using SPM99 software (Wellcome Department of Imaging Neuroscience, London, UK).

2.5. Data analyses

Event-related BOLD responses were modeled using multiple regression in voxbo software (http://www.voxbo.org). For Study 1, separate covariates modeled each combination of the participant's decision and the outcome on that trial, relative to a resting fixation baseline (inter-trial interval). The variable (2–8 s) duration of the ITI in this experiment allowed us to deconvolve overlapping BOLD responses associated with each trial type [52]. For Study 2, separate covariates were used to model the decision, anticipation, and evaluation phases of each type of event, relative to the variable (7–13 s) inter-trial interval.

All regression models incorporated empirically derived estimates of intrinsic temporal autocorrelation [1] and filters to attenuate frequencies above .24 Hz and below .01 Hz. Hemodynamic response functions (HRFs) were empirically derived for each participant using BOLD responses in the central sulcus during a visuomotor response task [2,34]. These HRFs were used to model BOLD responses to each event type in all analyses. In addition, the mean of each scanning run, the global signal (orthogonalized with respect to the design matrix [24]), and an intercept were included as nuisance covariates.

Following single-subject analyses, images of parameter estimates for each contrast of interest were entered into a one-sample *t* test, in which the mean estimate across participants for each voxel was tested against zero. Significant regions of activation were identified using an uncorrected two-tailed threshold of $P < 0.001$ and a cluster threshold of 6 contiguous voxels. In the figures, activations are overlaid on a single subject's T1-weighted image using MRIcro software (http://www.mricro.com).

Regions of interest (ROIs) were defined as contiguous, significantly active voxels that showed greater activity during trials in which participants were rewarded versus those in which they were not (Study 1), receiving versus not receiving a reward during the evaluation phase (Study 2), and reward anticipation greater than activity during the inter-trial interval (Study 2). Correlations between brain activity and extraversion and differences between genotype within these ROIs were performed using a two-tailed alpha value of .05. In the scatter plots in Figs. 3 and 5, beta values (i.e., parameter estimates) were normalized by dividing all betas by the maximum beta value, which linearly scales the betas to have a maximum value of 1.

3. Results

3.1. Study 1

Participants chose the low-risk option more often than the high-risk option (61% ± 3 versus 39% ± 3, respectively, mean ± SEM, $F(16) = 10.7$, $P < 0.01$). Extraversion was not significantly related to the number of high risk gambles chosen ($r = 0.24$, ns), the probability of using a win-stay/lose-switch strategy ($r = -0.26$, ns), or the probability of choosing a high-risk gamble following a high-risk win ($r = 0.20$, ns). Thus, individuals who differed in their extraver-

sion scores did not reliably use different strategies during the experiment.

We hypothesized that extraversion would predict the responsiveness to rewards within reward-sensitive regions. To test this hypothesis, we first identified regions in the brain that were more active on trials when participants were rewarded than on trials when they were not. This contrast yielded significant bilateral activations in medial orbitofrontal cortex, amygdala, and nucleus accumbens (see Fig. 2). Each of these regions has been consistently implicated in reward processing in neurophysiological studies of rodents and monkeys [29,68,72,78] and neuroimaging studies of humans [3,9,28,58]. We defined each of these activations as regions of interest (ROIs) for further investigation. Outside of these ROIs, activations were observed in areas of the cerebellum and fusiform gyrus, which may reflect the increased engagement of attentional processes on trials associated with rewards [67]. Coordinates of these and all other activations reported in this paper are presented in Table 1.

We next investigated whether individual differences in extraversion predicted the magnitude of the reward response, defined as the difference in activation between receiving and not receiving a reward, in each of these ROIs. We found that participants higher in extraversion exhibited a significantly greater reward response in 3 out of 6 of these ROIs (left medial orbitofrontal cortex: $r = 0.53$, $P = 0.028$; right medial orbitofrontal cortex: $r = 0.59$, $P = 0.012$; right nucleus accumbens: $r = 0.61$, $P = 0.01$; see Fig. 3). Fig. 3 also displays the reward > no reward contrast for two individual subjects with relatively high and low extraversion scores, both thresholded at $P > 0.001$, two-tailed.

Because participants received different magnitudes of rewards on different trials ($1.25 versus $2.50), we further examined whether the difference between receiving a high reward and a low reward changed as a function of extraversion and found no significant correlations in any of our ROIs (all r's < 0.26). We finally tested whether extraversion scores predicted reward-related brain activity in regions outside of the reward system and found no significant correlations in these regions (all r's > 0.28, all P's > 0.26).

3.2. Study 2

In Study 1, we demonstrated a link between extraversion and reactivity of the reward system to receiving rewards. However, there are at least two neural processes linked with rewards: anticipation and evaluation. By anticipation, we refer to the time period after participants made a behavioral response but before they learned whether they would be rewarded on that trial; and by evaluation, we refer to the time when participants learned whether they received a reward on that trial (see Fig. 1b). Structures within the neural reward system, such as orbitofrontal cortex and striatum, have been identified in both processes [7,44], but it is not known whether extraversion scores would relate to neural activity during both of these processes. Although there was a brief anticipatory period in Study 1, the rapid event-related design did not allow us to differentiate between neural activity related to anticipation from that related to evaluation. Thus, Study 2 was designed to separate these processes and examine whether and how extraversion was related to neural responses during both of these processes. This was accomplished by adding a 7.5 s delay after the participants' decision and before they learned the outcome on each trial (see Fig. 1b). This design allowed us to distinguish activity related to anticipating versus experiencing the outcome on each trial [18,26,42,62,63]. We additionally collected DNA samples from participants in Study 2 to be analyzed for the presence of the Taq1A polymorphism on the DRD2 gene.

Sixteen different participants (9 male, aged 20–27) were included in this study. As with Study 1, participants were not selected on the basis of personality or genetics. The high/low risk decision and probabilities of rewards were the same as in Study 1.

3.2.1. Extraversion

As in Study 1, extraversion was not significantly related to the number of high-risk gambles chosen ($r = -0.21$, ns), the probability of using a win-stay/lose-switch strategy ($r = 0.08$), or the probability of choosing a high-risk gamble following a high-risk win ($r = -0.34$, ns). Thus, as

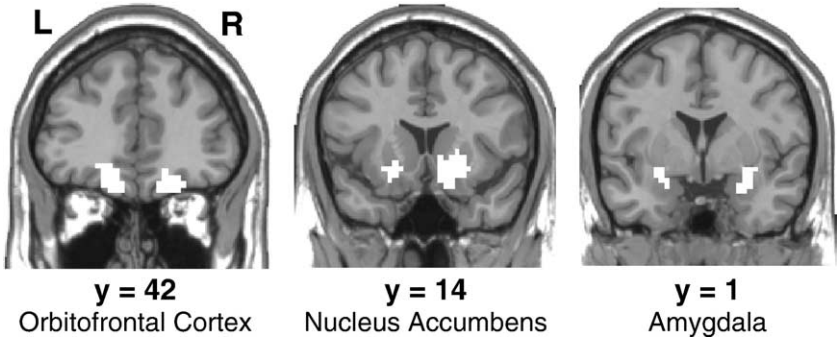

Fig. 2. Activation of the neural reward network in Study 1. Bilateral regions in the medial orbitofrontal cortex, amygdala, and nucleus accumbens exhibited more activity during trials in which participants were rewarded than during trials in which they were not.

Table 1

Region	BA	t	x	y	z
Study 1: reward–no reward					
R. orbitofrontal cortex	11	5.45	21	39	−21
L. orbitofrontal cortex	11	5.07	−10	42	−24
R. amygdala		4.77	27	−1	−21
L. amygdala		5.38	−23	0	−16
R. nucleus accumbens		8.12	14	14	−10
L. nucleus accumbens		6.94	−21	14	−10
R. hippocampus		5.12	28	−35	−3
R. hippocampus		4.85	39	−21	−14
L. fusiform gyrus	20	6.27	−38	−24	−17
R. calcarine sulcus	17	5.41	7	−87	0
L. cerebellum		5.25	−28	−45	−28
R. cerebellum		5.21	14	−45	−14
R. supplementary motor	6	4.75	25	−10	67
Study 2: anticipation					
R. parietal	40	10.23	56	−38	49
L. dorsolateral PFC	45	7.69	−52	35	14
L. posterior temporal	22	6.09	−59	−52	21
R. insula	48	5.95	49	14	−7
L. temporal/insula	21/48	5.88	−45	−7	−10
R. parietal	40	5.84	60	−45	28
R. thalamus		5.12	7	−10	11
R. ventrolateral PFC	6	5.02	53	7	11
R. cerebellum		4.81	49	−49	−35
L. temporal pole	38/21	4.70	−56	7	−14
L. thalamus		4.69	−10	−10	14
R. orbitofrontal cortex	11	4.54	25	49	−7
L. caudate		4.45	−17	−21	21
L. superior temporal gyrus	21	4.29	−63	0	−7
Study 2: reward–no reward					
R. amygdala		6.58	18	−7	−28
L. amygdala		6.47	−17	−3	−14
L. hippocampus		5.40	−28	−24	−14
L. orbitofrontal cortex	11	5.31	−21	21	−25
R. precuneus	23	5.21	4	−56	35
R. orbitofrontal cortex	11	5.11	25	25	−21
R. posterior insula		4.79	39	−21	14
R. nucleus accumbens		4.60	11	0	−14
R. nucleus accumbens		4.52	14	11	−14
R. postcentral gyrus	4	4.44	53	−17	46
L. hippocampus		4.23	−31	−14	−21
L. nucleus accumbens		4.30	−7	4	8

Brodmann (BA), MNI coordinates (x, y, z), and t values of regions active in each contrast. L = left; R = right.

in Study 1, individuals who differed in their extraversion scores did not reliably use different strategies during the experiment.

As in Study 1, we first identified regions responding to reward-related processes and then examined whether individual differences in neural responses to rewards were correlated with extraversion scores. In this experiment, however, we were able to separately identify regions responding to reward anticipation and reward evaluation.

We first identified regions of the brain that were significantly active during the anticipation phase of the trials. We observed significant activations in dorsal caudate nucleus, right ventral prefrontal cortex (BA 11/10), insula/ventral prefrontal cortex (BA 48) (see Fig. 4), bilateral prefrontal cortex (left BA 45 and right BA 6/44), and parietal cortex (BA 40). Extraversion scores did not correlate with activity in any of these regions, regardless of the decision chosen (all r's < 0.21, ns).

We next identified regions in the brain that were more active when participants received a reward than when they did not (during the evaluation phase). Consistent with findings from Study 1, we observed significantly greater activity in bilateral medial orbitofrontal cortex, right amygdala, bilateral nucleus accumbens, and left hippocampus (see Fig. 4) when participants were rewarded compared with when they were not rewarded. Participants higher in extraversion exhibited a significantly greater reward response (the difference in activation between receiving and not receiving a reward) in 5 out of these 6 ROIs (left medial orbitofrontal cortex: $r = 0.60$, $P = 0.013$; right medial orbitofrontal cortex: $r = 0.58$, $P = 0.018$; right amygdala: $r = 0.52$, $P = 0.038$; right nucleus accumbens: $r = 0.56$, $P = 0.025$; left nucleus accumbens: $r = 0.61$, $P = 0.011$; see Fig. 5a). Thus, about 33% of inter-subject variability of reward responses in these ROIs was explained by individual differences in extraversion. Finally, as in Study 1, we tested whether the difference in activation between high and low rewards was correlated with extraversion. We found that this correlation was significant in left medial orbitofrontal cortex ($r = 0.53$, $P = 0.03$) and marginal in the right nucleus accumbens ($r = 0.47$, $P = 0.06$), indicating that, in some regions, not only did individuals higher in extraversion exhibit increased activity when receiving a reward, they also exhibited a larger difference in activation between relatively larger compared to smaller rewards.

3.2.2. DRD2

Nine out of 16 participants had one or two copies of the A1 allele. The presence of this allele was not statistically related to extraversion scores ($t = 1.48$, ns) and was not related to race (66% Caucasian [34% Asian/other] with A1 allele, 57% Caucasian without A1 allele; $t = 0.13$, ns). Participants with the A1 allele did not take significantly more high-risk gambles than participants without the polymorphism ($t = 0.9$, ns), utilize a win-stay/lose-shift strategy to a different extent ($t = 0.1$, ns), or choose a high-risk gamble following a high-risk win more often ($t = 0.3$, ns). Thus, the presence of this allele did not affect the kinds of behavioral strategies that participants used during the task.

To test whether the presence of the DRD2 A1 allele affected neural responses to rewards, we compared activity in each functionally defined ROI identified above between participants who had versus did not have this allele. We first examined responses during anticipation and found that the two groups did not differ in activation magnitudes during anticipation in any of the regions that showed increased activity during anticipation, regardless of whether participants anticipated a high-risk or low-risk reward (all F's < 4, ns).

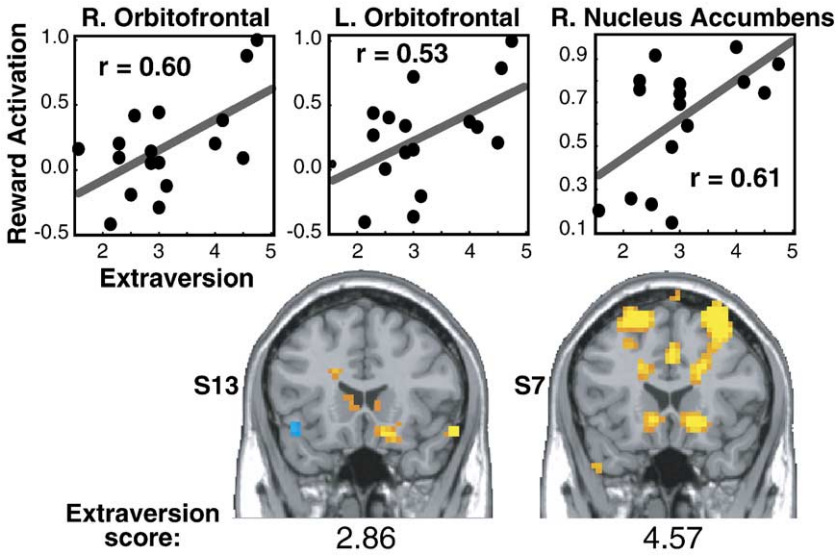

Fig. 3. Extraversion scores significantly predicted individual differences in the magnitude of BOLD responses to rewards in several of the regions identified in the reward contrast in Study 1 (see Fig. 2). Extraversion scores (higher scores indicate greater extraversion) are plotted on the x axis, and the maximum value normalized activation magnitudes from the reward > no reward contrast are plotted on the y axis. Activation maps of the reward > no reward contrast are displayed for two individual subjects at $y = 20$, along with their extraversion scores.

Next, we examined whether the groups differed in activation magnitudes when receiving rewards. A 2 (group) × 6 (region) ANOVA revealed that that the reward response was significantly less in participants who had the allele ($F_{1,14} = 6.41$, $P = 0.024$). As shown in Fig. 5b, this difference was significant in bilateral medial orbitofrontal cortex (left: $F_{1,14} = 5.99$, $P = 0.028$; right: $F_{1,14} = 5.49$, $P = 0.034$), right amygdala ($F_{1,14} = 7.11$, $P = 0.018$), left hippocampus ($F_{1,14} = 6.60$, $P = 0.022$), and marginal in right nucleus accumbens ($F_{1,14} = 4.12$, $P = 0.062$). Finally, we tested whether the difference in activation between high-risk and low-risk wins differed according to whether participants had or did not have the A1 allele and found that they did not (all F's < 2, ns). Thus, the presence of the A1 allele on the DRD2 gene has a significant effect on our participants' neural responses to reward processing.

4. Discussion

In this study, we found that individual differences in extraversion and the presence of the DRD2 A1 allele

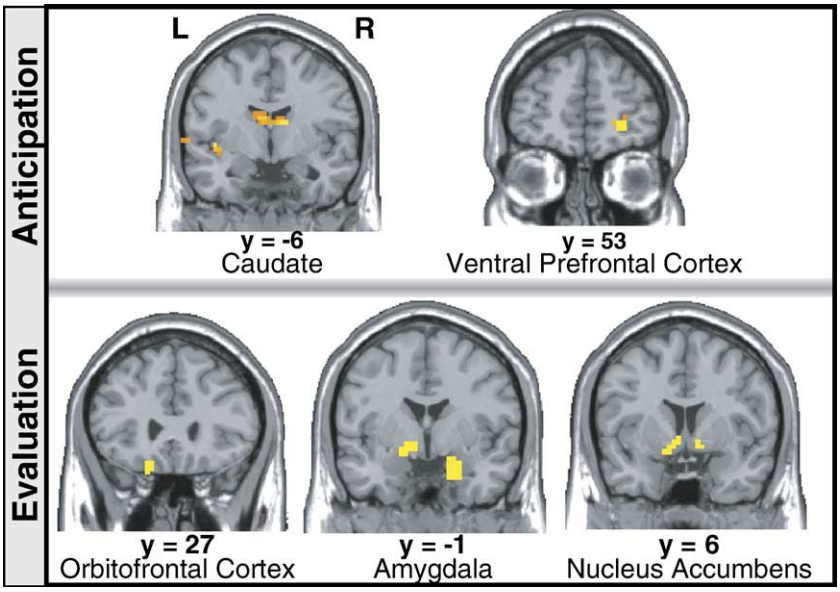

Fig. 4. Activation related to reward anticipation and reward evaluation in Study 2. (a) Regions in the striatum, insula, and prefrontal cortex were active during the anticipation period prior to receiving a reward. (b) Regions in the orbitofrontal cortex, amygdala, and nucleus accumbens showed greater activity when receiving rewards than when not receiving rewards (evaluation period).

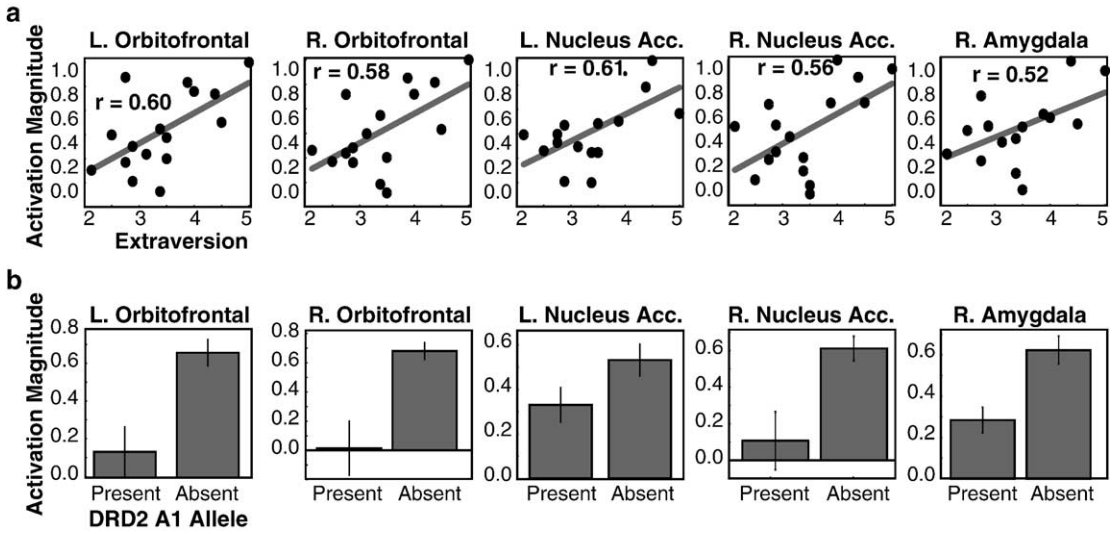

Fig. 5. Extraversion and DRD2 variability predict neural reward responses during the evaluation phase of Study 2. (a) Scatter plots depict the relationship between extraversion scores and reward responses in regions showing greater activity in the reward > no reward contrast during the evaluation phase (Fig. 4). Conventions are as in Fig. 3. (b) Bar graphs show reward responses in subjects with (left) and without (right) the DRD2 gene polymorphism. Error bars represent one standard error of the mean across subjects.

predicted the responsiveness to rewards in orbitofrontal cortex, amygdala, and nucleus accumbens. Importantly, decision-making strategies did not vary as a function of extraversion or the presence of the DRD2 allele, suggesting that our observed correlations were not driven by differences in task performance. We note that, although we did not collect on-line behavioral indices of subjective enjoyment of the reward, results from previous neuroimaging studies have shown that reward-related activations are correlated with subjective ratings of enjoyment of the reward [3,43]. Accordingly, the association between neural reward responsiveness and extraversion and the DRD2 A1 allele in the present study was likely related to individual differences in subjective reward enjoyment.

4.1. Extraversion

Our finding that individual differences in extraversion predicted variability in the reactivity of the reward system when receiving monetary rewards supports a growing literature that highlights the importance of reward sensitivity to extraversion. Diener and colleagues have argued that the core feature of extraversion is reward sensitivity and that other facets of extraversion, such as social engagement and subjective well-being, are by-products of this sensitivity [25]. Depue and Collins [22] provided a neurobiological framework for this hypothesis by suggesting that this reward sensitivity is mediated by differences in the efficacy of dopaminergic inputs from the brainstem to regions including the nucleus accumbens, orbitofrontal cortex, and amygdala. Our results offer direct support for this theory by demonstrating that individuals who scored relatively high on measures of extraversion exhibited increased activation in reward-sensitive regions when receiving rewards.

Prior to the present report, a few neuroimaging studies investigated how differences in extraversion relate to brain activation. For example, Canli and colleagues [12,13] correlated brain responses during passive picture-viewing tasks with extraversion scores. Consistent with our results, these researchers found that extraversion was associated with increased activity in the amygdala, among other regions, when viewing positively valenced pictures. In another study by Johnson and colleagues [37], positron emission tomography was used to correlate extraversion scores with measures of glucose metabolism when participants were resting and not performing any tasks. Their results showed that extraverts had higher resting levels of metabolism in the amygdala, among other regions, than did introverts. Our findings, and the findings of the previously described fMRI studies [12,13], seem inconsistent with this result because extraversion was only related to activity in the brain during events that were likely interpreted by the participants as being rewarding or pleasurable. However, it is important to note that fMRI does not measure absolute levels of brain activity, only relative levels. Thus, it is possible that extraverts might have relatively more tonic activity than introverts as well as enhanced phasic responses to rewarding events. This remains an open question that could be addressed in future studies.

We additionally observed that the relationship between extraversion and brain activity was specific to reward evaluation and was not observed during anticipation. It is important to note that reward anticipation has been operationalized differently in different studies. Here, as in some other studies [18], anticipation was operationalized as a state of waiting to learn whether a reward will be received, whereas other researchers have operationalized

reward anticipation as a state that produces motivation to engage in reward-seeking behaviors. For example, anticipating a drug-induced reward motivates addicted individuals to engage in drug-seeking behaviors [7]. It is thus possible that extraversion is related to brain activity during reward anticipation if that anticipatory state could induce behaviors that increase the probability of receiving a reward [22]. This or other methodological differences (e.g., smoothing kernels, scan parameters, etc.) might also explain differences in the localization of anticipation-related activity across studies. For example, we observed anticipation-related activations in the dorsal striatum, whereas others have reported anticipation-related activity in other regions such as the ventral striatum [43,44] or the amygdala [10,39].

The present report focused on extraversion, but a wide range of personality measures have been used to investigate reward sensitivity and reward motivation. For example, traits such as reward dependency, the behavioral activation system (BAS), and positive emotionality are correlated with extraversion and have been linked behaviorally to reward-related processes [15,22,36]. Although the terminology and precise definitions of these traits differ, they likely measure somewhat overlapping constructs [22,36,77]. Although it is unknown whether the correlations observed here would generalize to other similar personality measures, the present results, along with those from other groups [12,32,33,61], suggest that individual differences in personality are related to meaningful individual differences in neural responses during emotional and cognitive processes. Accordingly, functional neuroimaging might be a promising source of evidence for contrasting competing models of fundamental personality dimensions.

4.2. DRD2

Over half (9 of 16) of our sample had at least one copy of the A1 allele on the DRD2 gene, a proportion that is slightly higher than reported in previous studies [56]. Participants were self-selected from a university population and were not prescreened for their genetic make-up or any behavioral factors that might be related to genetics. fMRI data showed that participants with this allele exhibited relatively less differentiation in activation between receiving and not receiving rewards in orbitofrontal cortex, amygdala, and, to a lesser extent, nucleus accumbens. This allele did not affect activation magnitudes during anticipation.

Although clinical research has linked the DRD2 A1 allele with alcoholism and other addictive disorders [19,35,54], ours is the first study to investigate how the presence of this allele affects brain activity in a nonclinical population when receiving rewards. Our findings support the idea that a reduced concentration of DRD2 in the reward system leads to reduced sensitivity to rewards [73–75] and that this may help form the basis of why individuals with this allele are more likely to develop addictive [45,55,75] or reward deficiency disorders [8,56]. Variation on this allele may also relate to differences in subjective enjoyment from rewards, which has been shown to correlate with activity in regions including the ventral striatum [3,43]. Future studies could help elucidate this by having subjects explicitly report subjective pleasure obtained from different sized rewards.

Given that DRD2 is found in highest concentrations in the ventral striatum, it is surprising that the effects of the allele on reward-related activity in nucleus accumbens were not robust. However, previous reports of DRD2 concentration and addiction have reported robust findings in orbitofrontal cortex [76], and it is possible that orbitofrontal functioning in this task is more sensitive to this allele's phenotypic expression than is functioning of the nucleus accumbens. It is also important to note that the presence or absence of the DRD2 Taq1A allele is only one of many variables that factor into the functioning of the dopamine system, and thus the nonsignificant differences in nucleus accumbens between groups do not imply that dopaminergic neurons in this region are not involved in the task.

The fact that differences were not observed during anticipation may also be related to the fact that, in our study, anticipation could not lead to increased probability of rewards, as discussed above. Indeed, the DRD2 system is heavily involved in reward anticipation and reward prediction [29,70,73], but it is possible that the presence of the DRD2 Taq1A allele only affects experiential or consumatory reward processes, and not all reward processes. This pattern of results also argues against an alternative explanation that the differences in reward activation are simply due to the polymorphism affecting the BOLD response.

In our sample, the presence of the DRD2 A1 allele was not significantly related to extraversion scores, although there was a weak trend for individuals with the A1 allele to have lower extraversion scores. One might actually predict the opposite association because both having the A1 allele and scoring high on measures of extraversion have been associated with reward-seeking behaviors, although two variables being related to a third does not necessitate that they be related to each other. Although a link between the A1 allele and extraversion has been reported previously [48,60], other studies have failed to find such an association [41], even with large sample sizes. Noble has suggested that the relationship between these two variables is moderated by environmental factors, such that emotional stress during childhood can change the direction of the relationship between the presence of the allele and extraversion scores [60]. Thus, a link between this allele and extraversion might be subtle and moderated by environmental or other genetic factors. It is important to note that, as previously mentioned, the DRD2 Taq1A gene site is only one variable that affects the functioning of the

dopamine system. Thus, it is possible that there is a strong link between extraversion and dopaminergic neurotransmission but that it is weak or not apparent when examining this particular allele.

4.3. Caveats and conclusions

There are a few caveats about our findings that we emphasize. First, we only investigated our pre-determined ROIs for effects related to DRD2 genotype or extraversion. It is therefore possible that activity in other regions of the brain may also be modulated by DRD2 genetic variability or personality. However, focused ROI analyses are commonly used [53,64], and we chose to limit our ROI analyses to regions identified as exhibiting enhanced responses to monetary rewards. Second, studies linking genetic mutations to behavior or brain activity must always be cautious of spurious effects being driven by population differences that might be related to genetic polymorphisms (e.g., ethnic groups). We observed no differences in race (classified as Caucasian vs. Asian/other) between our subjects with and without the A1 allele, and other studies have demonstrated that ethnic differences are not a likely confounding factor with DRD2 [27,57]. Nonetheless, it is possible that there were other differences between our groups that we did not measure or that our effects were due to other functional mutations, perhaps in the promoter region of the gene, that covary with the presence of the D2 A1 allele [40].

Our findings demonstrate clear links between stable individual differences in personality, genetics, and functioning of the brain's reward system. This anatomically and functionally interconnected network [16] is critical for both biological and social survival, and our findings suggest that variation in the functioning of this system is linked with socially and emotionally relevant conditions. For example, both low extraversion scores and the DRD2 A1 allele have been linked to psychiatric disorders including depression [47,51], drug dependency [11,66,76], and compulsive gambling [17,69]. Thus, an important question for future research is whether the relationships between individual differences in personality, genetics, and brain activation observed here might relate to clinical disorders and whether neuroimaging could be used to guide new approaches for diagnosis and treatment of such conditions.

Acknowledgments

This work was supported by an Extramural Research Grant from the Institute for Research on Pathological Gambling and Related Disorders and a faculty research grant from the University of California at Davis. The authors thank Tonya Jacobs and Eveline Crone for their help.

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