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Effort and Appetitive Responding in Depression: Examining Deficits in Motivational and Consummatory Stages of Reward Processing Using the Effort-Doors Task

Colin B. Bowyer, C.J. Brush, Christopher J. Patrick, and Greg Hajcak

ABSTRACT

BACKGROUND: Reward sensitivity is a dimensional construct central to understanding the nature of depression. Psychophysiological research on this construct has primarily focused on the reward positivity, an event-related potential (ERP) that indexes consummatory reward sensitivity. This study extended prior research by focusing on ERPs that index the motivational component of reward.

METHODS: A novel effort-for-reward task was used to elicit motivational and consummatory ERPs. Groups consisting of 34 participants with depression and 32 participants without depression were compared across a range of reward-related ERPs.

RESULTS: Participants with depression exhibited reduced responsivity to effort completion cues following high effort expenditure, reduced anticipation of rewards after low effort expenditure (i.e., the stimulus preceding negativity), and reduced reward positivity following high effort expenditure. ERPs occurring prior to reward receipt accounted for unique variance in depression status and differentiated between subgroups of depressed individuals.

CONCLUSIONS: Findings support the utility of leveraging multiple ERPs that index separate reward processing deficits to better characterize depression and depressive subtypes.

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Reduced reward sensitivity is a core feature of major depressive disorder (MDD) (1), which has been extensively studied within neurophysiology using event-related potentials (ERPs) such as the reward positivity (RewP)—an ERP that occurs in response to gain versus loss outcomes in choice-feedback tasks (2). The RewP is an indicator of consummatory reward sensitivity—that is, an individual's sensitivity to rewarding events and the impact of that sensitivity on their subjective valuation of those events (2–7). Research in depression has shown a reduced RewP in currently depressed individuals (8–11) and in individuals without depression who later experience depressive episodes (12–14). Additionally, among individuals with depression, a reduced RewP is associated with more severe and chronic depressive symptoms (15), greater odds of experiencing a more chronic depression course [i.e., nonremission (16)], and treatment-related depressive symptom reduction (17,18). Collectively, these data support the utility of the RewP as a biomarker of MDD.

Although the RewP indexes consummatory reward processing deficits, other aspects of reward processing—such as the motivation to pursue rewards (19,20)—are likely important for understanding depression. Extensive animal and human research has delineated distinct reward processing subcomponents, including liking (i.e., hedonic value assigned to rewarding stimuli) and wanting [i.e., incentive salience associated with reward predictive cues (19–20)]. Wanting is thought to govern effortful behavior and motivation, both of which appear to increase with task difficulty until the assigned task is no longer worth the effort (21). Importantly, the threshold at which this change occurs is much lower for individuals with depression (22). A paradigm developed to investigate these relationships is the effort expenditure for rewards task (23). Research examining group differences between subjects with depression and healthy control subjects in effort expenditure for rewards task performance revealed that compared with control subjects without depression, individuals with depression were less willing to expend effort to obtain rewards and exhibited a reduced capacity to calculate the opportunity cost of effort expenditure for rewards (24). These findings, which have been replicated in subsequent studies (25–27), converge with extensive research documenting reduced effortful behavior in depression (28,29) and add to evidence of depression-related deficits in the motivational component of reward.

In 2021, Bowyer and colleagues introduced the effort-doors task, a procedure for examining motivational and consummatory components of reward processing using distinct ERPs (30). In this task, an effort manipulation akin to that of the effort expenditure for rewards task paradigm was added to the doors

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choice-feedback task, a procedure commonly used to elicit the RewP. The doors task indexes consummatory reward valuation by having participants choose between 2 adjacent doors to either win $0.50 or lose $0.25 on each trial (2). In the effort-doors task, participants are required to expend either high effort (50% of trials) or low effort (50% of trials) on each trial before choosing between the 2 doors. One ERP evident in this task is the cue-P3, a positive-polarity ERP that indexes allocation of attention toward cues containing salient contextual information [e.g., the probability of reward on an upcoming trial (31)]. Bowyer *et al.* quantified this P3 between 300 to 500 ms following high and low effort completion cues at electrode Cz and found that this response—hereafter termed the effort-P3—was augmented for high-effort completion cues (i.e., signaling fulfillment of required effort expenditure on high effort trials) compared with low effort completion cues. These investigators also examined the impact of effort on the stimulus-preceding negativity (SPN), an ERP that indexes anticipatory attention toward upcoming stimuli (32,33). They quantified the SPN at electrode Oz within a 200-ms window preceding the onset of gain/loss feedback and examined its amplitude as a function of effort expenditure, along with examining the impact of effort on the RewP to gain/loss feedback cues, quantified at electrode Cz between 250 and 350 ms following feedback-cue onset. The SPN was found to be less negative, and the RewP less positive, following high as compared with low effort expenditure. Additionally, Bowyer *et al.* examined the feedback-P3, an ERP component quantified at electrode Pz following the RewP (i.e., between 350 and 500 ms following feedback onset) that indexes the absolute value of feedback (34) and found it to be smaller within the high effort condition.

Taken together, these results accord with prior work showing that effort expenditure lowers the perceived value of subsequent rewards while increasing the value of rewards obtained within the same context for less effort (35,36). Furthermore, these results extend prior findings by demonstrating an impact of effort expenditure across distinct temporal substages of reward processing. Compared with low effort, high effort expenditure increased the effort-P3 and attenuated the SPN, RewP, and feedback-P3. In other words, following high compared with low effort expenditure, there was 1) an increased allocation of attention toward effort completion cues, 2) diminished anticipatory activity prior to upcoming feedback, and 3) reduced consummatory valuation and salience.

The present study built on prior investigations of reward-related deficits in depression by administering the effort-doors task to adults with MDD and healthy control (HC) subjects. Given the evidence for distinct motivational and consummatory components of reward processing (20,37,38), and evidence supporting the RewP as an index of consummatory reward-processing deficits in depression (2), we sought to determine whether we could leverage ERPs in the effort-doors task to index distinct reward-related deficits in depression. We further predicted that deficits in ERPs indicative of the motivational component of reward processing (effort-P3 and SPN) would account for unique variance in depression status apart from that predicted by consummatory ERPs (RewP and feedback-P3). Finally, given evidence in prior work linking reduced RewP to MDD subjects with impaired mood reactivity—a subgroup characterized by reduced hedonic capacity (8,18,39)—we conducted exploratory post hoc analyses that examined ERP group differences among MDD subjects with impaired mood reactivity, those with intact mood reactivity, and HCs.

METHODS AND MATERIALS

The effort-doors task was included as part of a larger longitudinal study (hereafter referred to as the parent study) that examined MDD and HC groups over 3 visits spread across an 18-month time span (follow-up visits were completed 9 and 18 months after the initial visit). The overarching goal of the parent study was to examine changes in psychophysiological correlates of MDD over time. Data and study-specific details related to the parent study have been included in prior published work (8,16,39–42).

Participants

Participants in the parent study were initially recruited from the community in Tallahassee, Florida. Inclusion criteria were determined through 1) a prescreening phone interview ensuring normal-to-corrected vision, no neurological disorder, and no severe head trauma; 2) the Structured Clinical Interview for DSM-5–Research Version (43) to ensure that MDD participants met diagnostic criteria for a current major depressive episode; and 3) the Mini-International Neuropsychiatric Interview (44) to ensure that MDD participants had no history of bipolar, psychotic, or substance use disorders. Membership in the HC group required no lifetime diagnosis of any psychiatric disorder. All clinical interviews were conducted by one of two Ph.D.-level clinical psychologists according to procedures outlined in prior published work (8,39–44).

The effort-doors task was added to the parent study protocol partway through data collection, with 41 participants completing the task during their 9-month follow-up visit and 25 completing it during their initial baseline visit. Of those tested, 34 met the above-noted criteria for MDD, and 32 met the criteria for assignment to the HC group[1]. Because of excessive ERP artifacts (defined below), 2 participants (1 MDD and 1 HC) were excluded from analysis of the RewP, and 1 MDD participant was excluded from analysis of the feedback-P3.

All participants provided written informed consent and received $20/h of study participation and an additional $7.50 for completion of the effort-doors task. All study procedures were conducted in accordance with the Declaration of Helsinki and approved by the university's institutional review board.

Measures

Effort Doors Task. The effort doors task (30) was administered using PsychoPy software version 2 (45); the trial structure of the task is depicted in Figure 1. Each trial of the task began with an image of a locked padlock positioned below text indicating the number of button presses required to unlock the padlock. Participants then pressed either the "q" or

[1]Of those tested, 32 HC participants and 10 MDD participants completed the effort-doors task during their follow-up visit. A total of 24 MDD participants completed the task at their initial baseline visit. No interventions were implemented between visits. A comparison of demographics for subsets of MDD participants tested at the two points revealed that the baseline-visit MDD group was significantly younger than the follow-up MDD group, $t_{32} = 4.89$, $p < .001$.

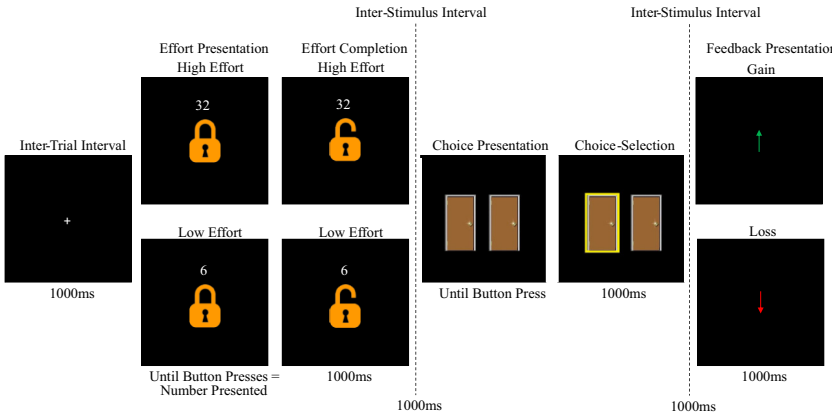

Figure 1. Effort doors task trial structure and stimulus timing.

"p" key with their nondominant pinky finger the indicated number of times. Next, an unlocked padlock image appeared for 1000 ms (i.e., the locked padlock appears to unlock), signaling effort completion. A white fixation cross then appeared for 1000 ms, followed by an image of 2 doors, which remained on the screen until participants made a choice using either the left or right arrow key. The chosen door was highlighted with a yellow rectangle for 1000 ms; a white fixation cross then reappeared for 1000 ms and was followed by the presentation of a 1000-ms feedback cue (i.e., either a green up arrow or a red down arrow, signaling a monetary gain of $0.50 or a loss of $0.25, respectively). A 1000-ms white fixation cross on a black background followed, after which a message appeared on-screen, prompting participants to press the spacebar to proceed to the next trial.

The task included 60 trials, 30 high effort, and 30 low effort, occurring in random sequence. The required number of button presses for the low-effort condition ranged from 1 to 12 (mean = 6, SD = 2) while the high-effort condition ranged from 24 to 36 (mean = 30; SD = 2). Monetary gain and loss probabilities within each condition were predetermined such that 50% of trials within the high- and low-effort trials resulted in monetary gain.

Task behavioral measures were calculated as follows: the proportion of gain trials where the participant repeated their response on the following trial (i.e., win-stay), the proportion of loss trials where the participant changed their response on the following trial (lose-shift), reaction time in milliseconds to the lock stimulus, and reaction time in milliseconds to the doors stimulus.

Table 1. ERP Component Time Windows and Scoring Sites

ERP Component	Time Window	Electrode Site
Effort-P3	300 to 500 ms relative to onset of effort completion signal	Cz
Prefeedback SPN	−200 to 0 ms relative to feedback onset	Oz
RewP	50-ms window surrounding maximum positive value in the gain-loss difference wave occurring between 200 and 500 ms relative to feedback onset	Cz
Feedback-P3	350 to 500 ms relative to feedback onset	Cz

The average number of trials included for calculation of these ERP components were as follows: Effort-P3 (high effort): mean = 29.21, range = 18–30; Effort-P3 (low effort): mean = 26.77, range = 18–30; SPN (high effort): mean = 29.40, range = 18–30; SPN (low effort): mean = 28.64, range = 22–30; RewP (gain, high effort): mean = 13.09, range = 6–15; RewP (gain, low effort): mean = 13.08, range = 6–15; RewP (loss, high effort): mean = 14.17, range = 7–15; RewP (loss, low effort): mean = 12.76, range = 7–15.

ERP, event-related potential; RewP, reward positivity; SPN, stimulus-preceding negativity.

Electroencephalographic Data Recording and Processing. Continuous electroencephalographic (EEG) data were recorded using an active electrode system (ActiChamp; Brain Products GmbH) from 32 scalp electrodes positioned in accordance with the 10–20 system (ActiCAP; Brain Products GmbH). EEG data were sampled at 1000 Hz using an online low-pass filter of 100 Hz, with signal activity referenced online to electrode Cz. Vertical electrooculogram activity was measured from electrodes placed 1 cm above and below the left eye, and horizontal electrooculogram activity was measured from 2 electrodes positioned at the outer canthi of each eye.

Following collection, raw EEG data were subjected to preprocessing procedures discussed in EEG Pre-Processing in the Supplement. Following EEG data preprocessing, the time window and measurement site for each ERP component was selected using the collapsed localizers approach (46). The RewP was scored by subtracting the average loss-trial waveform for each participant from their average gain-trial waveform, searching for the peak in this difference waveform between 200 and 500 ms, and quantifying the mean activity within −25 to 25 ms relative to this peak[2]. All remaining ERP components were scored as mean amplitudes within the parameters described in Table 1. Grand average waveforms and corresponding topographic maps of ERP components are presented in Figure 2.

[2]Prior research has determined that the RewP should be quantified as a difference wave (50) to effectively represent the underlying frontocentral positivity that reflects consummatory reward sensitivity.

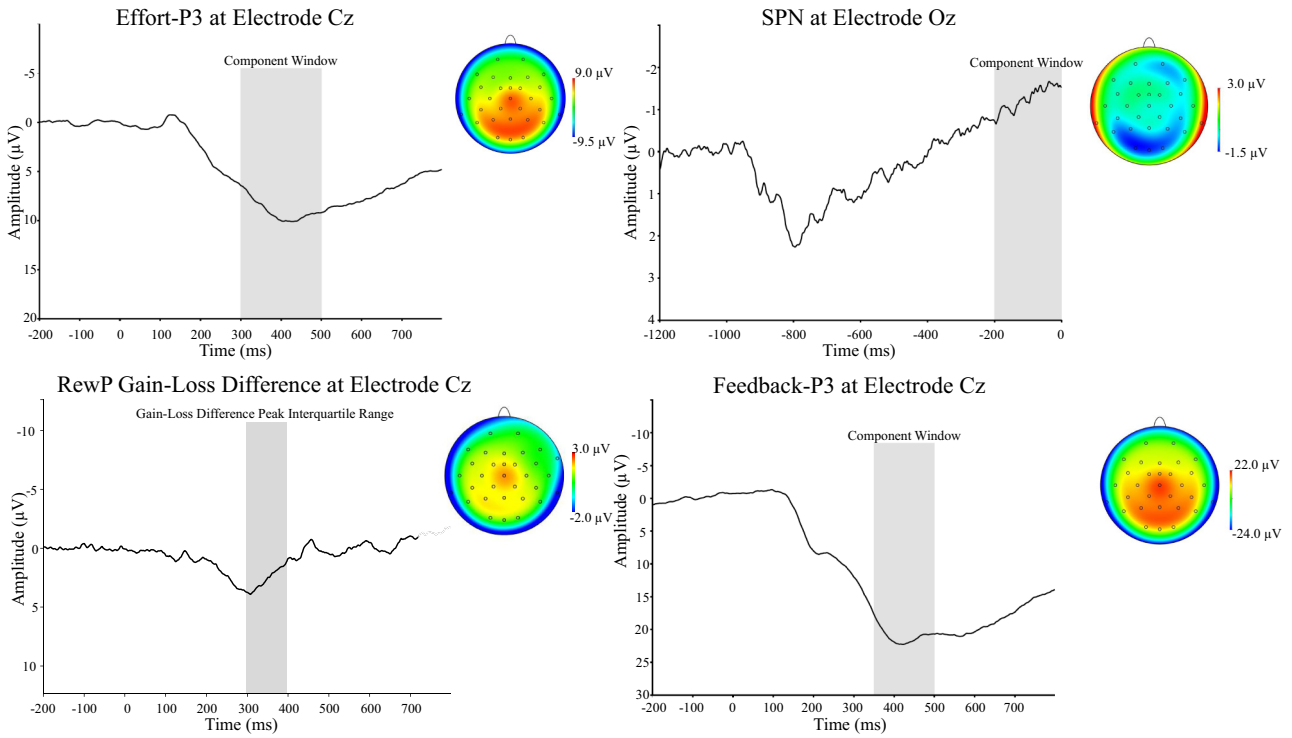

Figure 2. Grand averages and topographical maps of event-related potential (ERP) components. Panels described moving clockwise from the top left: panel 1 depicts the effort-P3, panel 2 depicts the stimulus-preceding negativity (SPN), panel 3 depicts the search range used for the reward positivity (RewP) peak, and panel 4 depicts the feedback-P3.

Data Analysis

Analyses were conducted using SPSS version 23 (IBM Corp.). As an initial step, age and gender composition were compared between the MDD group and HC group using an independent samples *t* test and χ^2 test, respectively. Outlying values for each ERP measure were winsorized (47) to the median ± 2 times the interquartile range. Following outlier correction, descriptive statistics and Spearman-Brown corrected split-half reliability coefficients (48,49) were computed for each ERP component.

To examine task effects (i.e., high- vs. low-effort condition differences), paired-samples *t* tests compared high- and low-effort conditions for each ERP across the sample. To confirm that the RewP difference score was significantly greater than 0, one-sample *t* tests were run for both the high- and low-effort RewP. Next, 4 separate binary logistic regressions evaluated whether depression diagnostic status (0 = HC, 1 = MDD) was associated with high- and low-effort ERPs, specifically: effort completion (effort-P3, model 1), feedback anticipation (SPN, model 2), reward valuation (RewP, model 3), and feedback salience (feedback-P3, model 4). In these analyses, demographic variables that differed between the 2 groups were included as covariates. Next, we examined ERPs from the previous step that were associated with diagnostic status and quantified the total amount of variance in depression diagnostic status explained when these ERPs were entered as concurrent predictors. Finally, we conducted exploratory analyses of covariance (ANCOVAs) to examine whether observed group differences in each ERP were driven by distinct MDD subgroups (i.e., MDD with impaired mood reactivity vs. MDD with intact mood reactivity vs. HC subjects). Group differences of the covariate-adjusted estimated marginal means in each ANCOVA were then decomposed using Tukey's post hoc tests.

RESULTS

Group Demographic Comparisons

The MDD (76% female) and HC (82% female) groups did not differ significantly on sex, $\chi^2_{2\ (N\ =\ 66)} = 1.25$, $p = .536$; however, the MDD group was younger (mean = 31.52 years, SD = 10.56) than the HC group (mean = 40.39 years, SD = 14.41); $t_{56.68} = 2.84$, $p = .006$. Given this group difference, age was included as a covariate in subsequent analyses.

Descriptive Statistics and Psychometrics

Table 2 displays sample descriptives and Spearman-Brown–corrected split-half reliability coefficients. Corrected split-half (odd vs. even trial) reliabilities were acceptable-to-good for all ERP variables except the low-effort RewP. Table 3 displays behavioral data for the effort doors task divided by effort condition and denotes significant differences between conditions for each variable.

ERP Condition Differences

Effort-P3 amplitude was larger following high- compared with low-effort trials ($t_{63} = 5.47$, $p < .001$), whereas no condition

difference was evident for the SPN (t_{64} = 1.57, p = .121) or the RewP (t_{61} = 0.32, p = .751)—although both the high-effort RewP (t_{61} = 10.11, p < .001) and low-effort RewP (t_{61} = 10.08, p < .001) differed significantly from 0. Finally, feedback-P3 amplitude was significantly larger for low- compared with high-effort trials (t_{61} = 2.97, p = .004)[3].

Group ERP Effects

Results from binary logistic regression analyses are shown in Table 4, and ERP waveforms along with covariate-adjusted means for the 2 diagnostic groups are presented in Figure 3. In model 1, HC participants showed larger effort-P3 amplitude following high-effort trials compared with MDD participants. In model 2, HC participants showed more negative SPN amplitude on low-effort trials than MDD participants. In model 3, MDD participants showed a blunted RewP following high effort expenditure compared with HC participants; however, there were no significant group differences in the feedback-P3 following either high- or low effort expenditure (model 4).

Results from the exploratory post hoc binary logistic regression analysis are shown in Table 5. In this analysis, when controlling for age, blunted effort-P3 and RewP for high-effort trials each explained unique variance in MDD status; however, the SPN did not uniquely account for variance in MDD status, indicating that variance in MDD predicted by the SPN overlaps with the other 2 ERP predictors. Overall, this model explained 72% of the variance in depression diagnostic status[4].

Exploratory Post Hoc Analyses

Given that the MDD participants had a blunted effort-P3 amplitude and blunted RewP following high effort expenditure trials compared with HC participants and considering that each of these ERPs predicted unique variance in depression status, we conducted post hoc ANCOVAs to determine whether these findings were driven by distinct MDD subgroups. As in the main group analyses, age was included as a covariate in these ANCOVAs, given that HCs were significantly older than MDD individuals. We also included the low-effort ERP counterpart as a covariate in each ANCOVA to evaluate whether group status explained variance specific to high-effort-P3 and RewP following high effort expenditure. The ANCOVA for effort-P3 included 64 participants (31 HC participants, 12 MDD participants with intact mood reactivity, and 21 MDD with impaired mood reactivity), and the RewP ANCOVA included 62 participants (31 HC participants, 11 MDD participants with intact mood reactivity, and 20 MDD participants with impaired mood reactivity). When covarying for age and effort-P3 following low effort expenditure, group differences were evident in the effort-P3 following high effort expenditure ($F_{2,59}$ = 3.24, p = .046, η^2 = 0.05), such that the effort-P3 following high effort expenditure was blunted among MDD individuals with impaired mood reactivity (mean = 8.41 μV, SE = 1.26) compared with to HC participants (mean = 13.14 μV, SE = 1.09; t_{59} = 2.52, p = .038, d = 0.95). MDD individuals with intact mood reactivity (mean = 9.63 μV, SE = 1.52) did not differ from HC participants (t_{59} = 1.74, p = .198, d = 0.70) or MDD individuals with impaired mood reactivity (t_{59} = 0.67, p = .780, d = 0.25).

After covarying for age and RewP following low effort expenditure, group differences were evident in the RewP following high effort expenditure ($F_{2,57}$ = 4.76, p = .012, η^2 = 0.12), with MDD participants exhibiting impaired mood reactivity showing smaller RewP in this condition (mean = 4.59 μV, SE = 1.27) than HC participants (mean = 9.60 μV, SE = 1.02; t_{57} = 2.97, p = .012, d = 0.92), and (and a trend level) relative to MDD participants with intact mood reactivity (mean = 8.97 μV,

Table 2. Sample Descriptive Statistics

	n	Mean (SD)	Spearman-Brown Reliability
Effort-P3			
High effort	64	10.93 (9.36)	0.94
Low effort	64	7.26 (7.22)	0.90
SPN			
High effort	65	−0.87 (3.29)	0.68
Low effort	65	−1.35 (3.19)	0.76
RewP			
High effort	62	7.87 (6.13)	0.52
Low effort	62	8.16 (6.22)	0.28
Feedback-P3			
High effort	62	20.82 (9.97)	0.93
Low effort	62	22.19 (10.03)	0.88

RewP, reward positivity; SPN, stimulus-preceding negativity.

Table 3. Descriptive Statistics for Effort-Doors Behavioral Variables

	High Effort	Low Effort	t
Win-Stay	0.52	0.44	t_{62} = 3.51[a]
Lose-Shift	0.56	0.53	t_{59} = 1.17
Effort RT	883.70	804.65	t_{63} = 3.64[a]
Doors RT	760.43	881.80	t_{62} = 3.74[a]

Win-Stay refers to the proportion of gain trials where the participant repeated their response on the following trial. Lose-Shift refers to the proportion of loss trials where the participant changed their response on the following trial. Effort RT indicates reaction time in milliseconds to the lock stimulus, Doors RT indicates reaction time in milliseconds to the doors stimulus. The t statistic refers to the paired-samples t test comparing high and low effort for each behavioral variable.

RT, reaction time.

[a]p < .05.

[3]Given that the feedback-P3 did not differ between gain and loss trials, t_{61} = 1.01, p = .32, we quantified this ERP by averaging feedback-P3 scores for gains and losses together within the high- and low-effort conditions.

[4]To gain insight into the specific variance explained by the ERPs only, we reconducted the same binary logistic regression analysis without covarying for age. In this analysis, the overall model was significant (χ^2_3 = 40.7, p < .001) with a Nagelkerke R^2 of 0.65. In this model, MDD status was associated with a blunted effort-P3 on high-effort trials (odds ratio = 0.76, 95% CI, 0.67–0.86, p < .001, variance inflation factor = 1.19), but not with the RewP on high-effort trials (odds ratio = 0.89, 95% CI, 0.77–1.02, p = .091, variance inflation factor = 1.11) or SPN on low-effort trials (odds ratio = 1.23, 95% CI, 0.91–1.67, p = .187, variance inflation factor = 1.07).

Table 4. Binary Logistic Regression Results Predicting Diagnostic Status (MDD, HC) From ERPs

			Diagnostic Status (MDD, HC)		
Model With Predictors	R^2	χ^2	OR (95% CI)	*p* Value	VIF
Model 1					
Effort-P3	0.65	42.9[a]	–	–	–
High Effort[b]	–	–	0.85 (0.72–0.99)	.038	1.59
Low Effort	–	–	0.87 (0.73–1.04)	.137	1.60
Age	–	–	0.96 (0.91–1.02)	.168	1.02
Model 2					
SPN	0.22	11.8[c]	–	–	–
High Effort	–	–	0.81 (0.62–1.05)	.114	2.41
Low Effort[b]	–	–	1.31 (1.0003–1.71)	.0497	2.42
Age[c]	–	–	0.94 (0.90–0.98)	.007	1.05
Model 3					
RewP	0.26	13.5[c]	–	–	–
High Effort[b]	–	–	0.89 (0.80–0.99)	.039	1.30
Low Effort	–	–	1.03 (0.94–1.13)	.513	1.09
Age[c]	–	–	0.93 (0.88–0.97)	.002	1.21
Model 4					
Feedback-P3	0.24	12.5[c]	–	–	–
High Effort	–	–	1.03 (0.88–1.20)	.755	7.05
Low Effort	–	–	0.92 (0.79–1.09)	.330	7.08
Age[c]	–	–	0.94 (0.90–0.99)	.009	1.01

Logistic regression was used to predict depression diagnostic status (0 = HC, 1 = MDD).

The Nagelkerke R^2 and χ^2 statistics are reported for the logistic regression model and reflect statistics comparing the full model to the null model.

HC, healthy control; MDD, major depressive disorder; OR, odds ratio; RewP, reward positivity; SPN, stimulus-preceding negativity; VIF, variance inflation factor.

[a] $p < .001$.

[b] $p < .05$.

[c] $p < .01$.

SE = 1.65; t_{57} = 2.97, p = .094, d = 0.80). There were no differences between MDD individuals with intact mood reactivity and HC- participants (t_{57} = 0.32, p = .945, d = 0.12).

DISCUSSION

This study was undertaken to extend psychophysiological conceptualizations of reward dysfunction in MDD. To achieve this aim, a novel choice-feedback paradigm, the effort-doors task (30), was used to elicit ERPs that indexed both motivational and consummatory subcomponents of reward processing—namely, the effort-P3 following completion of effort expenditure, the SPN during anticipation of feedback, and the RewP and feedback-P3 following feedback delivery. While this study and previous work have demonstrated the utility of the RewP in accounting for appreciable variance in depression status [e.g., (2,8)], the present findings indicate that ERPs indexing motivated reward pursuit—the effort-P3 and SPN—may be used along with the RewP to better characterize reward processing deficits in depression.

In this study, reward processing deficits in depression manifested first at the effort-completion stage of the effort-doors paradigm, such that MDD participants showed a reduced effort-P3 following high effort expenditure compared with HC participants. This result parallels prior findings of depression-related deficits in estimating the opportunity cost of effort expenditure (24,26,27) and suggests that the reduction in the high effort-P3 may reflect this deficit within MDD participants.

Following effort completion, a reduced SPN on low-effort trials evidenced depression-related deficits in reward anticipation. This finding mirrors other research demonstrating a reduced capacity to anticipate rewards in MDD participants (51,52) and extends this research by demonstrating that MDD participants exhibit difficulties in encoding the cost of effort expenditure during reward anticipation. Moreover, consummatory valuation of rewards (indexed by the RewP to feedback cues) was attenuated in high-effort trials for MDD compared with HC participants. Adding to this finding, supplemental regression analyses revealed that the impact of effort on the RewP in MDD participants was independent of the impact of effort on prefeedback ERPs, providing initial evidence for distinct reward-processing deficits in MDD. Despite MDD participants' exhibiting greater reduction in consummatory valuation following high effort expenditure than HC participants, no group difference was evident for perceived salience

Figure 3. Grand average waveforms by group and covariate-adjusted mean amplitudes. Panels described from top to bottom: panel 1 depicts group differences for the effort-P3, panel 2 depicts group differences for the stimulus-preceding negativity (SPN), panel 3 depicts group differences for the reward positivity (RewP), and panel 4 depicts group differences for the feedback-P3. HC, healthy control; MDD, major depressive disorder.

Table 5. Post Hoc Binary Logistic Regression

	Diagnostic Status (MDD, HC)				
Model With Predictors	R^2	χ^2	OR (95% CI)	*p* Value	VIF
Overall Model	0.72	47.4[a]	–	–	–
High Effort P3[a]	–	–	0.74 (0.62–0.87)	<.001	1.60
Low Effort SPN	–	–	1.30 (0.94–1.79)	.113	1.13
High Effort RewP[b]	–	–	0.78 (0.64–0.96)	.021	1.97
Age[b]	–	–	0.91 (0.83–0.99)	.022	1.70

Logistic regression was used to predict depression diagnostic status (0 = HC, 1 = MDD). The Nagelkerke R^2 and χ^2 statistic are reported for the logistic regression model and reflect statistics comparing the full model to the null model.

HC, healthy control; MDD, major depressive disorder; OR, odds ratio; RewP, reward positivity; SPN, stimulus-preceding negativity; VIF, variance inflation factor.

[a]$p < .001$.

[b]$p < .05$.

of feedback as indexed by the feedback-P3. Of note, prior research using the standard doors task has reported a similar lack of difference between MDD and HC participants in feedback-P3 response (41,53–55).

Finally, exploratory post hoc ANCOVAs revealed that a specific subgroup of depressed individuals with impaired mood reactivity (a unique characteristic of melancholic depression) exhibited reduction of both effort-P3 and RewP amplitudes, while depressed subjects with intact mood reactivity did not significantly differ from HC participants. These findings build on prior reports of reduced RewP in MDD participants with versus without impaired mood reactivity (8,39) by demonstrating that the former MDD subgroup is also more sensitive to the valuation-dampening impact of high effort expenditure. Importantly, melancholic MDD is a phenotypic expression of depression that has historically lacked distinction from atypical depression (56); however, coupled with existing research concerning unique deficits in reward processing within this subtype of depression (57), the current work could help to separate these subtypes of depression more meaningfully.

Limitations and Future Directions

Some limitations should be acknowledged that highlight specific directions for follow-up research. First, the MDD group in this study was significantly younger than the HC group, and a portion of MDD participants was administered the effort-doors task during a baseline visit, with the remainder administered this task during their follow-up visit. Although no interventions were administered between visits, these MDD subgroups differed in age, and therefore, age was included as a covariate in the reported analyses. However, future research should seek to match MDD participants and HC participants on age and other demographic characteristics to control for potential confounds. A further point is that this study focused primarily on the utility of different reward-processing ERPs for differentiating between individuals with and without a current diagnosis of MDD. However, recent research has highlighted the importance of moving away from categorical conceptualizations and toward dimensional models of MDD (15,58–60). Furthermore, follow-up research using the effort-doors task should seek to clarify the role of the effort-P3 within the larger effort-based reward processing framework. This study demonstrates that individuals with depression exhibit a reduced effort-P3 after expending large amounts of effort, suggesting that this ERP may reflect modulation of motivational arousal as a function of task difficulty [e.g., (21)].

Finally, given prior work outlining the interplay between inflammatory cytokines, effort expenditure, reward, and depression (61–64), future investigations of aberrant reward processing in depression using the effort-doors paradigm might benefit from including indicators of inflammation. Specifically, chronic low-grade inflammation [a commonly co-occurring symptom of MDD (64)] depletes metabolic resources, inflammatory cytokines communicate this information with neural reward systems, the perceived cost of effort rises, and the perceived value of subsequent rewards decreases to conserve available metabolic resources (35,36,61). Examination of these relationships using the effort-doors task could extend this work by disentangling the temporal dynamics of these systems.

In conclusion, this study expands upon existing psychophysiological conceptualizations of depression by using a novel effort-reward paradigm to index distinct components of reward processing via ERP measures. ERPs occurring prior to feedback delivery revealed that MDD participants exhibited a reduced capacity to encode the relative cost of effort expenditure and an impaired ability to use this information when anticipating upcoming rewards. Additionally, current findings demonstrated a more pronounced devaluation of rewards requiring high effort in MDD participants compared with HC participants—an effect that occurred independently of reward processing deficits indexed by prefeedback ERPs. Collectively, these findings suggest that the reward-related ERPs elicited by the effort-doors paradigm might be integrated with the RewP in MDD research as potential targets for novel intervention strategies, indices of depression severity, and predictors of depression onset and course.

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ARTICLE INFORMATION

From the Florida State University, Tallahassee, Florida (CBB, CJB, CJP, GH).

CJB is currently affiliated with the University of Idaho, Moscow, Idaho.

Address correspondence to Colin B. Bowyer, Ph.D., at Bowyer@psy.fsu.edu.

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