Abstract: Depressed patients are characterized by hypoactivity of the left and hyperactivity of the right frontal areas during the resting state. Depression is also associated with impaired decision-making, which reflects multiple cognitive, affective, and attentional processes, some of which may be lateralized. The aim of this study was to investigate brain asymmetry during a decision-making task performed in negative and positive feedback conditions in patients with Major Depressive Disorder (MDD) in comparison to healthy control participants. The electroencephalogram (EEG) was recorded from 60 MDD patients and 60 healthy participants while performing a multi-stage decision-making task. Frontal, central, and parietal alpha asymmetry were analyzed with EEGlab/ERPlab software. Evoked potential responses (ERPs) showed general lateralization suggestive of an initial right dominance developing into a more complex pattern of asymmetry across different scalp areas as information was processed. The MDD group showed impaired mood prior to performance, and decreased confidence during performance in comparison to the control group. The resting state frontal alpha asymmetry showed lateralization in the healthy group only. Task-induced alpha power and ERP $P_{100}$ and $P_{300}$ amplitudes were more informative biomarkers of depression during decision making. Asymmetry coefficients based on task alpha power and ERP amplitudes showed consistency in the dynamical changes during the decision-making stages. Depression was characterized by a lack of left dominance during the resting state and left hypoactivity during the task baseline and subsequent decision-making process. Findings add to understanding of the functional significance of lateralized brain processes in depression.

Keywords: EEG; brain asymmetry; lateralization; alpha rhythm; event related potential; depression; decision-making

1. Introduction

Many studies have explored relationships between brain asymmetry and clinical depression, using methods including electroencephalography (EEG) and brain-imaging [1]. Depression relates to resting alpha asymmetry [2], but the functional significance of resting state asymmetry for cognitive processing during task performance requires further investigation [3]. Diminished ability to think or concentrate is a diagnostic criterion for depression in the Fifth Edition of the Diagnostic and Statistical
Manual of Mental Disorders (DSM-5) [4]. Experimental studies have confirmed decision-making deficits in depressed patients, although findings vary somewhat across different tasks [5]. Lateralized processing such as use of language, regulation of attention, and computation of costs and benefits may contribute to depression effects on decision-making [6], but direct evidence is lacking. The present study aimed to test whether patients with major depressive disorder (MDD) differed from controls in lateralized brain responses during a decision-making task, assessed using event-related potentials (ERPs) and alpha power measures.

1.1. Lateralization in the Resting Frontal EEG as a Marker of Depression

Lateralization in frontal EEG activity has been extensively studied as a diagnostic measurement of depression [2–9]. Resting frontal alpha asymmetry (FAA) implies differentiation between depressed and healthy participants. Depressed patients were characterized by greater alpha power over the left frontal brain area in comparison to the right hemisphere, meaning hypoactivity of the left and hyperactivity of the right hemisphere [10–14]. Moreover, frontal and parietal asymmetry both served as predictive markers of the treatment effect by antidepressants or characteristic of non-responders [7,14,15]. However, FAA does not always discriminate MDD patients from control participants [16]. Indeed, a meta-analysis of 16 studies comparing frontal asymmetry during resting state in MDD patients (1883) and controls (2161) showed non-significance in the grand mean effect size [8] and raised doubts about its diagnostic capability. The authors highlighted that heterogeneity related to gender, age, and depression severity should be considered in future research. It is also unclear whether abnormality in FAA is best considered as an index of vulnerability to depression [17,18] or as a marker of brain functional state during task performance in acute depression or remission state [7,19].

1.2. Resting Frontal Asymmetry as a Trait-Like or State-Like Measurement

Anatomical differences may underlie stability of the EEG resting frontal asymmetry, supporting an idea of a trait-like alpha asymmetry [12,20]. From the trait perspective, FAA can be linked to the balance between the behavioral inhibition system (BIS) and the behavioral activity system (BAS) [21]. Right hemisphere hyperactivity represents inhibition, avoidance, and withdrawal whereas left hemisphere hyperactivity is associated with approach motivations. High trait BIS score and low BAS score are risk factors for depression and anxiety [22,23]. Similarly, the FAA characteristic of depression represents an affective style that is associated with deficient emotion regulation, negative affect, and low sociability and positive affect [18,24–27]. FAA was suggested as a measurement of “affective style” with moderating influences on the type of responses to emotional stimuli [2].

Alternatively, FAA may represent a transient state of brain activity that reflects situational factors including reward and punishment signals and immediate task demands as well as stable traits [18]. Consistent with the state perspective, indices of FAA may change dynamically during the resting measurement period [28]. The state perspective supports examination of asymmetry during task performance as well as at rest. FAA measurements during emotional tasks showed more powerful differences between depressed patients and controls than the resting state measure [19,29–32]. Alpha asymmetry measured during performance might contribute to understanding how disorganization of the right hemisphere contributes to deficits on a range of cognitive and emotional tasks [33]. States of asymmetry may also be associated with EEG responses to reward and punishment signals [34]. Care is necessary in determining whether states should be conceptualized as predictors, outcomes, mediators, or moderators [28].

1.3. Decision Making in Depression and Brain Asymmetry

Decision-making tasks involve multiple stages associated with diverse brain areas, responsible for mental functions including information processing, estimation of future results, attention to stimuli, comparison to previous experience stored in memory, evaluating future outcomes, making a choice after weighting cost/benefits, processing feedback, and comparison with estimation. Reviews of depression
and decision [35,36] have, broadly, distinguished two types of mechanisms for depression effects. First, diminished energy and drive are central to depression. These motivational aspects may be associated with deficits in attention and executive control [37], deficits in effortful cognitive processing [38], and underestimation of the expected utility or value of processing effort [35,36]. Depressed patients are unwilling to expend efforts to obtain rewards, a deficit that may be associated with reduced decreased mesolimbic dopaminergic function [39,40]. Such deficits may contribute to general impairments in decision-making competence [41] and speed [37,42] observed in depressed patients.

Second, depression may be systematically related to biases in processing of rewards and threats, such as overly negative interpretations of the decision-making space [36] and underestimation of future rewards and outcomes [35,43]. A study with a battery of 10 decision-making tasks highlighted that MDD patients differed from the control group in reward and punishment learning and probability judgment tasks, as well as in pessimism bias in future expectations [44]. Impaired decision making in depression has been related to attentional bias toward negative stimuli as well as altered sensitivity to reward [37,45]. Approach and avoidance motivations are linked to congruent processing biases such as increased attention to reward and threat stimuli respectively [46]. Depression may be associated with lateralized processing biases as well as with approach/avoidance motivational tendencies.

Existing studies of the neuropsychology of decision-making provide complex findings on lateralization. A meta-analysis of functional magnetic resonance imaging (fMRI) studies [47] reported right hemisphere lateralization for some areas (e.g., prefrontal cortex, frontal eyefield) and left lateralization for others (e.g., intraparietal sulcus, basal forebrain). Lateralization is likely to be dependent on the specific cognitive processes engaged by the decision-making task, such as right hemisphere control of spatial cognition and left lateralization of language-based tasks [47]. Attentional processes contribute to a variety of tasks. A predominantly right-hemisphere frontoparietal network supports alertness and readiness [48], although other attentional networks may not be strongly lateralized [49,50]. Evidence from ERP studies on lateralization during decision-making is limited. The P300 has been used to investigate feedback processing in gambling tasks [51] but lateralization is not typically the major focus for such studies. Research that addresses lateralization explicitly has investigated alpha power asymmetry, most commonly in gambling-based paradigms [52]. For example, a bias towards reward on the Iowa Gambling Task, seen in high-BAS individuals, was associated with an increased left-hemisphere activity in response to losing [53]. It is largely unknown how depression might moderate asymmetry during decision-making.

1.4. ERPs in Depressed Patients

Previous EEG/ERP studies showed that ERP waves were sensitive to cognitive and emotional impairments in depression. Reviews of this literature [1,54] suggest that depression primarily impacts later waves with effects including reduced P300 amplitude and increased amplitude in the late positive potential (LPP). However, findings are not entirely consistent; effects on P300 may vary with factors including depressive subtype and the nature of the cognitive demands imposed by the task [54]. Effects on early ERPs appear to be relatively weak. The reviews cited found four studies in which N100 amplitude was reduced in depressed patients but larger numbers in which there was no depression effect. MDD patients also exhibit diminished brain activity and prolonged stimulus processing based on decreased peak amplitude and larger latency of P100 in cognitive tasks [55,56], but also at least one contrary finding is reported [57].

The effects of depression on ERPs may be modulated by affective factors. The general expectation is that depression will be associated with heightened sensitivity to stimuli of negative valence and reduced response to positive stimuli. Neuroimaging studies have tended to confirm that depressed patients show elevated brain activity to negative emotional stimuli [58,59]. Results from ERP studies are more complex. Bruder et al.’s [54] review cites studies showing reduced P300 response in depressives to both positive and negative stimuli. By contrast, other studies suggest mood-congruent effects associated with depressed individuals exhibiting increased P300 amplitude to negative stimuli including...
words of negative valence [60] and sad faces [61]. Monnart, Kornreich, Verbanck, and Campanella [62] reviewed studies using various attentional tasks to investigate inhibitory processes. Depression was associated with both increased and decreased $P_{300}$ response to emotive stimuli in different task conditions, but results generally suggested that depression leads to dysfunctional inhibition of negative material. Comparable results have been found for earlier ERP components, including $P_{100}$, implying that depression influences multiple processing stages [62,63].

Depressed participants may be impaired in reinforcement learning processes, although depression does not appear to reliably affect the ability to learn from explicit positive and negative feedback [64]. ERP studies link depression to increased error related negativity (ERN), perhaps reflecting increased threat sensitivity or a negative cognitive bias [65], although effect sizes tend to be weak and heterogeneous [66]. Similarly, depressed participants were characterized by a larger feedback related negativity (FRN) ERP to negative feedback in comparison to the control group [25]. ERP studies have also confirmed that MDD patients are characterized by blunted reward sensitivity by using $P_{300}$ amplitude measurements [67,68]. Another relevant indicator is the reward positivity (RewP) ERP component, which tends to be decreased in MDD patients, although results are rather mixed [66,67,69].

Bruder, Stewart, and McGrath [6] reviewed lateralization of brain function in depression through integration of findings from behavioral, electrophysiological, and brain imaging data. They concluded that the bulk of the evidence from these different sources is consistent with reduced left frontal and right parietotemporal function in depression. Consistent with this perspective, lower right-hemisphere $P_{300}$ amplitude in depression has been observed in several studies [70]. This review [6] also discussed three studies in which depressed individuals showed reduced ERPs to emotional stimuli in the right parietal regions. Low-resolution electromagnetic tomography (LORETA) has been used to infer sources of lateralization in several studies. Consistent with Bruder et al.’s [6] conclusions, Kawasaki et al. [71] reported lower $P_{300}$ source activity in both left frontal and right temporoparietal areas, as well as bilateral prefrontal areas. Lower $P_{300}$ source activity has been observed in the right frontal lobe, insula and limbic areas as well as in the right parietal and temporal lobes [70].

A challenge for further work in this area is that decision-making may reflect multiple brain processes that may be differentially related to depression. Many real-life decisions, like which house or a car to buy, can be taken on a rational basis, by weighing up the benefits and costs of each option. The unwillingness of depressed individuals to invest effort in demanding cognitive activity [35,36,39] leads to decision-making deficits. Biases in processing information on costs and benefits may also impair decision-making over and above insufficient effort. Depression promotes behavioral inhibition and avoidance motivation over behavioral activity and approach, which may be associated with deficits in effortful processing [72]. Such motivational deficits may be accompanied by cognitive biases that promote attention towards threat and away from reward [46]. Dysfunctional lateralization may be indexed by alpha power asymmetry [28], but ERPs may be better suited for investigating cognitive processing contributing to decision-making. Thus, for the present study, we utilized an explicit decision-making task that afforded manipulation of cost and benefit information, as well as positive and negative feedback on decisions.

1.5. Study Aims

The overall aim of the study was to test whether participants with MDD showed asymmetry in ERP responses during a cognitively demanding decision-making task, in comparison with healthy control subjects. We investigated the asymmetry of frontal, central, and parietal ERP amplitudes ($P_{100}$ and $P_{300}$) and alpha spectrum power during both the resting state and performance. We anticipated that depressed patients would show asymmetries indicative of maladaptive avoidance-withdrawal tendencies [2]. We also investigated whether depression effects were moderated by different stages of processing and by affective factors.

The study utilized a decision-making task [73] that allowed ERPs to be recorded at different task stages. The task requires the participant to make a series of route choices in an Antarctic
search-and-rescue scenario, in order to find the fastest route to a party of lost explorers. Choices can be made rationally by assessing the likely benefits and costs of each route, but it is demanding and effortful to do so. Previous studies confirmed the sensitivity of task performance to a range of affective factors, in nonclinical samples [73–75]. Task stages include ‘Start’ (initial preparedness), ‘Hazard’ and ‘Benefit’ text messages indicating potential losses and gains, ‘Choice’ (response selection), and ‘Feedback’ (positive or negative). The study also manipulated emotional context; half the participants experienced generally positive outcomes, whereas the remainder were exposed to negative outcomes. The following specific issues were investigated.

1. Lateralization of alpha during rest. Based on previous research we hypothesized that the MDD group would be characterized by lower right alpha power (i.e., right cortical hyperactivity) during the resting state.

2. Lateralization of decision-making stages. We anticipated a stronger right hemisphere response at the Start stage, reflecting the right-hemisphere frontoparietal network for alertness [48]. Processing verbal material describing costs and benefits should elicit a left hemisphere response, possibly modulated by a right-hemisphere negative emotional response to Hazard messages. However, these predictions were tentative, given the complexity of functional lateralization [47].

3. Emotional context and lateralization. We expected that emotional context would influence lateralization of ERPs. In the negative emotion condition, the experimental software was rigged so that participants’ choices typically led to negative outcomes, leading to progressively diminishing likelihood of rescuing the explorers, and frequent negative feedback. We anticipated heightened right-hemisphere response amplitude in this condition, especially in response to hazard messages and negative feedback.

4. Impact of major depression. We expected that depression would be associated with resting alpha asymmetry [2,59], and we tested for this effect persisting during task performance. We also anticipated reduced right temporoparietal P_{300} amplitude in MDD patients [6,70]. We expected this effect of depression to be stronger in response to benefit messages and to feedback in the positive emotion condition, given evidence for reduced sensitivity to reward [6,67]. Findings with threat-related stimuli have been more equivocal; in some studies negative-valent stimuli evoke a stronger response in depressed individuals [60,61]. Most previous studies have investigated P_{300}, but we anticipated parallel effects for P_{100}, given that depression may also impair early attentional processes [62,63].

5. Relationships between task-induced alpha asymmetry and ERP amplitude. Previous studies have not investigated how ERP amplitude asymmetry during task performance is related to the asymmetry in alpha power. We measured the alpha response to the task stages for comparison with ERPs. As this was a supplementary analysis, we restricted it to frontal and parietal alpha in the time interval corresponding to P_{300}. These sites have been the main focus of previous studies of alpha asymmetry [2]. We expected that task-induced alpha would show depression effects on lateralization similar to the well-known FAA effect. To determine the equivalence of alpha and ERP measures of lateralization, we correlated measures of asymmetry in resting and task-induced alpha with measures of asymmetry in ERP response.

2. Method

2.1. Participants

Sixty volunteers who were diagnosed for the first time with major depressive disorder (MDD group: 30 males and 30 females: mean age = 26.62, SD = 7.45) and 60 healthy volunteers (control group: 30 males and 30 females: mean age = 25.35, SD = 6.42) participated. The study was approved by the Ethics Committee of the Faculty of Medicine and Health Care of the Al-Farabi Kazakh National University. Healthy participants were recruited by advertisement through social networks from the general public of Almaty city area and patients from Republican Scientific and Practical Center of
Mental Health. All participants were medication-free and had not started any treatment. They were right-handed and had normal or corrected vision. Volunteers with substance or alcohol abuse were excluded from the study. Women were excluded if they were having a menstrual period, or if they had been diagnosed with PMS (premenstrual syndrome). After signing the consent form all subjects completed the Inventory of Depressive Symptomatology I (IDS: Rush et al., 1996). Subjects who had an IDS score higher than 20 completed the Hamilton Rating Scale for Depression (HRSD, 1980). They were then interviewed by a clinical psychologist and by a psychiatrist for diagnosis (based on ICD-10, International Statistical Classification of Diseases and Related Health Problems).

2.2. Design and Procedure

The study utilized a $2 \times 2$ (group: healthy vs. depressed $\times$ feedback condition: positive vs. negative feedback) design, with repeated measures for feedback condition. Participants meeting the inclusion criteria initially completed the mood scale, and then viewed a detailed PowerPoint description of the decision-making task. Electrodes for EEG were attached and a 1-min baseline recording with eyes closed was obtained. Participants performed 30 trials on the decision-making task in each feedback condition, with order of conditions counterbalanced across participants. Mood and confidence ratings were obtained after every 10 trials. Finally, participants were debriefed.

2.3. Questionnaire Measurements of Emotional State

The first section of the Dundee Stress State Questionnaire (DSSQ) [76] assessed energetic arousal, tense arousal, hedonic tone, and frustration and anger before the decision-making task. Additionally, after every ten trials during task performance participants were asked “How much positive mood are you experiencing?” and “How confident are you about your ability to make the best choice?” (along with other questions). Participants responded on a 1–4 scale anchored by “Not at all” and “Very much”.

2.4. Decision-Making Task

The “search-and-rescue” tactical decision-making task [73,75] was programmed in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA). It was adapted to the EEG/ERP experiment. The participant performed a rescue operation with a goal to find as fast as possible a lost party of explorers in the Antarctic and save their lives [75]. The participant was required to make 30 successive route choices (trials) to find the fastest route while driving a snowcat vehicle to the location of the lost party. Each trial presented a map of the terrain with two alternative color-coded routes and four icons for potential hazards and benefits on the routes (one hazard and one benefit on each route). A statement about probabilities of loss or gain and their percentage likelihoods in each route appeared to participants when they placed a cursor over icons, using the mouse. For example, a hazard might be a 20% chance of an avalanche that would cause a 40-min delay. After assessing the cost and benefit information, participants were prompted to make a route choice by clicking on one of two color-coded circles presented on the display. Information about the result of the choice was given after each route selection following each trial, which contained an image of the occurred event and a statement of time that had been lost or gained. The feedback screen described overall time lost or gained across all trials, with an image of either a contented or discontented explorer. EEG markers were added to the E-Prime task for the key events of each trial: start, benefits, hazards, choice of route, and feedback.

Each participant performed in positive and negative feedback conditions. The outcomes for each route choice were predetermined. In the positive feedback condition, benefits (time gains) were obtained on the majority of trials, whereas in the negative feedback condition, costs (time losses) predominated [75]. Thus, in the former condition, participants accumulated gains (with occasional losses) so that they became progressively further ahead of the schedule necessary to reach the lost party before the explorers expired. In the negative feedback condition, prospects of reaching the lost party became increasingly unlikely. Following the final trial, success or failure was confirmed according to feedback condition (Figure 1).
Dependent measures were overall decision time, and the total time taken by the participant to inspect the hazard and benefit text descriptions (“inspection time”).

2.5. EEG Recording

EEG was recorded with a Neuron-Spectrum_4 system (Neurosoft Ltd., Ivanovo, Russia) in the following situations: baseline recording with closed eyes (1 min); performance of the decision-making task (40 min). Ag/AgCl electrodes were placed by using the 10–20% international system monopolar from the left and right frontal, parietal, occipital, and central areas (F3, F4, F7, F8, C3, C4, P3, P4, O1, O2, FPz, Fz, FCz, Cz, CPz, Pz, O2) using an electrode cap (Neurosoft) with an indifferent ear electrode. An additional two electrodes were used for vertical and horizontal electrooculogram recording. Electrode impedance was below 5 kOhm. EEG data were acquired with a sampling rate of 256 Hz. Synchronization between EEG and E-Prime software was programmed to elicit ERPs on the markers sent by the E-Prime task.

2.6. EEG Preprocessing

Spectral power density (SPD) was analyzed in Neuron-Spectrum NET software, version 3 for Windows (Neurosoft, 2019). Alpha SPD values were generated between 8–13 Hz from the right and left frontal (F3, F4) and parietal (P3, P4) electrodes, at rest and at each task stage. The alpha asymmetry coefficient was calculated by the formula ln[Right]-ln[Left] [77]. Data on reliability and validity of the coefficient are provided in [77]. ERP preprocessing was done in EEGLAB/ERPLAB toolbox [78,79] based on MATLAB R2019b [80]. The analysis included DC correction, epoching, baseline correction, artifact rejection (±75uV), and artifact removal by using ICA (independent component analysis). ICA identifies mutually independent component time courses in the spatially distributed recording [78]. Artifacts are independent from brain signals and may be presented as separate components that are easy to detect visually. EEGLAB performs ICA decomposition using the runica() algorithm, an automated and enhanced version of the infomax ICA algorithm [78]. ICA components with their time course were visually inspected. Frontal muscle tension artifacts usually appear at high frequencies (more then 20–50 Hz) and are localized spatially. Eyeblink artefacts can also be identified in a smoothly decreased EEG spectrum with far-frontal localization. Artifactual components were rejected on this basis. Rejected data were less than 10% overall. High bandpass 0.1 Hz filtering and low bandpass 30Hz filtering were applied in two steps to further reduce EMG artefact and to remove line noise during the entire recording. Artifact free EEG epochs between 200 ms pre-stimulus and 800 ms post-stimulus were extracted for the following events representing successive stages of decision-making:
Start. Participant clicks left mouse key following the presentation of the word “start” on the screen, initiating the next trial and displaying the routes on the map.

Hazards and Benefits. The map display includes warning triangle and smile icons for each route. The mouse is used to display a text box associated with the icon that states the probability of losing or gaining a fixed amount of time. The event for the ERP is the first occasion on which the participant accesses the hazards or benefits text. The participant chooses whether hazard or benefit information is accessed first but must access both.

Choice. The participant clicks on one of two colored circles on the map to make their route choice.

Feedback. The positive or negative feedback screen appears, showing overall progress relative to the time schedule for reaching the explorers.

P_{300} amplitude was measured as a peak between 200–500 ms, P_{100} as a peak between 50–150 ms at each stage for each electrode.

Additionally, ERP power spectrum for alpha frequency (8–13 Hz) was calculated for each category of stimulus during task performance, during the 200–500 ms interval after each event.

2.7. Statistical Analysis

The primary dependent variables from the EEG were P_{100} and P_{300} amplitudes. Mixed-model ANOVAs with two within-subject variables (‘side’: left (L) and right (R); ‘feedback condition’: positive and negative) and one between-subject variable (‘group’: MDD and Hth) were performed in SPSS for corresponding lateralized electrode pairs [81]. Supplementary analyses were conducted on alpha power. The dependent variable for analyses of alpha response during task performance indexed asymmetry of activity, measured at frontal (F_3–F_4) and parietal (P_3–P_4 sites). Effect sizes were quantified using the partial eta squared (\eta^2_p) statistic, defined as the ratio of the variability accounted for by an effect and the variability of that effect plus its associated error.

3. Results

3.1. Demographic Data

Demographic data and depression scores (IDS) for both groups are presented in Table 1. There was no difference in mean age between groups. Mean IDS score was significantly higher in the MDD group (t = 14.834, p < 0.0005) in comparison to Healthy participants.

| Group  | Gender | N   | Age       | IDS Score  |
|--------|--------|-----|-----------|------------|
| MDD    | Females | 30  | 27.10, SD = 7.68 | 42.73 SD = 9.23 |
|        | Males  | 30  | 26.13, SD = 7.31 | 37.13 SD = 10.20 |
|        |        | 60  | 26.62, SD = 7.45 | 39.93 SD = 10.05 |
| Healthy| Females | 30  | 24.6, SD = 7.07  | 17.90 SD = 6.43  |
|        | Males  | 30  | 26.10, SD = 5.71 | 15.40 SD = 7.12  |
|        |        | 60  | 25.35, SD = 6.42 | 16.65, SD = 6.84 |

3.2. Mood Assessment

Pretask DSSQ parameters such as tense arousal (t = 5.264, p < 0.0001) and anger/frustration (t = 5.146, p < 0.0001) were significantly larger, whereas energetic arousal (t = -5.759, p < 0.0001) and hedonic tone (t = -7.129, p < 0.0001) showed lower scores in the MDD group in comparison to Hth group participants (Figure 2). Cronbach’s alphas for DSSQ scores were as follows: tense arousal 0.796; anger/frustration 0.796; energetic arousal 0.564; hedonic tone 0.719. These data confirm the consistency of the translated questionnaire, except for energetic arousal.
There were no further significant interactions involving the group factor. Thus, it was confirmed positive information.

Figure 2. DSSQ scores before experiment: BEA—Energetic Arousal, BTA—Tense Arousal; BHT—Hedonic Tone; BAF—Anger/Frustration. MDD group in blue, Hth group in red. * p < 0.05.

The mood and confidence ratings obtained during the task were analyzed with 3 × 2 × 2 (trial × feedback condition × group) mixed-model ANOVAs, where trial refers to ratings after 10, 20, and 30 trials. For mood, there was a significant main effect of condition (F(1,118) = 17.694, p < 0.0001, η²_p = 0.130), with poorer mood in the negative condition (mean = 2.333, SE = 0.083) in comparison to the positive condition (mean = 2.625, SE = 0.092). A trend towards poorer mood in the MDD group failed to reach significance. There were no significant interactions. For confidence, there was a significant main effect of condition (F(1,118) = 49.000, p < 0.0001, η²_p = 0.293), moderated by a condition × trial interaction (F(2,236) = 8.149, p < 0.0001, η²_p = 0.065). Confidence was lower in the negative feedback condition, with the effect increasing across trials. At trial 10, confidence means were 2.883 (SE = 0.079) in the negative condition and 3.117 (SE = 0.066) in the positive condition. By trial 30, means were 2.583 (SD = 0.090) in the negative condition and 3.217 (SD = 0.074) in the positive condition. There was also a significant effect of group (F(1,118) = 11.230, p < 0.01, η²_p = 0.087). Confidence was higher in the healthy group (M = 3.164, SE = 0.083) than in the depressed group (M = 2.772, SE = 0.083). There were no further significant interactions involving the group factor. Thus, it was confirmed that feedback condition influenced mood and confidence as expected, but depression was associated primarily with a decrease in confidence.

3.3. Behavioral Results

Table 2 shows behavioral data from the decision-making task. Overall decision time (DT) from the onset of the map stimulus to the time of the participant’s choice of route was analyzed using a 2 × 2 (feedback condition × group) mixed-model ANOVA. There were no significant main effects or interaction.

The inspection times (ITs) for benefits and hazards refer to the total times during which the participant was using the mouse to display the text information on potential time gains and costs for each route. Data were analyzed with a 2 × 2 × 2 (feedback condition × information type × group) mixed-model ANOVA, where information type contrasts benefits and hazards. The analysis showed a significant group effect (F(1,118) = 7.067, p = 0.009, η²_p = 0.057) with longer ITs in MDD in comparison to Hth group participants (Figure 3). A significant information type effect (F(1,118) = 12.284, p = 0.001, η²_p = 0.094; longer for hazard) provided evidence that participants attended more to negative than to positive information.
were no main or interactive effects of group on resting alpha power at the paired frontal and parietal sites. The analysis showed a significant group effect only in the healthy group (F(1,118) = 7.590, p = 0.007, \(\eta^2_p = 0.060\)) with higher alpha SPD in the right frontal F4 (mean = 3.55, SE = 0.35) in comparison to F3 (mean = 3.30, SE = 3.12) electrodes in all participants. There were no significant group effects or group \(\times\) side interactions. Given the reliability of FAA differences in previous depression studies, we tested for side effects in each group separately, as planned comparisons, despite the lack of a significant interaction. There was a significant side effect only in the healthy group (F(1,59) = 4.85, p = 0.032, \(\eta^2 = 0.076\), F3: mean = 3.50, SE = 0.50; F4: mean = 3.73, SE = 0.50). We observed lower alpha power in the left hemisphere in the healthy group but no asymmetry in the MDD group. The side effect was significant for alpha at parietal electrodes P3 vs. P4 (F(1,118) = 6.644, p = 0.011, \(\eta^2_p = 0.053\)), resulting from higher alpha power in the right hemisphere (mean = 8.30, SE = 1.04) in comparison to the left (mean = 7.14, SE = 0.96). However, there were no main or interactive effects involving group at parietal sites. Repeated-measures t-tests showed no significant group effects on the alpha asymmetry coefficient for either frontal or parietal electrodes.

3.4.2. Effects of Task Factors and Depression on ERP Amplitudes

Mixed-model 2 \(\times\) 2 \(\times\) 2 (side \(\times\) feedback condition \(\times\) group) ANOVAs were used to analyze factors influencing P100 and P300 amplitudes. Analyses were run separately for four lateralized electrode pairs, i.e., F3 vs. F4, F7 vs. F8, C3 vs. C4, and P3 vs. P4. Data were analyzed for ERPs to the key stages of the task: start of the trial, accessing hazard and benefit information, responding with a route choice, and receiving feedback.

Results from these analyses are presented in three subsections reflecting the aims of the study. First, we report the main effects of the side factor, which indicate the extent to which ERPs were generally lateralized during stages of decision-making. Second, we report the main effects of feedback condition and condition \(\times\) side interactions, indicating the impact of emotional context and its effect on lateralization. Third, we report the main and interactive effects for the group factor, defining differences between healthy and depressed groups overall and in lateralization. Effects relevant to study aims are illustrated with amplitude plots and topographic maps as appropriate. The relevant cell means for each set of analyses are included in Supplementary Materials.

Lateralization of ERP Amplitudes during Decision-Making Task

The ANOVAs revealed significant (p < 0.05 or better) effects of side for responses at all task stages: Start (Figure 3), Hazard/Benefit (Figure 4), Choice (Figure 5), and Feedback (Figure 6). Analyses of P100 amplitude to Start revealed significant side effects in the central (C3 vs. C4, F(1,118) = 18.177, p < 0.0001, \(\eta^2_p = 0.133\)), and parietal (P3 vs. P4, F(1,118) = 13.645, p < 0.0001, \(\eta^2_p = 0.104\)) electrodes, with higher right response in both cases. P300 amplitude was higher in the right side in frontal (F3 vs. F4, F(1,118) = 4.969, p = 0.028, \(\eta^2_p = 0.040\)), and parietal (P3 vs. P4, F(1,118) = 14.259, p < 0.0001, \(\eta^2_p = 0.108\)) electrodes.

### Table 2. Response time data for MDD and healthy groups as function of feedback condition.

| Group  | Condition | DT decision-making, ms | IT benefits, ms | IT hazards, ms |
|--------|-----------|------------------------|----------------|---------------|
| MDD    | Negative  | 15,548.74, SD = 3517.06 | 920.87, SD = 352.25 | 966.39, SD = 465.42 |
|        | Positive  | 14,954.47, SD = 4462.41 | 834.59, SD = 261.74 | 896.20, SD = 309.73 |
|        | Both conditions | 14,639.11, SD = 3495.28 | 877.73, SD = 312.03 | 931.29, SD = 395.23 |
| Healthy| Negative  | 14,854.67, SD = 3671.71 | 734.60, SD = 238.73 | 840.91, SD = 302.64 |
|        | Positive  | 14,046.56, SD = 3602.41 | 762.20, SD = 240.49 | 811.24, SD = 305.65 |
|        | Both conditions | 14,450.61, SD = 3644.57 | 748.40, SD = 239.00 | 826.08, SD = 303.23 |

Note DT = Decision time, IT = Inspection time.
Contrary to these trends, right dominance of \( P_{300} \) amplitude in the central \( C_7 \) upper) and of \( F_5 \).

The Choice stage was characterized by larger \( P_{100} \) and \( P_{300} \) amplitudes in the left frontal (\( F_3 \) vs. \( F_4 \): \( P_{100} \), \( F(1,118) = 5.054, p = 0.026, \eta^2_p = 0.041 \), \( P_{300} \), \( F(1,118) = 4.829, p = 0.030, \eta^2_p = 0.039, F_7 \) vs. \( F_8 \): \( P_{100} \), \( F(1,118) = 4.448, p = 0.037, \eta^2_p = 0.036 \)) and in the right central and parietal electrodes (\( C_3 \) vs. \( C_4 \): \( P_{300} \), \( F(1,118) = 4.503, p = 0.036, \eta^2_p = 0.037 \), \( P_3 \) vs. \( P_4 \): \( P_{100} \), \( F(1,118) = 7.327, p = 0.008, \eta^2_p = 0.058 \)) (see Figure 5).

Hazard and Benefit. The most consistent effect was left-lateralization of \( P_{100} \). Hazard produced higher left \( P_{100} \) amplitude in the analyses of \( F_3 \) vs. \( F_4 \) (\( F(1,118) = 8.573, p = 0.004, \eta^2_p = 0.068 \), Figure 4, upper) and of \( F_2 \) vs. \( F_3 \) (\( F(1,118) = 7.939, p = 0.006, \eta^2_p = 0.063 \)). Benefit induced higher left \( P_{100} \) amplitude in the central \( C_3 \) vs. \( C_4 \) (\( F(1,118) = 6.968, p = 0.009, \eta^2_p = 0.056 \), Figure 4, lower) analysis. Contrary to these trends, right dominance of \( P_{100} \) amplitude was observed to Benefit in parietal electrodes (\( P_3 \) vs. \( P_4 \): \( F(1,118) = 3.991, p = 0.048, \eta^2_p = 0.033 \)).
Figure 5. (a) ERPs for P_{100} and P_{300} to Choice on F_{3} (black line) and F_{4} (red line) electrodes (left dominance) and for P_{100} to Choice on P_{3} (black line) and P_{4} (red line) electrodes (right dominance), * p < 0.05. Right upper: 2-d map of mean P_{100} amplitude. (b) lower: 2-d map of mean P_{300} amplitude.

In response to Feedback, P_{100} and P_{300} amplitudes in the right central (C3 vs. C4: P_{100} (F(1,118) = 5.336, p = 0.023, \eta^2_p = 0.043); P_{300} (F(1,118) = 10.835, p = 0.001, \eta^2_p = 0.084) and right parietal (P3 vs. P4: P_{100} (F(1,118) = 16.849, p < 0.0001, \eta^2_p = 0.125); P_{300} (F(1,118) = 7.843, p = 0.006, \eta^2_p = 0.062) electrodes showed lateralization effects. Elevated right parietal response is shown in Figure 6. By contrast, left frontal dominance was observed in F7 vs. F8 P_{300} amplitude (F(1,118) = 4.378, p = 0.039, \eta^2_p = 0.036).

Figure 6. (a) ERPs for P_{300} on feedback on P_{3} (black line) and P_{4} (red line) electrodes. (b) 2-d map of mean P_{300} amplitude, ** p < 0.01, *** p < 0.001.

ERP Amplitudes and Brain Asymmetry in Positive and Negative Feedback Conditions

Significant main effects of feedback condition revealed larger ERP amplitudes in the negative condition at the Benefit (F_{3}/F_{4}: P_{100}. F(1,118) = 4.695, p = 0.032, \eta^2_p = 0.038; P_{3}/P_{4}: P_{100}. F(1,118) = 5.985, p = 0.016, \eta^2_p = 0.048); Choice (F_{3}/F_{4}: P_{100}. F(1,118) = 5.133, p = 0.025, \eta^2_p = 0.042); and Feedback stages (F_{3}/F_{4}: P_{100}. F(1,118) = 6.616, p = 0.011, \eta^2_p = 0.053).

There were a few significant feedback condition × side effects in ERPs amplitudes during task performance supporting the hypothesis about hemisphere emotional valence to some extent. The negative feedback condition was characterized by a tendency towards a later hyperactivity in the right central areas, whereas the positive condition induced an earlier stronger left frontal dominance.
However, the left/right hemisphere prevalence was dependent on the task stage, as shown in the following significant condition × side effects. Stronger right dominance in negative condition was observed to Start (P_{300}, C_3 vs. C_4: F(1,118) = 4.651, \( p = 0.033 \), \( \eta^2_p = 0.038 \)) and Hazard (C_3 vs. C_4: F(1,118) = 3.930, \( p = 0.050 \), \( \eta^2_p = 0.032 \)). Left dominance in positive condition was found in P_{100} amplitude to Benefit (F_{3} vs. F_{4}: F(1,118) = 6.452, \( p = 0.012 \), \( \eta^2_p = 0.052 \) and Choice (F_{7} vs. F_{8}: F(1,118) = 4.125, \( p = 0.044 \), \( \eta^2_p = 0.034 \)). The significant main effects of feedback condition implied a general tendency towards lower early frontal activity in the positive condition. The interactions suggest that this effect was driven primarily by reduced activity in the right hemisphere following positive feedback (see Figure 7).

![Figure 7](image)

**Figure 7.** 2-d maps of for P_{300} amplitude to Start and Hazard 300 ms after stimulus onset; and P_{100} to Benefit and Choice in 100 ms after stimulus onset in both feedback conditions: negative and positive.

ERP Amplitudes and Brain Asymmetry Differences in MDD and Hth Groups

Significant main effects of the group factor showed that depressed individuals had weaker parietal P_{300}s at Benefit and Feedback stages, but stronger P_{100} response at Choice. Parietal ERP amplitudes during decision making were significantly larger in Hth group in comparison to MDD participants to Benefit (P_{300}, P_{3} vs. P_{4}: F(1,118) = 4.926, \( p = 0.028 \), \( \eta^2_p = 0.040 \)) and Feedback (P_{300}, P_{3} vs. P_{4}: F(1,118) = 4.293, \( p = 0.040 \), \( \eta^2_p = 0.035 \)). By contrast, at the Choice stage, there was higher response amplitude in the MDD group in the frontal (P_{100}, F_{3} vs. F_{4}: F(1,118) = 10.052, \( p = 0.002 \), \( \eta^2_p = 0.078 \); F_{7} vs. F_{8}: F = 4.517, \( p = 0.036 \), \( \eta^2_p = 0.037 \)) and central areas (P_{100}, C_{3} vs. C_{4}: F(1,118) = 11.945, \( p = 0.001 \), \( \eta^2_p = 0.092 \)) in comparison to control group.

Significant group × side effects were found to Start in the central electrodes (P_{300}, C_{3} vs. C_{4}: F(1,118) = 9.138, \( p = 0.003 \), \( \eta^2_p = 0.072 \)) with larger right dominance in the MDD group, supporting the hypothesis of the left hypoactivity in depression. There was a significant main effect of the side factor for this ERP with stronger right response; this lateralization was more pronounced in depressed individuals, as shown in Figure 8. Parietal asymmetry to Hazard in the MDD group was characterized by left dominance and Hth group by right dominance (P_{3} vs. P_{4}: F_{100}, F(1,118) = 6.261, \( p = 0.014 \), \( \eta^2_p = 0.050 \), P_{300}, F(1,118) = 5.282, \( p = 0.023 \), \( \eta^2_p = 0.043 \)), probably, as result of an overreaction to hazards in the MDD group. There was a significant main effect of side on P_{300} parietal response to Hazard, associated with right dominance; the interaction suggests this effect was driven by the healthy group.
3.4.3. Effects of Task Factors and Depression on the Task-Induced Alpha Asymmetry Coefficient

The alpha asymmetry coefficient was calculated for each stage at frontal and parietal sites. There was a trend towards dominance of the right hemisphere at the feedback stage. However, none of the means for the whole sample differed significantly from zero on Bonferroni-corrected 1-sample t-tests, indicating that task-induced alpha was not lateralized overall.

Effects of independent variables on the task-induced alpha asymmetry coefficient were analyzed with a series of $2 \times 2$ (feedback condition × group) mixed-model ANOVAs. Several significant main effects of group showed that the coefficient was significantly lower in the MDD group in frontal area to Start ($F(1,118) = 4.95, p = 0.028, \eta^2_p = 0.040$) and Feedback ($F(1,118) = 4.183, p = 0.043, \eta^2_p = 0.034$) and in parietal area to Start ($F(1,118) = 14.633, p < 0.0001, \eta^2_p = 0.110$), Hazard ($F(1,118) = 4.306, p = 0.040, \eta^2_p = 0.035$), and Choice ($F(1,118) = 8.392, p = 0.004, \eta^2_p = 0.066$). Means for the coefficient in the two groups are shown in Table 3. The healthy group showed a general trend towards left lateralization (i.e., higher alpha power in the right hemisphere) whereas the depressed participants tended to show the opposite tendency or minimal lateralization. Figure 9 shows topographic maps for the two groups and the difference between them at the feedback stage. No significant main or interactive effects of feedback condition were found.

Figure 8. ERPs 2-d maps of the amplitude for P300 to Start (500 ms) and Hazard (400 ms) in MDD and Healthy groups.

Figure 9. Alpha power spectrum to ‘feedback’ between 8–13 Hz in MDD and Healthy groups and difference between groups (Hth-MDD).
### Table 3. Mean (and SE) values for alpha asymmetry coefficient at multiple task stages in frontal and parietal areas, in healthy and depressed groups.

|                | Frontal Hth | Frontal MDD | Parietal Hth | Parietal MDD |
|----------------|-------------|-------------|--------------|--------------|
| Start          | 0.091 (0.069) | -0.127 (0.069) | 0.484 (0.106) | -0.086 (0.106) |
| Hazard         | 0.038 (0.082) | 0.002 (0.082) | 0.234 (0.103) | -0.067 (0.103) |
| Benefit        | 0.075 (0.093) | -0.164 (0.093) | 0.114 (0.123) | 0.149 (0.123) |
| Choice         | 0.104 (0.071) | -0.035 (0.071) | 0.320 (0.102) | -0.097 (0.102) |
| Feedback       | 0.175 (0.077) | -0.050 (0.077) | 0.336 (0.115) | 0.181 (0.115) |

3.4.4. Correlations between Resting State Alpha Coefficient, Task-Induced Alpha Asymmetry Coefficient, and Task-Induced Amplitude Coefficient

To investigate the relationship between the alpha asymmetry coefficients and asymmetry in P<sub>300</sub> response, correlations were calculated between the two sets of measures, as shown in Table 4. For this analysis, P<sub>300</sub> asymmetry coefficients were calculated by analogy to the alpha coefficient, i.e., \( \ln[\text{Right}] - \ln[\text{Left}] \) [77]. There was only one significant positive correlation between the resting state alpha asymmetry coefficients and the ERP measures: for the parietal response at the Choice stage. However, the task-induced alpha coefficients tended to correlate positively with P<sub>300</sub> amplitudes, more strongly for the parietal response (range of rs: 0.129–0.454) than for the frontal response (range of rs: 0.069–0.297). Thus, during task performance, asymmetry in alpha was related to asymmetry in ERP amplitude, although correlation magnitudes were typically small to moderate (Table 4).

| Alpha Asymmetry Coefficient | P<sub>300</sub> Amplitude Asymmetry Coefficient |
|-----------------------------|-----------------------------------------------|
|                             | Start | Benefit | Hazard | Choice | Feedback |
| Frontal Resting State       | 0.030 | 0.017   | 0.028  | -0.037 | 0.082    |
| Start                       | 0.213 * | 0.091   | 0.220 * | 0.110  | 0.091    |
| Benefit                     | 0.165 | 0.146   | 0.116  | 0.289 ** | 0.147 |
| Hazard                      | 0.213 * | 0.133   | 0.089  | 0.287 ** | 0.207* |
| Choice                      | 0.157 | 0.178   | 0.148  | 0.297 ** | 0.281 **|
| Feedback                    | 0.069 | 0.140   | 0.182* | 0.111  | 0.124    |
| Parietal Resting State      | 0.135 | 0.053   | 0.144  | 0.185 * | 0.109    |
| Start                       | 0.364 ** | 0.193 * | 0.331 ** | 0.244 ** | 0.137 |
| Benefit                     | 0.242 ** | 0.216 * | 0.257 ** | 0.341 ** | 0.129    |
| Hazard                      | 0.317 ** | 0.313 ** | 0.452 ** | 0.454 ** | 0.198 * |
| Choice                      | 0.248 ** | 0.276 ** | 0.429 ** | 0.379 ** | 0.220 * |
| Feedback                    | 0.373 ** | 0.144   | 0.201 * | 0.281 ** | 0.184 * |

Note * \( p < 0.05 \), ** \( p < 0.01 \)

4. Discussion

The aim of the study was to compare brain asymmetry between participants with MDD and a healthy control group during a multi-stage decision-making task. We also compared ERPs and task-induced alpha as measures of asymmetry during decision-making; to our knowledge, this is the first study to do so. We confirmed affective and behavioral impacts of depression in the decision-making paradigm. The MDD group showed initial mood impairments, and they expressed less confidence in their ability to perform the task. They also took more time to inspect information on costs and benefits of decisional choices. Thus, the task seemed suitable as a test bed for investigating neurocognitive characteristics of depression.
To accomplish the overall study aim we investigated five specific issues as listed previously, with the following broad outcomes. First, analyses of resting alpha provided some limited evidence for left dominance of frontal response in healthy but not depressed participants, as hypothesized. Second, there was strong evidence for lateralization of ERP response during decision-making, depending on task stage, electrode site, and ERP wave. Third, we found support for the hypothesis that persistent negative feedback and processing negative information would increase right-lateralization of ERPs, although the relevant effects on asymmetry were highly specific to stages. Fourth, we confirmed that depression influenced asymmetry in ERP response, although effects were stage-specific and there was no general right dominance in the MDD group. Fifth, task-induced alpha was moderately correlated with ERP amplitude, but only ERPs showed overall lateralization effects. However, healthy participants showed a general trend towards left dominance of alpha response, as predicted. The remainder of this section discusses key issues in more depth and acknowledges some study limitations.

4.1. Asymmetry in ERP Response during Decision-Making

Table 5 summarizes significant ERP lateralization effects. Overall, asymmetry in response was quite prevalent, but lateralization varied with task stage, recording site and ERP component. Both \( P_{100} \) and \( P_{300} \) responses tended to show right parietal and central lateralization. There was also a tendency for frontal ERPs to be left lateralized, with \( P_{100} \) effects reaching significance for Hazard, Benefit, and Choice stages, and \( P_{300} \) response showing left lateralization at Choice and Feedback stages. The table also illustrates significant moderator effects, specifying factors that tended to accentuate main effects of side. Positive feedback tended to increase left frontal lateralization of \( P_{100} \) response at Benefit and Choice stages, whereas negative feedback increased right lateralization of \( P_{300} \) response at the Start stage. We discuss these effects in more detail in this section.

| Stage    | \( P_{100} \) Lateralization | \( P_{100} \) Moderator Factors | \( P_{300} \) Lateralization | \( P_{300} \) Moderator Factors |
|----------|------------------------------|---------------------------------|-----------------------------|-------------------------------|
| Start    | Right: C, P                  |                                 | Right: F, C, P              | C: Neg. Feedback              |
|          |                              |                                 |                             | C: MDD                        |
| Hazard   | Left: F                      |                                 | Right: P                   | P: Healthy                    |
| Benefit  | Left: F, C                   | F: Pos. Feedback                |                             |                               |
| Choice   | Left: F                      | F: Pos. Feedback                | Left: F                    |                               |
|          | Right: P                     |                                 | Right: C                   |                               |
| Feedback | Right: C, P                  |                                 | Left: F                    |                               |
|          |                              |                                 | Right: C, P                |                               |

Note: Effects significant at \( p < 0.01 \) are bolded. Entries for moderator factors indicate factor that enhanced main effect; e.g., right central lateralization of central \( P_{300} \) at Start was stronger in the negative feedback condition (and weaker in the positive condition).

Based on previous lateralization studies [47,48] we tentatively hypothesized an initial right lateralization at Start, followed by a shift to left dominance as the person processes verbal material at the Hazard through Choice stages. Data confirmed the initial right lateralization for both ERP components. Parietal and central right lateralization tended to persist into the later stages. As expected, we also found left lateralization of frontal \( P_{100} \) as the person attended to hazard and benefit information and processed this information to arrive at a decision (Choice). A weaker trend towards asymmetry in these stages in \( P_{300} \) was significant only at Choice. Right dominance at the start of the trial may reflect the right-hemisphere frontoparietal network for alertness [48]. The influence of this network on ERPs becomes diminished as left-hemisphere language areas are engaged to process the statements of hazard and benefit information. Such dynamic changes in lateralization are consistent with a “state” perspective on asymmetry [18].
Generally, P_{100} reflects early attentive processes controlled by stimulus features [82], sensory selection [83], “cost of attention” [84,85], and “gain control” [86]. It is mostly topographically mapped to visual posterior areas contralaterally to visual stimulus. Anterior P_{100} component originates from frontal generators [87], whereas posterior P_{100} is generated in extrastriate cortex [88], and fusiform gyrus [84]. The current data suggest lateralization of early attention depending on the extent to which attention reflects visuospatial or language-based processes. Lateralization of P_{300} at Start, Choice, and Feedback stages was similar to that for P_{100}, suggesting that it may be sensitive to common attentional networks. P_{300} amplitude asymmetry in the frontal areas may reflect attention engagement, whereas central and parietal P_{300} may indicate executive control and cognitive workload [89,90]. We also expected P_{300} to be sensitive to the cognitive demands of decision-making, given its sensitivity to attention allocation and memory updating [91]. Working memory for verbal or symbolic material tends to be left-lateralized [92] implying stronger left hemisphere response during processing of the hazard and benefit text. However, P_{300} was not lateralized during this stage of the task.

We anticipated that experimental conditions likely to provoke negative emotion such as receiving frequent negative feedback and processing hazard information would tend to elicit hyperactivity in right central areas, whereas positive condition would induce stronger left frontal dominance to benefits, in line with theories of the emotional valence of brain hemispheres [93,94]. Several main effects of feedback condition were associated primarily with stronger frontal P_{100} response in the negative condition at multiple stages. These effects are generally consistent with previous studies suggesting that negative emotion tends to enhance ERP amplitude [95,96], reflecting the high priority of attending to stimuli associated with negative arousal [96]. Feedback condition effects on frontal P_{100} response at Benefit and Choice stages varied with side: reduced frontal activity in the positive condition was especially evident in the right hemisphere. Results also showed a stronger P_{300} right hemisphere response in the negative feedback condition at central sites in Start and Hazard stages. Taken together, these results are consistent with a positive emotional context promoting early left dominance and a negative context leading to later right dominance, as anticipated. However, effect sizes were relatively small, and the effects were significant only at certain stages.

4.2. Decision Making in Depression and Brain Asymmetry

Our literature review suggested two types of effect of major depression on brain functioning. First, depressed patients tend to be over-sensitive to threat [60,61], especially when the task requires inhibition of negative stimuli [62], and under-sensitive to reward [67,68]. Second, the alpha asymmetry literature [2,9,97] implies that avoidance predominates over approach in depression, leading to left frontal hypoactivity. Both characteristics of depression may influence ERPs.

Evidence for greater threat sensitivity and lower reward sensitivity in depressed participants was limited. Depressed patients were expected to show (1) reduced ERP response to benefits relative to hazards, and (2) reduced responsiveness in the positive feedback condition relative to the negative feedback condition, especially at the Feedback stage. Consistent with expectation, depressed participants showed a smaller P_{300} response at the Benefits stage. However, we did not confirm an overall elevated response to hazard information. In fact, there was a lateralized response to Hazard for both P_{100} and P_{300}, with the depressed group showing a stronger left parietal response, and the healthy group showing right lateralization. There were also no significant group £ feedback condition effects; depressed patients did not show any general sensitivity to progressive failure at the task. Evidence for expected lateralization effects was limited to the Start stage, at which the depressed group showed a stronger central P_{300} lateralization effect.

4.3. Alpha Asymmetry: Comparison with ERP Data

Previous studies have more often focused on alpha power than ERPs. The present study provided the opportunity to compare two types of EEG measure directly. In accordance with previous studies, we tested for the resting state FAA that was reported as a biological marker of depression [2,7–9,97,98].
We expected that left hyperactivity, associated with approach behavior, would predominate in healthy persons and right hyperactivity, associated with withdrawal behavior, would feature in depressed individuals [24]. Our results confirmed this assumption to a limited extent. There was a general trend towards initial left lateralization at both frontal and parietal sites. There were no significant depression effects in the omnibus ANOVAs, but planned comparisons showed that left dominance in alpha was significant only for healthy individuals, consistent with expectation. The limited evidence for group differences is consistent with data questioning the reliability of depression effects on the FAA [8].

The ERP data suggested early right-lateralization at the start, followed by a more complex pattern of lateralization varying with wave and electrode site in intermediate stages, and a more general central-parietal right lateralization at the final, feedback stage. We did not observe any asymmetry in task-induced alpha at any stage, suggesting that the ERP data are more sensitive to lateralization. For example, there was no counterpart in the alpha data to the significant left frontal lateralization of P100 response evident in the intermediate stages at which the person performs verbal processing. Alpha may be insensitive to specific decision-making processes such as left-lateralized attention to language-based stimuli that are better captured by ERP measures.

The analyses of alpha also showed evidence for depression effects on lateralization of parietal response during Start, Hazard, and Choice stages, and of frontal response at Start and Feedback stages. In each case, the asymmetry coefficient was positive but close to zero in the MDD group. That is, the healthy group showed left dominance (right frontal or parietal hypoactivity, depending on stage), but the depressed individuals showed a more symmetrical response. The relative dominance of the right hemisphere activity in the MDD group compared to healthy controls is consistent with the interrelation of brain asymmetry and depression previously reported [2,9,97].

Previous studies have typically focused on resting FAA, although, similar to our findings, depressed patients had lower left asymmetry during a task requiring processing of facial expression [98]. The present data showed a trend towards a depression effect on resting alpha asymmetry, but it did not reach significance in the analysis of the asymmetry coefficient. Lateralization was stronger during decision-making than at rest, consistent with previous suggestions that frontal asymmetry during affective tasks is a more powerful marker of depression than at rest [19,98,99]. Some studies report that emotion induction is accompanied by alpha desynchronization [100,101]. The strongest effects were observed at the Start stage at which the participant is preparing for task processing. As discussed in the previous section, the anticipated right lateralization of P300 response in the MDD group was found only at this stage. Task-induced alpha appears to be a more sensitive indicator of depression effects on lateralization than the ERPs. By contrast, we found that ERP amplitudes were more informative indicators of the dynamical changes in brain asymmetry across task stages then the alpha response, in the whole sample.

The correlational analysis suggested that P300 and task-induced alpha provide overlapping but distinct indices of brain activity, consistent with a “trait” model for individual differences in symmetry [2,21]. Positive correlations between alpha power asymmetry and ERP amplitude coefficients, especially in the parietal areas, confirm the consistency of individual differences in lateralization based on two different measurement approaches. However, significant correlations were small to medium in magnitude, implying that the measures are not interchangeable. Resting state alpha asymmetry was only minimally related to P300 amplitude, confirming that the resting state may be of limited functional significance for decision-making. However, we might expect that changes in ERP alpha power and ERP amplitude will have opposite directions since alpha oscillations are reverse indicators of brain activity [102,103]. On the other hand, different cognitive tasks such as working memory and Go-NoGo may elicit event-related alpha at parietal sites [104,105].

4.4. Clinical Implications

The present study was designed as basic rather than applied research, but we can suggest some tentative clinical implications. Previous authors have suggested several clinical applications
for assessment of FAA, including enhancement of diagnosis, identifying at-risk individuals, and anticipating the outcomes of pharmacological and psychological therapies [6,106]. However, while some studies show promising results, others are more equivocal, and the clinical value of measuring FAA in clients remains to be substantiated [6,8,106,107]. Methodological improvements are necessary to capitalize on the promise of FAA for enhancing diagnosis and anticipating treatment outcomes [3,8].

Consistent with [19], the present findings suggest that task-induced FAA is more strongly linked to depression than resting FAA. Thus, assessment of FAA for diagnostic purposes should be conducted during performance of tasks designed to elicit maximally the abnormal lateralized neurocognitive processes characteristic of depression. The challenge is to define the tasks that are most effective for this purpose. The current study suggests that asymmetry in alpha is not a fixed attribute of depressed patients throughout decision-making. In fact, parietal task-induced alpha asymmetry tended to be the strongest marker for depression, especially early in task processing (Start); the language-based processing at intermediate task stages tended to suppress depression effects. Further research might identify the brain network activated as the person initiates the information search supporting decision-making, such as the frontoparietal network supporting alertness [48], and develop a task version optimized for discrimination of depressed individuals.

The present findings also suggest that resting FAA and ERP measures linked to specific task stages may have diagnostic value over and above task-induced alpha asymmetry, given the modest intercorrelations of the different measures. In the present data, these measures appeared to have only limited diagnostic value. However, further work might develop task paradigms that enhance their ability to discriminate depressed and healthy individuals, such as those using emotionally evocative tasks [3,108]. Such work might support a multivariate diagnostic model, including multiple metrics derived from different tasks or task components. A toolbox for clinical diagnostic purposes could then be defined, using a complex of EEG markers (including ERP and alpha asymmetry metrics) for diagnosis, although further validation work would be needed.

4.5. Limitations

Several study limitations should be noted. First, depression effects on ERP's may vary with severity of illness, depression subtype [53], gender, and age differences. We did not attempt to test these factors as possible moderators of relationships between depression and symmetry of response to keep the number of analyses manageable. However, future research should further address the role of these personal characteristics. Other conditions associated with negative affect such as anxiety may also influence outcomes. Second, identification of asymmetries associated with depression may be enhanced by using more refined measures. For example, individual alpha peak frequency (IAPF), the maximum power value in the individual’s EEG frequency spectrum between 7.5 and 12.5 Hz [109], may be used to index FAA [110]. Also, EEG may be combined with other physiological measurements, including brain-imaging [6]. Investigations of stress and emotional factors may be enhanced by assessment of forehead muscle activity and stress hormones, including progesterone in studies of gender [111]. Resting FAA varies with phase of the menstrual cycle [112] and with the presence of PMS [113]. Third, we confirmed that the feedback manipulation we used influenced mood and confidence appropriately. However, an artificial laboratory task may not elicit emotional states representative of real-life depression, such as despair and hopelessness. The effects of the affective variables in this study were fairly modest, although broadly consistent with expectation. Stronger effects might be found with more realistic stressors. Fourth, the effects of depression were quite variable across the different stages of the decision-making task, consistent with other studies demonstrating variability across different information-processing tasks [53,62]. However, given the complexity of decision-making, a more comprehensive framework for decomposing decision-making into different processing components is needed.
5. Conclusions

Impacts of depression on decision-making may have important real-world consequences but the neurocognitive bases for such effects are poorly understood. The present ERP study confirmed that brain response to different stages of a decision-making task is asymmetrical. An initial right lateralization developed into a more complex spatial pattern of asymmetry as the person processed text-based messages on potential benefits and hazards. The effects of depression on lateralization were limited, but we found some evidence for the expected hyperactivity of the right hemisphere in the MDD group, especially in task-induced alpha data. MDD and healthy groups were most strongly discriminated by asymmetry in parietal alpha early in decision-making.

These findings can inform further investigations of asymmetry in depression and its functional significance in decision-making. The results indicate the need for a more nuanced understanding of neurocognitive features of MDD than the conventional linkage between depression and FAA suggests. Depression is not uniformly linked to right lateralization of processing throughout decision-making. The clinician may expect to find abnormalities linked to asymmetry only in specific circumstances. Future applied research should aim to develop tasks that strongly elicit these asymmetrical processes in support of clinical diagnosis and prediction of treatment outcomes.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-8994/12/12/2118/s1, Table S1. Means and SDs for ERP amplitudes by electrode pair and task stage (averaged across feedback condition and group), Table S2. Means and SDs for ERP amplitudes by electrode pair and task stage. For positive and negative feedback conditions (averaged across group), Table S3. Means and SDs for ERP amplitudes by electrode pair and task stage. For healthy and MDD groups (averaged across feedback condition). A list of abbreviations is also provided.

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