Published in final edited form as:
Pers Individ Dif. 2009 February 1; 46(3): 303. doi:10.1016/j.paid.2008.10.019.

Impulsivity in Decision-Making: An Event-Related Potential Investigation

Laura E. Martin[1] and **Geoffrey F. Potts**[2]

[1]University of Kansas Medical Center

[2]University of South Florida

Abstract

Impulsive individuals make risky choices, motivated more by immediate reward than potential long-term negative consequences. We used event-related potentials to study the impact of reward and punishment sensitivity in impulsivity on risky decision-making in a two-card choice task in groups of 14 high and 14 low impulsive undergraduates formed by a median split on the Barratt Impulsiveness Scale score. The high impulsives had a larger P3 and the low impulsives a smaller P3 to the cards when making a low-risk choice suggesting that the high-risk option was the default choice of the high impulsives and the low-risk choice the default for the low impulsives. The low, but not the high impulsives had a larger error-related negativity following high-risk choice indicating that the low impulsives evaluated the risky choice as a poor decision. The results indicate that high impulsive individuals are biased towards immediate reward during option evaluation but are less sensitive to the negative consequences of their choices.

Keywords

Impulsivity; decision-making; event-related potentials; error related negativity; P3

Introduction

Impulsive individuals make risky decisions, choosing immediate rewards despite potential long-term negative consequences (Moeller, Barratt, Dougherty, Schmitz, & Swann, 2001). Decision-making consists of multiple operations including option evaluation and actions and outcome monitoring. The current study used event-related potentials (ERPs) in a two-card forced choice task between high and low risk/reward options in participants separated into high- and low-impulsive groups based on a median split on Barrett Impulsiveness Scale score (BIS-11; Patton, Stanford, & Barratt, 1995) to examine impulsivity related differences during the option evaluation and action and outcome monitoring stages of decision-making.

Impulsivity

Impulsivity is a personality dimension described as “acting without thinking” and is associated with several psychiatric and personality disorders including mania, substance abuse, and

Corresponding Author: Geoffrey F. Potts, 4202 East Fowler Ave, PCD4118G, Tampa, FL 33620, Phone: 813-974-1085, Fax: 813-974-4617, Email: gpotts@cas.usf.edu.

antisocial personality disorder (Moeller et al., 2001). Impulsive individuals make risky decisions, motivated more by immediate reward rather than by the potential long-term negative consequences of their choices, suggesting heightened sensitivity to reward and/or reduced sensitivity to negative outcomes (Ainslie, 1975). Impulsivity may be a multidimensional construct, including a lack of behavioral inhibition and selection of immediate rewards. One two-factor impulsivity model identified a reward-related approach factor and a disinhibition related rash impulsivity factor (Dawe, Gullo, & Loxton, 2004) while a three-factor model identified disinhibition, reward delay discounting, and a cognitive dimension as factors (Dom, De Wildea, Hulstijnb, & Sabbeb, 2007). Gray's biologically based personality model has two similar factors: a behavioral inhibition system (BIS) that organizes behavior in response to aversive events and reward based behavioral activation system (BAS) (Gray, 1982). Gray (1987) linked impulsivity to an over-reactive BAS resulting in increased reward sensitivity, and later work linked impulsivity to both a hyperreactive BAS and hyporeactive BIS (Corr, 2002).

Studying Risky Choice Experimentally

In the Iowa Gambling Task (IGT; Bechara, Damasio, Damasio, & Anderson, 1994), participants choose a card from one of four decks, two high-risk/reward and two low risk/reward. Choosing primarily from the high-risk decks results in occasional large wins but a net loss while the low-risk choice results in net gain. Frontal lesion patients, substance abusers, and self-described risk-takers choose impulsively on the IGT, selecting more from the high-risk decks, presumably lured by the high-win cards, whereas control participants learn to choose primarily from the low-risk decks (Bechara et al., 1994; Bechara, Dolan, & Hindes, 2002). ERP decision designs often employ fewer options, usually two or three (e.g. Holroyd, Larsen, & Cohen, 2004; Gehring & Willoughby, 2002).

ERP indices of Decision-Making

ERP decision- related components include the P3 and the error-related negativity (ERN). The P3 is a centroparietal positivity approximately 300 – 400 ms post-stimulus most commonly associated with expectation violation (e.g. Courchesne, Hillyard, & Galambos, 1975; Donchin & Coles, 1988) and is also larger to motivationally salient and rewarding outcomes (Begleiter, Porjesz, Chou, & Aunon, 1983; Martin & Potts, 2004; Yeung & Sanfey, 2004).

The ERN is a frontocentral negativity occurring about 100 ms after an incorrect response (Gehring, Goss, Coles, Meyer, & Donchin, 1993) thought to index either error detection (Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996) or response conflict (Gehring & Fencsik, 2001). Holroyd and Coles (2002) proposed that the ERN reflects reward system activity comparing expected reward from an action with the reward actually received to optimize the motivation value of behavior.

If the participant does not know the correct response there is no ERN at motor execution, rather the ERN is elicited to feedback signaling the error. As the individual learns the task the ERN shifts from the feedback to the action (Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004). An ERN can also occur in the absence of an error when a choice yields a reward that is less than the best available outcome (Gehring & Willoughby, 2002).

ERPs and Impulsivity

Impulsive individuals have smaller and slower P3s compared to control subjects (Harmon-Jones, Barratt, & Wigg, 1997; Moeller et al., 2001), effects often seen in mental and neurological disorders (Polich & Herbst, 2000), sometimes interpreted as indexing general cognitive impairment. P3 amplitude is negatively correlated with BIS-11 score in cocaine dependent participants (Moeller et al., 2004) and impulsive aggressive prison inmates and

college students (Barratt, Stanford, Kent, & Alan, 1997; Gerstle, Mathias, & Stanford, 1998). Impulsive individuals also differ on early sensory and attention-related components, having smaller P1s and larger N1s indicating reduced gating and enhanced orienting (Houston & Stanford, 2001).

ERN findings in impulsivity indicate impaired behavior monitoring and reward bias. Participants who respond impulsively (faster with more errors) have smaller ERNs (Pailing, Segalowitz, Dywan, & Davies, 2002) as do individuals with borderline personality disorder and those who score high on externalizing personality (de Bruijn et al., 2005; Hall, Bernat, & Patrick, 2007), interpreted as reflecting reduced behavior monitoring efficiency and cognitive control. Impulsive individuals have larger ERNs when a reward violates their expectation, suggesting greater reward sensitivity (Martin & Potts, 2004). Impulsive individuals and low socialized individuals, individuals more likely to be impulsive, have smaller ERNs on punishment compared to reward motivated trials, suggesting reduced punishment sensitivity (Potts, George, Martin, & Barratt, 2006; Dikman and Allen, 2000).

Prior studies used simple attention or choice reaction time designs to elicit differential ERP responses in impulsivity. While these ERP responses index cognitive operations involved in decision-making, to our knowledge there have been no studies that examine the impact of impulsivity on these ERP components in the context of risky choice.

The Current Study

The current study used ERPs to investigate the impact of impulsivity on option evaluation and action and outcome monitoring during risky decision-making. Participants chose cards from one of two decks where one deck contained occasional large wins but consistently choosing from that deck would result in overall loss while the other deck contained smaller individual win values but would result in overall gain. We predicted that high impulsives would be more neurally sensitive to reward during evaluation of the choice options, indexed by the card-related P3, and less sensitive to risky choice during action monitoring, indexed by the ERN. Visual inspection of the waveforms also revealed apparent differences in the attention-related N1 to both the card and feedback so those were also analyzed.

Methods

Participants

Rice University's Institutional Review Board approved the procedures and participants provided informed consent. Twenty-eight Rice University students were divided into high and low impulsive groups by median split of BIS-11 score (median BIS = 59.5; high group: n = 14, female = 8, mean age = 19.1, SD = 1.2, mean BIS = 70.8, SD = 7.5; low group: n = 14, female = 3, mean age = 19.2, SD = 1.0, mean BIS = 55.1, SD = 2.2) (note that there was an unequal distribution of subject sex between groups but there were no significant differences for Sex on any measures). Six low impulsive and three high impulsive participants were excluded from the feedback-locked analysis due to artifact.

Task and Stimuli

Stimuli were presented and behavioral responses collected using E-Prime (PST, Inc., Pittsburgh, PA). Each trial began with 1000 ms of fixation followed by simultaneous presentation to the right and left of a high- and a low-risk card differentiated by back design and color. The location of the high- and low-risk cards and the payoff amount were randomized across trials. Participants chose a card by pressing a left or right key after which feedback appeared reporting the trial outcome and the running total for the block (the feedback followed the response by 25 – 40 ms, the 15 ms variation due to when in the monitor refresh cycle the

response occurred). The feedback screen stayed on until the participant initiated the next trial. The low-risk deck contained a relatively low reward value ($0.75) and low to moderate loss values (-$0.05, -$0.25, -$0.75, -$1.00, and -$1.25), and the high-risk deck contained a higher reward value ($1.25) and moderate to high loss values (-$0.75, -$1.25, -$1.75, -$2.25, -$2.75). Each deck also contained neutral cards yielding neither win nor loss. There were six blocks of 100 trials each. Participants were instructed to maximize their winnings but were not informed about the nature of the decks. The card backs changed each block so participants had to relearn which deck was high- and low-risk. Participants began with $5 and their total was reset to $5 at the beginning of each block. Participants were paid the highest amount won on any block or $5, whichever was greater.

Behavioral Analysis

Reaction time was analyzed by repeated-measures ANOVA with Choice (high-risk, low-risk) as the within factor and Group (high impulsive, low impulsive) as the between factor. Choice pattern was also analyzed with Net Choice (number of low-risk selections minus number of high-risk selections) and Group as factors. We also included trial within block, divided into five bins with Time (T1 = trials 1-20, T2 = trials 21-40, etc.), and Block (blocks 1-6) to examine learning rates.

ERP Acquisition and Analyses

EEG was acquired with a 128 channel Electrical Geodesics system (EGI., Eugene, OR) referenced to the vertex with .1 - 100 Hz analog filtering, digitized at 250 Hz, digitally lowpass filtered at 20 Hz, and segmented into epochs spanning 200 ms before to 800 ms after card presentation to assess option evaluation and from 200 ms before to 800 ms after the feedback for analysis of choice and outcome evaluation (since the feedback was temporally yoked to the response, the response ERN was available in the feedback-locked segments). The segments were screened for non-cephalic artifact and the remaining data averaged by condition to create the ERPs, baseline corrected over the first 200 ms, and rereferenced into an average reference representation. The individual subject ERPs were averaged to produce the mean waveforms across participants.

We examined the N1 and P3 to the cards presentation to assess attention to and evaluation of the choice options. We examined the response ERN to assess immediate monitoring of choice actions. We examined the N1, feedback ERN (FRN), and P3 to the feedback stimulus to assess attention to and evaluation of choice outcome. Since the scalp field distributions of these components have been reported elsewhere (Dehaene, Posner, & Tucker, 1994; Tarkka & Stokic, 1998; Van Veen & Carter, 2002), and all except the posterior N1 are usually largest at midline electrodes, we analyzed the midline electrodes corresponding to Fz, FCz, Cz, and Pz in the international 10/20 system. The electrodes and temporal windows for the components were: card-locked anterior and posterior N1 from 100 – 160 ms at FCz and Pz respectively, card-locked P3 from 300 – 450 ms at Pz, response-related ERN from 25 ms before to 50 ms after the feedback (corresponding to 0 – 15 ms before to 75 – 90 ms after the response) at Fz, from 75 – 150 ms post-feedback at Fz for the anterior N1, from 75 – 175 ms post-feedback at Pz for the posterior N1, from 200 – 275 ms at Fz for the FRN, and from 300 – 500 ms at Cz for the feedback-related P3. Mean ERP amplitudes were cast into repeated-measures ANOVAs with Choice (high-risk, low-risk) as the within factor for the deck-related N1 and P3, the ERN, and the feedback-related N1, and Choice and Outcome (Win, Loss, Neutral) as factors for the feedback FRN and P3, and Group (high impulsive, low impulsive) as the between factor. Waveform plots at the analyzed electrodes are presented with the analysis windows in Figure 1 (N1 & P3 to the card presentation and the response ERN and N1 to the feedback) and Figure 2 (Feedback FRN and P3).

Results

Behavioral

There were no significant differences between the groups in the choice reaction time or proportion of risky choices. The average reaction time across subjects and choices was 698 ms (SD = 249). High and low impulsive participants did not significantly differ in the number of low-risk choices (number of low-risk minus high-risk choices) p=0.74 or amount of money made: low impulsive: mean $17.98, SD 5.75; high impulsive: mean $18.68, SD 4.55; t (26) = -.36, p = .72. No significant learning effects were found within blocks, however a learning effect was present across blocks, $F(5, 115)=2.715$, $p<.05$, showing that participants selected fewer high-risk cards in the last, compared to the first block, $t(27)=2.62$, $p<.05$.

ERP

Cards presentation—There was a trend for Choice, F(1, 26) = 3.11, p = .090 on the posterior (Pz) N1 suggesting more negativity when evaluating for a later high-risk choice, modified by a Group × Choice trend, F(1, 26) = 3.50, p = .073, indicating that while the posterior N1 was larger in the low impulsive group, only the high impulsives showed a larger N1 when making a high-risk choice. There was also a Group × Choice trend for the frontal (FCz) N1, F(1, 26) = .067, suggesting a larger N1 in the high, compared to the low impulsive participants when making a high-risk choice.

There was a significant Group × Choice interaction on the P3 at Pz, F (1, 26) = 12.43, p = .002, showing that the P3 was largest in the low impulsive individuals and smallest in the high impulsive individuals when choosing from the high-risk deck (see Figure 1).

Feedback presentation—The ERN at Fz showed a main effect for Choice, F(1, 17) = 4.86, p = .042, larger following choices from the high-risk deck. A Group × Deck trend, $F(1, 17) = 3.17$, p = .093, indicated that this larger ERN following high-risk choice was present only in the low impulsive participants (see Figure 1).

The feedback-related frontal (Fz) N1 was larger in the low impulsive participants (F(1, 17) = 5.12, p = .030. There were no effects on the posterior (Pz) N1 (see Figure 1).

There were no effects on the FRN (FCz) but an effect of Outcome on the P3 (Pz), F(1, 17) = 17.90, p < .001, showed the largest P3 to win feedback, intermediate to loss feedback, and smallest to feedback showing a neutral outcome (see Figure 2).

Discussion

The P3 to the choice options (cards presentation) was smallest when the high impulsive participants were making a high-risk choice, the choice that held greatest potential for immediate reward but worst long-term outcome, and largest when the low impulsive individuals were making that same high-risk choice. No behavioral differences were found between groups, therefore the P3 difference was not due to a differential distribution of high- and low-risk choices or to differential effort (indexed by RT). Also the P3 was not indexing the greatest potential per-choice reward because, if it was then it would have been larger to the high-risk deck for all participants. Note also that the P3 window (300 – 450 ms) was well before the behavioral choice (nearly 700 ms), thus the P3 here reflects pre-response processing. The P3 here may reflect risk evaluation; if P3 amplitude reflects expectation violation (Donchin & Coles, 1988) then it would be larger when participants were making a decision that violated their optimal choice model. The high impulsives, with an immediate reward bias, would choose the high-risk card by default, resulting in a small P3 when their choice (high-risk) was consistent with their model (immediate reward is best). The low impulsive participants, in

contrast, had the largest P3 when making that same high-risk choice, suggesting that risky choice violated their context model (long-term outcome is best). Partial support for this interpretation comes from Yeung and Sanfey's (2004) report that when participants received feedback for alternative choices the P3 was larger if the alternative choice would have resulted in a better outcome than the participants' choice. In the current study the high and low impulsives may have different cognitive models of which choice would yield the 'better' outcome: the low-risk option for the high impulsives, the high-risk for the low impulsives.

The response ERN was larger following high-risk choice. Since the ERN reflects action evaluation, with a larger ERN associated with more negative evaluation (Bush, Luu, & Posner, 2000; Gehring & Willoughby, 2002), this indicates that participants evaluated the high-risk choice as negative. There was a Group × Choice trend indicating that this risky choice ERN was only present in the low impulsives, suggesting that only the low impulsive individuals evaluated risky choice as negative. Hewig et al. (2007) showed that individuals who made more risky 'hits' in a blackjack-like game had smaller ERNs to those risky choices than more cautious individuals and interpreted this as showing that the risk-choosing individuals did not have a negative evaluation of their risky actions. Like those risk-choosing individuals, the impulsive individuals here may not evaluate their risky choices as negative.

The anterior N1 to outcome feedback was smaller in the impulsive group. The anterior N1 is associated with attention (Vogel & Luck, 2000), so this effect suggests that the high impulsives paid less attention to choice outcome information. Houston & Stanford (2001) reported larger N1s in impulsivity indicating enhanced attention orienting. In the current study the feedback carried information, suggesting that the differences between the results may be related to the information content of the stimulus. Since the current stimulus contained choice outcome information, this is broadly consistent with the idea that impulsive individuals are not engaged by information about the consequences of their decisions.

The P3 to the feedback was largest to win, next largest to lose, and smallest to neutral feedback. Prior studies have shown that the P3 is larger to stimuli with motivational relevance (Begleiter et al., 1983) and is sensitive to reward, with greater amplitude to large compared to small (or no) reward (Ramsey & Finn, 1997; Yeung & Sanfey, 2004), and when a reward is larger then expected (Martin & Potts, 2004). In addition, the P3 is sensitive to positive motivation, being larger to positive compared to negative feedback (Johnson & Donchin, 1985). The current result is consistent with the P3 being sensitive to both reward and to motivational value (Begleiter et al., 1983; Ramsey & Finn, 1997; Yeung & Sanfey, 2004), largest to feedback signaling an outcome that was both relevant and rewarding (win), next largest to motivationally relevant but not rewarding (loss), and smallest to feedback signaling the least motivational value (neutral). In contrast with the choice option P3, the feedback P3 did not vary by impulsivity. Thus while impulsivity impacts assessment of potential rewards of a choice during option evaluation, impulsivity does not appear to impact assessment of the actually delivered motivational value during late-stage outcome evaluation.

There were trends for Group × Choice interactions in both the frontal and posterior N1s to the card presentation and they appeared larger in the high impulsive participants when choosing from the risky deck (see Figure 1). Like the anterior N1, the posterior N1s is associated with attention allocation (Mangun, 1995;Näätänen, 1992), so this may indicate that when the high impulsives paid more attention to the options they were more likely to make the riskier choice, implying either that risky choice is a controlled process, since cognitive resources were directed to the options, or that attention is automatically drawn to the risky option.

There were no significant effects on the FRN. Since prior studies have found an FRN to negative outcome feedback (Gehring & Willoughby, 2002), an FRN to losses might be expected.

However, in most designs used to elicit an FRN the choice option display contains no information about potential outcomes while in the current design the different card backs contained potential outcome information. Since the error effect is elicited by the information-carrying event (Nieuwenhuis et al., 2004), this option information may have reduced the FRN. Additionally, the feedback was tightly temporally coupled with the response in the current design, occurring within 25 – 40 ms of the response, which may have reduced the FRN.

There were no behavioral differences, indicating either that the impulsivity difference between the groups was small or that the BIS-11 is not a good predictor of risky choice. However, since the groups did not behave differentially, the ERP differences were not due to performance differences on the task but rather due to differences in the participants. The overall mean BIS-11 score for the low group was 55.1 and for the high group was 70.8, similar to mean scores found among other college populations (64.94; Patton et al., 1995). The group difference, while not large, puts the high group in the range of clinical populations such as substance abuse patients (69) and general psychiatric patients (70), but lower than prison inmates (76; Patton et al., 1995).

These results indicate that impulsive individuals are more engaged by the potential rewards available in the choice options than with evaluating the consequences of their decisions. The larger choice option-related P3 in the high impulsive individuals when making a low-risk choice indicates a short-term reward bias while evaluating the choice options. The smaller N1 to the outcome feedback in those impulsive individuals indicates less attention to outcome feedback and the trend for a smaller ERN after making a high-risk choice in the impulsive individuals suggests reduced sensitivity to the negative consequences of risky choices. The equivalent feedback P3 in the groups indicates that both groups were equally engaged in the final assessment of the outcome of their choices. These results suggest that risky choice in impulsive individuals may be due to differences in the way their brain evaluates choices, placing greater emphasis on the potential rewards available in the options and less emphasis on the outcomes associated with risky decisions.

Acknowledgments

This research was supported by the National Institute of Drug Abuse RO1-DA14073 & R21-DA023273 (Potts) & F31-DA018498 (Martin).

References

Ainslie G. Specious reward: A behavioral theory of impulsiveness and impulse control. Psychological Bulletin 1975;82(4):463–496. [PubMed: 1099599]

Barratt ES, Stanford MS, Kent TA, Alan F. Neuropsychological and cognitive psychophysiological substrates of impulsive aggression. Biological Psychiatry 1997;41(10):1045–1061. [PubMed: 9129785]

Bechara A, Damasio AR, Damasio H, Anderson SW. Insensitivity to future consequences following damage to human prefrontal cortex. Cognition 1994;50(13):7–15. [PubMed: 8039375]

Bechara A, Dolan S, Hindes A. Decision-making and addiction (part II): Myopia for the future or hypersensitivity to reward? Neuropsychologia 2002;40(10):1690–1705. [PubMed: 11992657]

Begleiter H, Porjesz B, Chou Cl, Aunon JI. P3 and stimulus incentive value. Psychophysiology 1983;20 (1):95–101. [PubMed: 6828618]

Bush G, Luu P, Posner MI. Cognitive and emotional influences in anterior cingulate cortex. Trends in Cognitive Sciences 2000;4(6):215–222. [PubMed: 10827444]

Corr PJ. J. A. Gray's reinforcement sensitivity theory: Tests of the joint subsystems hypothesis of anxiety and impulsivity. Personality and Individual Differences 2002;33(4):511–532.

Courchesne E, Hillyard SA, Galambos R. Stimulus novelty, task relevance and the visual evoked potential in man. Electroencephalography & Clinical Neurophysiology 1975;39(2):131–143. [PubMed: 50210]

Dawe S, Gullo MJ, Loxton NJ. Reward drive and rash impulsiveness as dimensions of impulsivity: Implications for substance misuse. Addictive Behaviors. Special Issue: Crossing Boundaries: Implications of Advances in Basic Sciences for the Management of Addiction 2004;29(7):1389–1405.

de Bruijn ERA, Grootens KP, Verkes RJ, Buchholz V, Hummelen JW, Hulstijn W. Neural correlates of impulsive responding in borderline personality disorder: ERP evidence for reduced action monitoring. Journal of Psychiatric Research 2005;40(5):428–437. [PubMed: 16257009]

Dehaene S, Posner MI, Tucker DM. Localization of a neural system for error detection and compensation. Psychological Science 1994;5(5):303–305.

Dikman ZV, Allen JJ. Error monitoring during reward and avoidance learning in high- and low-socialized individuals. Psychophysiology 2000;37(1):43–54. [PubMed: 10705766]

Dom G, De Wildea B, Hulstijnb W, Sabbeb B. Dimensions of impulsive behaviour in abstinent alcoholics. Personality and Individual Differences 2007;42(3):465–467.

Donchin E, Coles MG. Is the P300 component a manifestation of context updating? Behavioral & Brain Sciences 1988;11(3):357–427.

Gehring WJ, Fencsik DE. Functions of the medial frontal cortex in the processing of conflict and errors. Journal of Neuroscience 2001;21(23):9430–9437. [PubMed: 11717376]

Gehring WJ, Goss B, Coles MG, Meyer DE, Donchin E. A neural system for error detection and compensation. Psychological Science 1993;4(6):385–390.

Gehring WJ, Willoughby AR. The medial frontal cortex and the rapid processing of monetary gains and losses. Science 2002;295(5563):2279–2282. [PubMed: 11910116]

Gerstle J, Mathias C, Stanford M. Auditory P300 and self-reported impulsive aggression. Prog Neuropsychopharmacol Biol Psychiatry 1998;22(4):575–583. [PubMed: 9682274]

Gray, JA. The Neuropsychology of Anxiety: An Inquiry into the Functions of the Septo-Hippocampal System. New York: Oxford; 1982.

Gray, JA. The neuropsychology of emotion and personality. In: Stahl, SM.; Iversen, SD.; Goodman, EC., editors. Cognitive neurochemistry. 1987. p. 171-190.

Hall JR, Bernat EM, Patrick CJ. Externalizing Psychopathology and the Error-Related Negativity. Psychological Science 2007;18(4):326–333. [PubMed: 17470258]

Harmon-Jones E, Barratt ES, Wigg C. Impulsiveness, aggression, reading, and the P300 of the event-related potential. Personality & Individual Differences 1997;22(4):439–445.

Hewig J, Trippe R, Hecht H, Coles MGH, Holroyd CB, Miltner WHR. Decision-Making in Blackjack: An Electrophysiological Analysis. Cereb Cortex 2007;17(4):865–877. [PubMed: 16723407]

Holroyd CB, Coles MG. The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. Psychological Review 2002;109(4):679–709. [PubMed: 12374324]

Holroyd CB, Larsen JT, Cohen JD. Context dependence of the event-related brain potential associated with reward and punishment. Psychophysiology 2004;41(2):245–253. [PubMed: 15032989]

Houston RJ, Stanford MS. Mid-latency evoked potentials in self-reported impulsive aggression. International Journal of Psychophysiology 2001;40(1):1–15. [PubMed: 11166104]

Johnson R, Donchin E. Second thoughts: Multiple P300s elicited by a single stimulus. Psychophysiology 1985;22(2):182–194. [PubMed: 3991845]

Mangun GR. Neural mechanisms of visual selective attention. Psychophysiology 1995;32:4–18. [PubMed: 7878167]

Martin LE, Potts GF. Reward sensitivity in impulsivity. Neuroreport 2004;15(9):1519–1522. [PubMed: 15194887]

Moeller FG, Barratt ES, Dougherty DM, Schmitz JM, Swann AC. Psychiatric aspects of impulsivity. American Journal of Psychiatry 2001;158(11):1783–1793. [PubMed: 11691682]

Moeller FG, Barratt ES, Fischer CJ, Dougherty DM, Reilly EL, Mathias CW, et al. P300 Event-Related Potential Amplitude and Impulsivity in Cocaine-Dependent Subjects. Neuropsychobiology 2004;50 (2):167–173. [PubMed: 15292673]

Näätänen, R. Attention and Brain Function. Hillsdale, New Jersey: Erlbaum; 1992.

Nieuwenhuis S, Yeung N, Holroyd CB, Schurger A, Cohen JD. Sensitivity of Electrophysiological Activity from Medial Frontal Cortex to Utilitarian and Performance Feedback. Cerebral Cortex 2004;14(7):741–747. [PubMed: 15054053]

Pailing PE, Segalowitz SJ, Dywan J, Davies PL. Error negativity and response control. Psychophysiology 2002;39(2):198–206. [PubMed: 12212669]

Patton JH, Stanford MS, Barratt ES. Factor structure of the Barratt Impulsiveness Scale. Journal of Clinical Psychology 1995;51(6):768–774. [PubMed: 8778124]

Polich J, Herbst KL. P300 as a clinical assay: Rationale, evaluation and findings. International Journal of Psychophysiology 2000;38(1):3–19. [PubMed: 11027791]

Potts GF, George MRM, Martin LE, Barratt ES. Reduced punishment sensitivity in neural systems of behavior monitoring in impulsive individuals. Neuroscience Letters 2006;397(12):130–134. [PubMed: 16378683]

Ramsey SE, Finn PR. P300 from men with a family history of alcoholism under different incentive conditions. Journal of Studies on Alcohol 1997;58(6):606–616. [PubMed: 9391920]

Scheffers MK, Coles MGH, Bernstein P, Gehring WJ, Donchin E. Event-related brain potentials and error-related processing: An analysis of incorrect responses to go and no-go stimuli. Psychophysiology 1996;33(1):42–53. [PubMed: 8570794]

Tarkka IM, Stokic DS. Source localization of P300 from oddball, single stimulus, and omitted-stimulus paradigms. Brain Topography 1998;11(2):141–151. [PubMed: 9880172]

Van Veen V, Carter CS. The anterior cingulate as a conflict monitor: fMRI and ERP studies. Physiology & Behavior. Special Issue: The Pittsburgh special issue 2002;77(45):477–482.

Vogel EK, Luck SJ. The visual N1 component as an index of a discrimination process. Psychophysiology 2000;37:190–203. [PubMed: 10731769]

Yeung N, Sanfey AG. Independent Coding of Reward Magnitude and Valence in the Human Brain. J Neurosci 2004;24(28):6258–6264. [PubMed: 15254080]

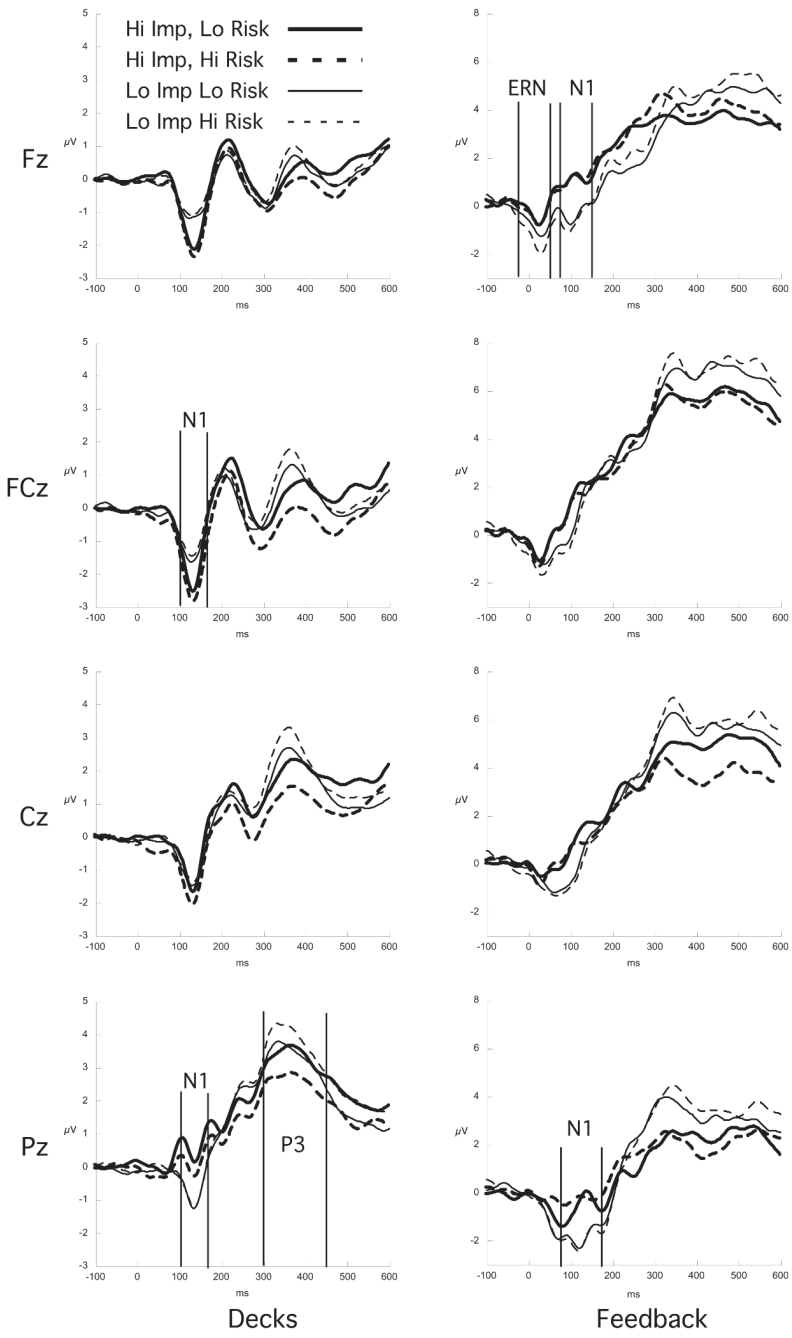

Figure 1.

Grand average waveforms to choice option (Cards, left column) and response and outcome feedback (right column) from the midline electrodes corresponding to Fz, FCz, Cz, and Pz showing data from the high impulsive (thick lines) and low impulsive (thin lines) when making high-risk (dashed lines) and low-risk (solid lines) choices. The analysis windows are shown on the electrodes at which the analysis was performed.

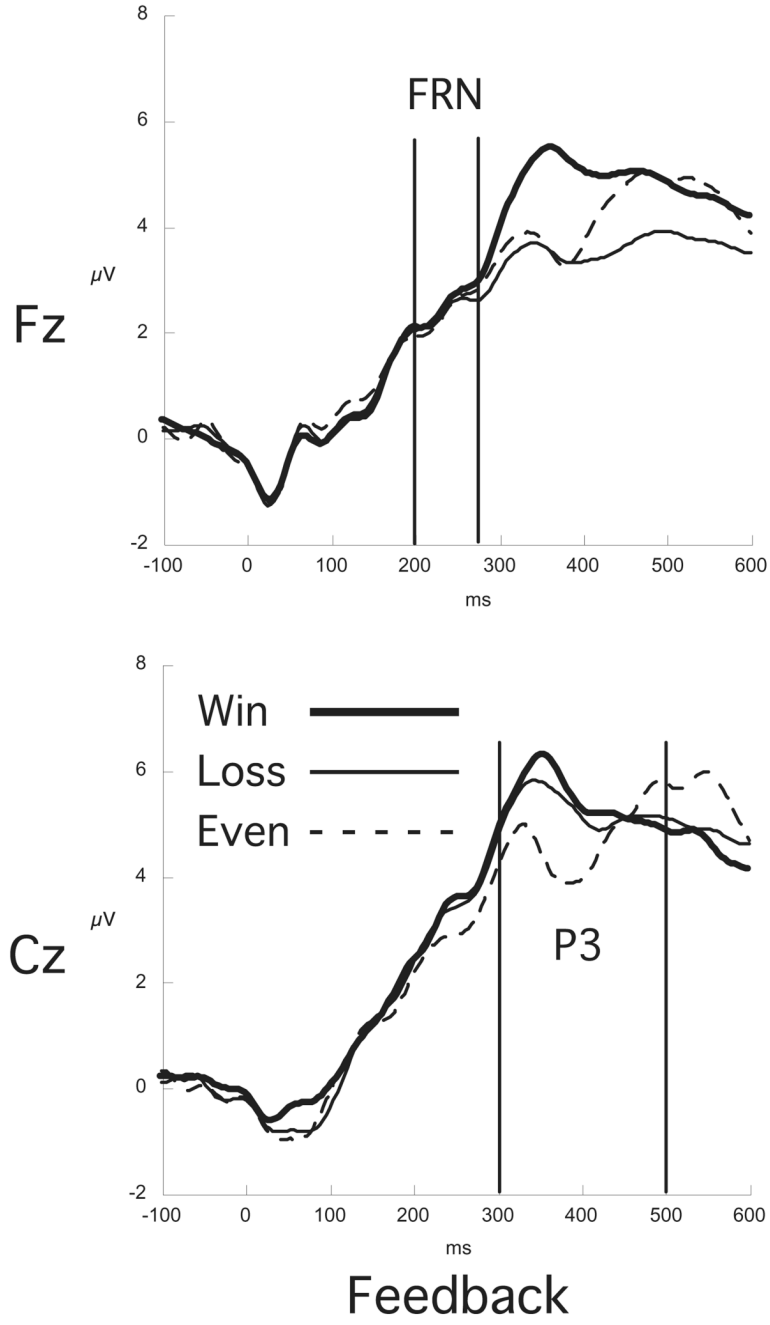

Figure 2.
Response/feedback waveforms from Fz and Cz separated by outcome, averaged across choice and group (since there were no effects of choice or group) showing the FRN and P3 analysis windows.