International Journal of Psychophysiology 151 (2020) 1–6

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Brief report on the relationship between temporal discount rate and error related negativity for immediate versus future choice options☆

Andrea L. Patalano*, Sydney L. Lolli, Charles A. Sanislow*

Wesleyan University, USA

ARTICLE INFO

Keywords:
Temporal discounting
ERN
Decision making

ABSTRACT

It is well documented that individuals vary in their economic patience – their willingness to choose delayed larger rewards (e.g., $100 in a month) over immediate smaller rewards (e.g., $25 now) – and that high levels of impatience, or *temporal discounting*, can be behaviorally problematic. Using event-related potential (ERP) method, we investigated error monitoring, as indexed by the error related negativity (ERN) component, as a function of discounting behavior. This work builds on prior work on risky decision making that revealed that individuals have greater ERNs for trials in which they select a risky option over a certain one (Yu and Zhou 2009), especially individuals not inclined towards risk taking (Martin and Potts 2009). In the present study, participants completed a temporal discounting task (choosing between a fixed immediate reward versus a future reward that varied across trials) while electroencephalogram (EEG) activity was recorded. We found an asymmetric relationship between discounting and the ERN: the greater an individual's overall rate of discounting, the greater the ERN component of the ERP waveform on trials where the future reward was selected, but not on trials in which the immediate reward was selected. The ERN may reflect an early warning signal alerting high discounters to potential negative consequences of future-oriented choices.

1. Introduction

People are often faced with choices between immediate and future benefits and costs, referred to as intertemporal decisions (Frederick et al., 2002). In a common experimental paradigm, one might be offered choices between "$10 immediately versus $20 in a week" or "$15 in a week versus $18 in a month." In these types of decisions, the subjective value of a reward (or a loss, but the focus here is on rewards) decreases as a function of delay in its receipt. This phenomenon is known as *temporal discounting*. One striking characteristic of human temporal decision making is the overwhelming preference that people show for immediate rewards (O'Donoghue and Rabin, 1999). Discounting can be further quantified in terms of the rate at which subjective value declines over time, with some individuals showing a faster decline in the value of future rewards as a function of time than other individuals. Discounting research was developed in a seminal work by Ainslie (1975), and remains a key area of decision research (see Urminsky and Zauberman, 2016, for recent review).

While some discounting is considered rational from an economic perspective (Loewenstein and Prelec, 1992; Samuelson, 1937), higher rates of discounting, including a greater preference for immediate rewards, have been associated with a wide range of measures of well-being and life success including poorer academic performance (Kirby et al., 2005; Reimers et al., 2009), psychopathology (e.g., Pinto et al., 2014; Pulcu et al., 2014), deficits in social functioning (Hirsh et al., 2008), poor economic choices (Chabris et al., 2008; Meier and Sprenger, 2010), and less healthy behaviors (e.g., Chapman et al., 2001; MacKillop et al., 2011). Consistent with these negative outcomes, greater discounting is often referred to as *impatient* or *impulsive*. High discounting has implications for psychological conditions such as depression and anxiety, and for pathological personality traits such as impulsiveness (e.g., Hartley and Phelps, 2012; Xia et al., 2017).

In the present work, we investigated the electrophysiological correlates of the relationship between economic impatience and choice using event-related potential (ERP) methodology with a focus on the ERP component known as error related negativity (ERN). The ERN, a frontocentral negative deflection ~50 ms after task response, reliably occurs after an objective error has been made (Falkenstein et al., 1990; Gehring et al., 1990). A common example of an ERN-eliciting task is Eriksen's Flanker task, where one quickly reports the central target amidst a string of distractors (e.g., the correct response to "HHSHH", is "S"; Gehring et al., 1990). The ERN has generally been thought to

☆ This work benefited from NSF DRL-1561214 to A.L.P.

* Corresponding authors at: Department of Psychology, Wesleyan University, 207 High Street, Middletown, CT 06459, USA.
E-mail addresses: apatalano@wesleyan.edu (A.L. Patalano), slolli@wesleyan.edu (S.L. Lolli), csanislow@wesleyan.edu (C.A. Sanislow).

https://doi.org/10.1016/j.ijpsycho.2020.02.006
Received 30 March 2019; Received in revised form 1 February 2020; Accepted 9 February 2020
Available online 11 February 2020
0167-8760/

reflect error detection (Scheffers et al., 1996) or, alternatively, response conflict between competing response options (Gehring and Fencsik, 2001; Botvinick et al., 2004), and found to emanate from the anterior cingulate cortex (see Gehring et al., 2012). The ERN, reflecting a process of evaluating and signaling the need for cognitive control, is believed to prompt changes in attentional focus and other strategic adjustments associated with performance (Shackman et al., 2011). The magnitude of the ERN has also been shown to be related to motivational and individual-difference measures, sometimes in the absence of any differences in task behavior. For example, it is smaller for individuals low in conscientiousness (in tasks that reward accurate performance; Pailing and Segalowitz, 2004), high in risk propensity (including both risk taking and sensation seeking; Santesso and Segalowitz, 2009), and high in ruminative thinking (Tanovic et al., 2017), and it is larger among individuals high in perfectionism (Perrone-McGovern et al., 2017).

The ERN was initially observed in objectively defined tasks, and it has been codified in a large body of research involving such tasks. However, there has been growing interest in whether or not ERNs are also generated in subjectively defined tasks (Martin and Potts, 2009; Yu and Zhou, 2009) and, if so, under what conditions. In the domain of temporal discounting, we know of no ERN-based studies, but findings from functional magnetic resonance imaging (fMRI) studies provide important clues. Cognitive control areas of the brain have been found to be more active when a future-reward option is selected over an immediate one, but not the reverse (McClure, Laibson, Loewenstein, & Cohen, 2004), or when a choice is made that goes against one's dominant preference (i.e., dominant meaning the type of choice one makes most frequently; Manning et al., 2014). Relevant ERP studies in the related domain of risky decision making (e.g., "Would you prefer $100 for certain vs. 50% chance of $300?") reveal an ERN when a risky option is selected over a certain one, but not the reverse (Yu and Zhou, 2009), especially for individuals who are not impulsive (Martin and Potts, 2009). These studies are intriguing in that they suggest that some subjective decisions might elicit error signals because of specific choice features (e.g., risk, delay) or because a choice violates one's dominant preference, rather than because the correct response is apparent from the stimulus or from any accompanying feedback. In terms of behavioral function, such a pattern would be consistent with a need to signal cognitive control in order to take corrective future action.

Related work on the ERP signal known as feedback related negativity (FRN) may also offer insight into the ERN in temporal discounting. The FRN, rather than being time-locked to one's response, occurs approximately 250–350 ms following a feedback stimulus. Miltner and colleagues (Miltner et al., 1997) found that error-feedback stimuli (e.g., a tone indicating whether a response is correct) elicit activity that is similar to the ERN in scalp location and likely neural generators. In a risky decision making task, Gehring and Willoughby (2002) had participants make a choice between two dollar amounts. Participants then received feedback regarding gain or loss outcome for each of the dollar amounts. An FRN was present when the selected dollar amount was associated with a loss rather than a gain, even when the alternative choice would have resulted in a greater loss, suggesting that the FRN might reflect the motivational impact of the outcome information. However, in later work using a time-estimation task, the FRN was present after infrequently occurring positive of negative feedback, but not after intermediate feedback (Ferdinand et al., 2012), raising the possibility that the signal is related to the unexpectedness of an event rather than its valence.

Also relevant, reward positivity (RewP) is based on the same ERP component as the FRN but reflects an interpretation of the signal in terms of its responsiveness to positive feedback rather than to errors (see Holroyd and Umemoto, 2016; Proudfit, 2015). RewP is described as a neural index of the encoding of reward values (Lukie et al., 2014). In temporal discounting tasks, RewP has been shown to be larger for immediate relative to future rewards, particularly for individuals with high discounting rates (Cherniawsky and Holroyd, 2013; Xia et al., 2017). In these studies, unlike those focused on the ERN, brain activity is typically measured in response to presentation of each choice option rather than in response to one's selection of a preference among multiple options. According to reinforcement learning theory (Holroyd and Coles, 2002), before a system establishes a relationship between stimuli, responses, and rewards, responses are evaluated using external feedback. However, once learning has occurred, response errors can be detected directly from the response, without need for feedback. By this account, an ERN might be predicted to arise whenever the outcome of the selected choice is less desirable than what is expected based on past learning.

For the present study, we were interested in how the ERN might be related to intertemporal decision making. We considered three possibilities. One possibility, building on Manning et al. (2014), is that the ERN is generated when an individual makes a non-dominant choice. This would mean that, for trials in which the future reward is chosen, the ERN should be greater for individuals who typically choose the immediate-reward option (i.e., have high economic impatience). And, for trials on which the immediate reward is chosen, the ERN should be greater for individuals who typically choose future rewards (have high patience). An alternative possibility, drawing on Yu and Zhou (2009), is that options involving delay might generally signal the need for cognitive control, as there are negative consequences associated with reward delay, including the risk that the reward will not be received or that the reward will be needed before it is received. If this is the case, there should be an ERN on trials when a future-reward option is selected but not when an immediate-reward is selected, especially for impatient individuals. Finally, a third possibility is that the ERN does not emerge in temporal decision making contexts in which there is competition between two responses but no objectively defined correct response. We considered these possibilities here. We did not generate specific predictions based on existing FRN and RewP studies but, in the discussion, we will consider findings with regard to this literature as well.

Data were collected during an experimental session in which laboratory participants performed a temporal discounting task that consisted of choices between a hypothetical $10 today versus a reward in the future, with the amount of delay and future reward varying by trial. Both behavioral and EEG data were collected. For each participant, an index of economic impatience (k) was computed from the behavioral data, using a standard hyperbolic discounting function. Details about the participants, the discounting task, and the index of economic impatience are described here in complete detail. Two sets of analyses were planned using these data. One set of analyses focused on the stimulus-locked P3 waveform deflection (an indicator of motivated attention to the stimuli), for research goals unrelated to the present investigation, and is reported in Patalano et al. (2018). Here, in the second set of planned analyses, we report on the ERN waveform deflection relative to choice behavior. Specifically, the goal of the present work was to evaluate the relationship between an individual's overall discount rate and the presence/magnitude of the ERN for trials grouped based on whether the immediate versus the future reward response was chosen.

2. Method

2.1. Participants

Data were analyzed from 84 college students (34 men and 50 women; 7 left-handed), the same as in Patalano et al. (2018).[1] An

[1] In addition to the discounting task, all participants completed other cognitive tasks and scales unrelated to the present work. While a 5-min gratitude mood induction (write about an experience of gratitude) or control (write about

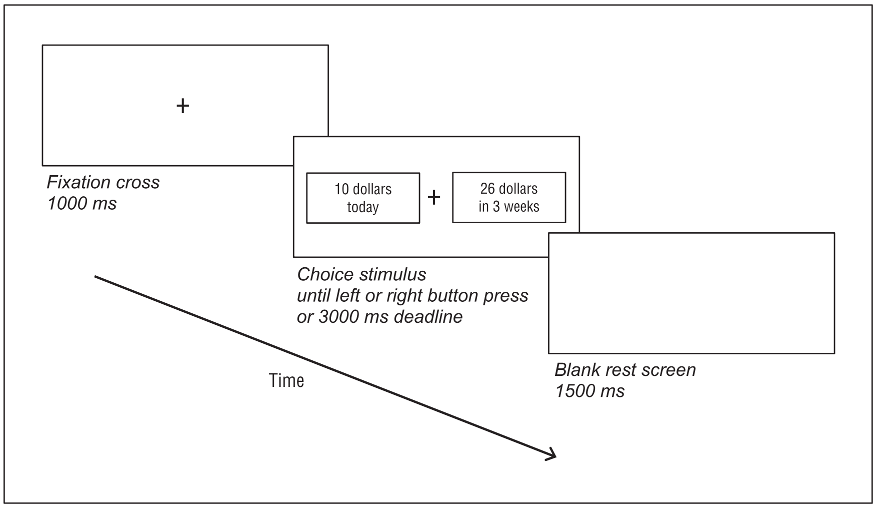

Fig. 1. Example of a delay discounting choice in which one must select a preference between the immediate smaller reward (at left) and the future larger reward (at right). The immediate reward remained constant across trials while the future reward varied across trials in dollar value and in length of delay period.

additional 24 participants completed the temporal discounting task but were excluded from analyses due to EEG noise or to an insufficient number of trials of one of the response types (< 20 immediate-reward choice or future-reward choice trials) after artifact removal. The a priori cutoff of 20-trials per response type was set to obtain an acceptable signal to noise ratio was based on prior established practices (see Luck, 2014; Woodman, 2010). A power analysis indicated $N = 84$ to be the sample size needed to identify a moderately small correlation ($r = 0.30$) with a power of 0.80. The original data collection and the present analyses were approved by the Wesleyan University IRB, and all participants gave their informed consent prior to their inclusion in the study.

2.2. Temporal discounting task

Each participant was presented with 120 unique choices, which were then repeated in a different order for a total of 240 trials (task procedure adapted from Li et al., 2012; McClure et al., 2007; Oswald and Sailer, 2013). Each participant saw the trials on a computer screen in one of four randomized orders. All of the choices were between receiving $10 today (on the left side of the display; see Fig. 1) and a larger amount of money in the future (on the right side of the display; all rewards were hypothetical). The magnitude of the future reward varied over 12 amounts: $11, $12, $13, $14, $15, $16, $25, $26, $27, $28, $29, and $30. The delay of the future reward varied over 10 levels: 1, 2, 3, 4, 5, 12, 13, 14, 15, and 16 weeks (12 amounts × 10 delay levels = 120 trials). Magnitude and delay values were selected so that the future reward option would be chosen approximately half of the time on average across participants (see Oswald and Sailer, 2013).

As shown in Fig. 1, each trial consisted of a 1000 ms fixation cross followed by presentation of a choice stimulus. A 3000 ms response window started at the same time as the presentation of the stimulus. As soon as a response was given (or at the end of 3000 ms if this came first), the stimulus was replaced with a blank rest screen for 1500 ms before the next trial began. Participants were instructed that they could choose the immediate choice with their left index finger, which was to be placed over the leftmost button on the response box, or the future choice with their right index finger, which was to be placed over the rightmost button. Both buttons were black, and all other buttons were covered with white paper. Participants were asked to focus on the fixation cross to avoid excessive eye movement, and were given a 2-min rest break after each set of 60 trials. Before performing the primary task, 12 practice trials were given that used smaller dollar values (e.g., $1 today or $2 in one week). Participants had the opportunity to ask questions and, if needed, to repeat the practice trials.

2.3. EEG recording and data processing

EEG recordings were collected using a 64-channel cap (Cortech Solutions, Wilmington, NC), and the BioSemi ActiveTwo system (BioSemi, Amsterdam, Netherlands), with electrode sites arranged based on the 10–20 System. Discounting task trials were segmented into response-locked epochs from 400 ms before to 1000 ms after the motor response. The Gratton and Coles algorithm (Gratton et al., 1983) was used to perform ocular corrections. Baseline correction was performed using the period 400 to 200 ms prior to motor response (see Riesel et al., 2013). Following Patalano et al. (2018), artifacts were detected and rejected through automatic inspection, with segments falling outside of these parameters automatically marked for rejection: a maximal voltage step of 75 μV/ms, a maximal difference of 175 μV between the highest and lowest points in an interval of 400 ms, and activity below 0.5 μV for 100 ms (3% of trials were rejected). Individual channel mode was used.

3. Results

3.1. Choice behavior

Participants gave a response to an average of 238 out of 240 trials ($SD = 2.5$, range = 223–240). Across repeated stimuli, participants gave the same response a mean of $M = 86\%$ of the time ($SD = 8$, range = 50–98, only 4 means were < 70), indicating high reliability. Immediate-reward choices were given $M = 150$ times ($SD = 47$, range = 29–207) and future-reward choices were given 88 times ($SD = 47$, range = 33–211). The average percentage of immediate-reward choices was 63% ($SD = 20$, range = 12–86). A hyperbolic discount factor (k) was estimated using a modified version of DeSteno et al.'s (2014) Matlab program. This estimation process assumes a hyperbolic discount function, where dollar value is multiplied by $1/(1 + k * \text{days of delay})$ to predict discounted value, a function that well

(*footnote continued*)
a typical day) task was administered at the start of the study session, the between-subjects manipulation had no effect on any behavioral or ERP outcome measures here ($Fs < 1.20$, $ps > .250$ for main effect of this manipulation as well as interaction with response type and k). Given that the mood induction was not related to the goals of the present work, it is not considered here (see Patalano et al., 2018, for session details).

describes human behavior (Mazur, 1987; Myerson and Green, 1995). Values of k can range from 0 to infinity, where a number closer to 0 indicates less discounting. Here, the mean k was 0.62 ($SD = 0.39$, range = 0.002–1.57) and was highly correlated with percentage of immediate choices made ($r = 0.90$). There were no differences in choices made in the first versus the second half of trials, with the exception that the total number of trials completed was slightly higher in the second half than in the first ($M = 119.6$ vs. 119.0 respectively; $t(83) = -3.16$, $SE = 0.20$, $p = .002$).[2]

3.2. Response times

There were no reliable difference in RTs for immediate-reward ($M = 1056$ ms, $SD = 234$, range = 542–1641) relative to future-reward choices ($M = 1080$ ms, $SD = 227$, range = 459–1624; $t(83) = -1.33$, $SE = 18$, $p = .187$). Average RT was not correlated with k, $r(82) = -0.09$, $p = .434$. However, k was correlated negatively with response time for immediate-reward choice trials ($r(82) = -0.27$, $p = .012$) and positively with response time for future-reward choice trials ($r(82) = 0.29$, $p = .009$). In other words, the more one discounted, the more quickly immediate-reward choices and the less quickly future-reward choices were made.

3.3. ERN analyses

Error-related negativity (ERN) was characterized as the mean amplitude of the waveform in the window from 0 to 100 ms after motor response occurred at the average of frontocentral electrodes FCz and Cz (see Fig. 2). This pair of electrodes was selected a priori based on common use in the past (e.g., Nash et al., 2014). As predicted, there were reliable differences in ERN amplitude between immediate-reward response trials ($M = 0.72$ μV, $SD = 3.92$, range = −10.46–14.18) and future-reward response trials ($M = -0.20$ μV, $SD = 3.75$, range = −11.62-7.27; $t(83) = 2.26$, $p = .026$), and the mean amplitude was negative only for future-reward response trials, warranting separate consideration of the two types of trials. Correlational analyses revealed that ERN amplitude was predicted by k, but only for trials on which the future-reward response was given. In other words, the more often one chose the immediate-reward response across all trials, the larger the ERN on the trials in which the individual chose the future-reward response ($r(82) = -0.28$, $p = .010$); there was no similar correlation for immediate-reward responses ($r(82) = 0.01$, $p = .962$). The pattern of correlations remained the same after controlling for response times for future reward choices ($r_p(81) = -0.23$, $p = .038$) and immediate-reward choices ($r_p(81) = -0.08$, $p = .475$), so it is unlikely that it arose from higher discounters being generally slower to give future-reward responses.

To further clarify the findings, we conducted a repeated-measures ANOVA with response type as a within-subjects categorical measure and k as a continuous measure. In addition to a main effect of response type ($F(1,82) = 5.20$, $MSE = 6.40$, $p = .025$, $\eta^2 = 0.05$), there was an interaction between response type and k ($F(1,82) = 7.44$, $MSE = 6.40$, $p = .008$, $\eta^2 = 0.08$), but no effect of k alone ($F(1,82) = 1.98$, $MSE = 22.23$, $p = .164$). As illustrated in Fig. 2 (with groups based on a median split on k for purposes of illustration), high discounters had more negative ERNs for trials in which they gave a future-reward response than for those trials in which they gave an immediate-reward response. In contrast, for low discounters, there was no difference in ERN between immediate- and future-reward trials. In sum, consistent with one of the possibilities initially proposed, the ERN was observed here only following future-reward responses (rather than both immediate- and future-reward responses), and ERN amplitude was greater the fewer future-reward responses one made.

4. Discussion

An ERN was observed after future-reward responses but not after immediate-reward responses. Further, across trials on which the future-reward option was chosen, ERN amplitude was correlated with discounting behavior (using k); the latter explained 6% of the variance in ERN amplitude. In categorical terms, an ERN was observed when individuals who generally chose the immediate-reward option chose the future-reward option. When these individuals chose the immediate-reward option, or when individuals who generally preferred the future-reward chose either option, no ERN was observed. This result echoes findings from studies of decision making under risk, in which selecting high-risk choice options has been associated with a greater ERN (Yu and Zhou, 2009), especially for individuals who generally prefer low-risk choice options (Martin and Potts, 2009). In risk contexts, outcome uncertainty (e.g., high risk) has been proposed to signal the riskiness of choices and the ERN has been thought to function as an early warning system that alerts the brain to prepare for potentially negative consequences associated with a risky action (Yu and Zhou, 2009). Delay of a reward can similarly be construed as involving uncertainty, in this case regarding whether the reward will actually be dispensed at the indicated future time. Individuals who find delay-related uncertainty aversive (at least as evidenced by their reduced willingness to choose such options) might have a heightened response following a future-reward choice. Taken together, present and past work suggests that the ERN might signal the need for heightened state of alertness in the context of uncertainty in subjective decision making contexts.

The findings can also be related quite straightforwardly to past work on temporal discounting and reward positivity. It has been shown that low discounters have a RewP that is of the same magnitude for immediate and future rewards, whereas high discounters have a larger RewP for immediate rewards (Cherniawsky and Holroyd, 2013). In other words, rather than undervaluing future rewards, high discounters appear to overvalue immediate rewards. For high discounters, the high reward value of the large immediate reward may serve as an expectation, leading to an error signal on trials on which the reward value of the chosen option is lower than expected, consistent with reinforcement learning theory (Holroyd and Coles, 2002). One might ask why, then, are future-reward options selected at all by high discounters? One possibility is that, on a particular trial, a large future-reward option might be preferable to a very small immediate-reward option, even if the resulting choice is less rewarding than what is expected based on the broader choice context. Low discounters would not show the same pattern because reward values for immediate- and future-choice options are similar for these individuals.

Earlier, we also considered the possibility that the ERN might occur with selection of one's non-dominant response option, whether the non-dominant response is the immediate-reward or the future-reward option. The findings here could be construed as partially consistent with this possibility. That is, we found that this was the case only for individuals whose dominant choice was the immediate-reward option. For these individuals, an ERN following future-reward responses might signal potential error based on response frequency, or might arise from response competition between a typically preferred option and a strong alternative. Why does the pattern not extend to individuals with a dominant preference for the future-reward option? One possibility is that these individuals (as evidenced in part by the fact that their default response is the future reward) do not have an affectively strong response to the immediate-reward option and thus generally experience less competition between response options. While the present finding fits more neatly with the possibility that the ERN reflects a response to uncertainty or a comparison to an unexpected outcome, this alternative

[2] We also ran all analyses in each of the following ways: using the natural log of k (to reduce skew); using an exponential discount function (see Berns et al., 2007, for discussion of both models); and excluding the 4 participants with low reliability scores. The findings remained the same in each case.

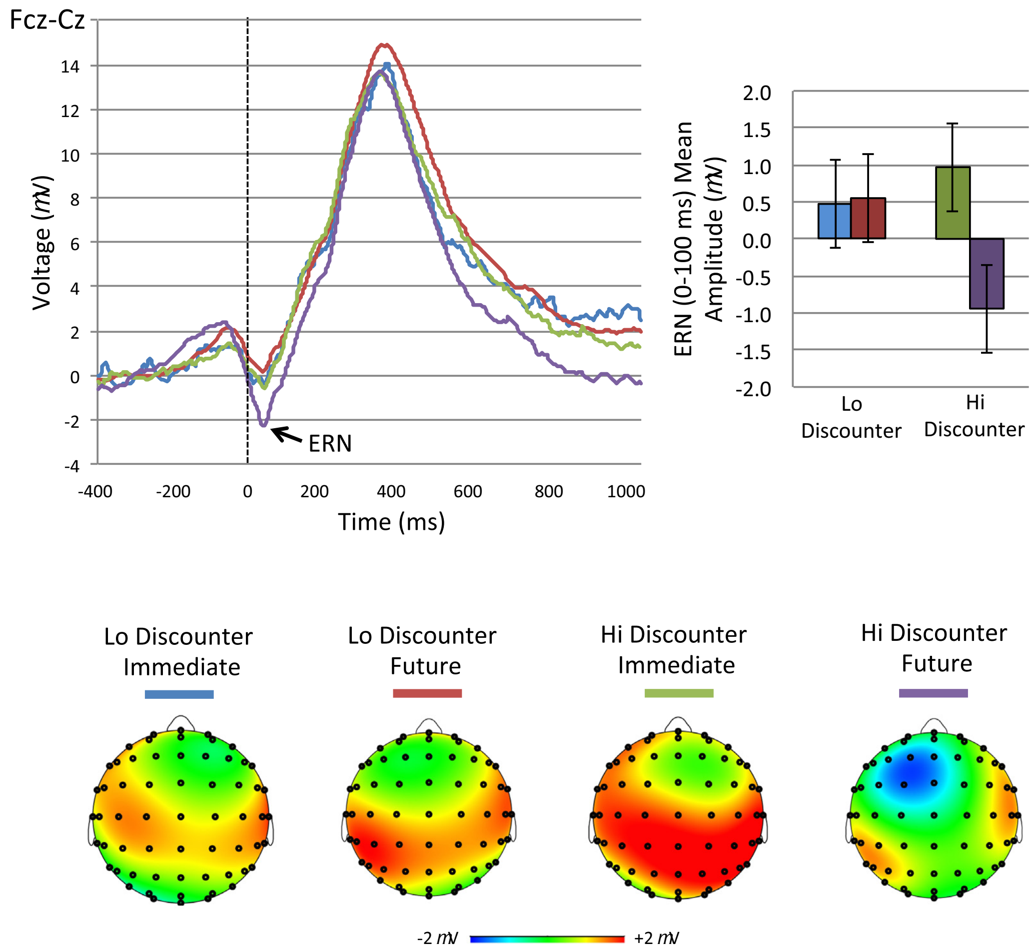

Fig. 2. (a) Response-locked average activity of electrodes Fcz-Cz by discount group (Lo vs. Hi Discounters by median split) and response type (Immediate vs. Future), (b) ERN mean amplitude in 0–100 ms time window after response, and (c) voltage maps for the same time window.

(that the ERN reflects a response to selection of the non-dominant alternative) presents an intriguing possibility.

We note three limitations of the study. First, one explanation of the findings that we cannot rule out is one based on response expectancy. It has been demonstrated that if a motor response made by one hand is more frequently required than one made by the other hand, the preparation of the most probable response will be favored, and there will be an ERN-like signal on trials in which the less probable response is made (Meckler et al., 2011). This occurs even when the unexpected response is objectively correct. It is possible then that an ERN-like signal would be produced when the non-preferred response was selected in the present study, although such an account cannot easily explain why the ERN was present for individuals who preferred the immediate-reward option but not for those who preferred the future-reward option. A second limitation is that we used hypothetical rather than real choices. We cannot conclude that the ERN observed here would also be present with real choices, although we suspect findings would be similar based on other work. For instance, there is evidence that behavioral discounting patterns are similar with real and hypothetical choices (e.g., Madden et al., 2004; Lagorio and Madden, 2005), and researchers have found similar patterns of brain activity (using fMRI) across methods (e.g., Bickel et al., 2009). A third limitation is that we used choice stimuli here in which the immediate reward was held constant and only the future reward varied across trials. Because we do not know how task structure impacts the findings, in future studies we plan to examine task variants in which immediate-choice reward values also (or instead) vary across trials.

The majority of studies of the ERN have been conducted using simple cognitive tasks, such as a modified version of the flanker task (Eriksen & Eriksen, 1974), where participants judge the direction of a center arrowhead placed among five arrowheads arranged horizontally (e.g.,Weinberg, Olvet, & Hajcak, 2010). In contrast, our decision task involved more elaborate cognitive processes and the ERN was derived from subjective errors in judgement. Thus, the modest magnitude of the ERN found in our study, relative to the magnitude of ERNs found in studies where an error versus response could be objectively discriminated from a correct response, is not surprising. Other studies that have examined ERN in relation to the commission of an error on a complex task have reported an ERN similar in magnitude to what we found (e.g., Yu and Zhou, 2009). Moreover, other researchers have demonstrated that tasks using stimuli with clearly discriminable features elicit an ERN greater in magnitude than those using stimuli that are more similar (Yeung and Sanfey, 2004). This is consistent with the consensus that ERN reflects a signal of cognitive control (Shackman et al., 2011). Further, the more elaborate component processes – beyond conflict detection – would be expected to be involved in cognitive control for subjectively preferred choice options (e.g., goal selection, updating, representation and maintenance, response selection, performance monitoring, as well as motivational and emotional factors associated with committing an error).

Interestingly, in objectively defined choice contexts, the ERN has also been associated with (low) degree of confidence that one's response is correct (Scheffers and Coles, 2000), a measure in some ways potentially similar to subjective choice evaluations. And, in studies of the feedback regarding choice outcome (e.g., whether or not a gamble leads to a reward), there is evidence that the FRN (feedback-related negativity) is modulated by features of the outcome besides whether the best choice was made (e.g., Johnston, 1979; Gehring and Willoughby 2002; Yeung and Sanfey, 2004). The present findings provide further evidence that the ERN is responsive to task characteristics besides objective error, and suggests promising possibilities for future research investigating the role of the ERN as a potential signal for cognitive control in subjective choice tasks involving more complex cognitive operations.

Declaration of competing interest

None.

References

Ainslie, G., 1975. Specious reward: a behavioral theory of impulsiveness and impulse control. Psychol. Bull. 82, 463–493.
Berns, G.S., Laibson, D., Loewenstein, G., 2007. Intertemporal choice—toward an integrative framework. Trends Cogn. Sci. 11, 482–488.
Bickel, W.K., Pitcock, J.A., Yi, R., Angtuaco, J.C., 2009. Congruence of BOLD responses across intertemporal choice conditions: fictive and real money gains and losses. J. Neurosci. 29, 8839–8846.
Botvinick, M.M., Cohen, J.D., Carter, C.S., 2004. Conflict monitoring and anterior cingulate cortex: an update. Trends Cogn. Sci. 8, 539–546.
Chabris, C.F., Laibson, D., Morris, C.L., Schuldt, J.P., Taubinsky, D., 2008. Individual laboratory-measured discount rates predict field behavior. J. Risk Uncertain. 37, 237–269.
Chapman, G.B., Brewer, N.T., Coups, E.J., Brownlee, S., Leventhal, H., Leventhal, E.A., 2001. Value for the future and preventive health behavior. J. Exp. Psychol. Appl. 7, 235–250.
Cherniawsky, A.S., Holroyd, C.B., 2013. High temporal discounters overvalue immediate rewards rather than undervalue future rewards: an event-related brain potential study. Cognitive, Affective, & Behavioral Neuroscience 13, 36–45.
DeSteno, D., Li, Y., Dickens, L., Lerner, J.S., 2014. Gratitude: a tool for reducing economic impatience. Psychol. Sci. 25, 1262–1267.
Eriksen, B.A., Eriksen, C.W., 1974. Effects of noise letters upon the identification of a target letter in a nonsearch task. Perception & Psychophys 16 (1), 143–149. https://doi.org/10.3758/BF03203267.
Falkenstein, M., Hohnsbein, J., Hoormann, J., Blanke, L., 1990. Effects of errors in choice reaction tasks on the ERP under focused and divided attention. Psychophysiological Brain Research 1, 192–195.
Ferdinand, N.K., Mecklinger, A., Kray, J., Gehring, W.J., 2012. The processing of unexpected positive response outcomes in the mediofrontal cortex. J. Neurosci. 32, 12087–12092.
Frederick, S., Loewenstein, G., O'Donoghue, T., 2002. Time discounting and time preference: a critical review. J. Econ. Lit. 40, 351–401.
Gehring, W.J., Fencsik, D.E., 2001. Functions of the medial frontal cortex in the processing of conflict and errors. J. Neurosci. 21, 9430–9437.
Gehring, W.J., Willoughby, A.R., 2002. The medial frontal cortex and the rapid processing of monetary gains and losses. Science 295, 2279–2282.
Gehring, W.J., Coles, M.G.H., Meyer, D.E., Donchin, E., 1990. The error-related negativity: an event-related brain potential accompanying errors. Psychophysiology 27, S34.
Gehring, W.J., Liu, Y., Orr, J.N., Carp, J., 2012. The error-related negativity (ERN/Ne). In: Luck, S.J., Kappenman, E. (Eds.), Oxford Handbook of Event-Related Potential Components. Oxford University Press, New York, pp. 231–291.
Gratton, G., Coles, M.G., Donchin, E., 1983. A new method for off-line removal of ocular artifact. Electroencephalogr. Clin. Neurophysiol. 55, 468–484.
Hartley, C.A., Phelps, E.A., 2012. Anxiety and decision-making. Biol. Psychiatry 72, 113–118.
Hirsh, J.B., Morisano, D., Peterson, J.B., 2008. Delay discounting: interactions between personality and cognitive ability. J. Res. Pers. 42, 1646–1650.
Holroyd, C.B., Coles, M.G.H., 2002. The neural basis of human error processing: reinforcement learning, dopamine, and the error related negativity. Psychol. Rev. 109, 679–709.
Holroyd, C.B., Umemoto, A., 2016. The research domain criteria framework: the case for anterior cingulate cortex. Neurosci. Biobehav. Rev. 71, 418–443.
Johnston, V.S., 1979. Stimuli with biological significance. In: Begleiter, H. (Ed.), Evoked Brain Potentials and Behavior. Plenum Press, New York, pp. 1–12.
Kirby, K.N., Winston, G.C., Santiesteban, M., 2005. Impatience and grades: delay-discount rates correlate negatively with college GPA. Learn. Individ. Differ. 15, 213–222.
Lagorio, C.H., Madden, G.J., 2005. Delay discounting of real and hypothetical rewards III: steady-state assessments, forced-choice trials, and all real rewards. Behav. Process. 69, 173–187.
Li, J.Z., Gui, D.Y., Feng, C.L., Wang, W.Z., Du, B.Q., Gan, T., Luo, Y.J., 2012. Victims' time discounting 2.5 years after the Wenchuan earthquake: an ERP study. PLoS One 7, e40316.
Loewenstein, G., Prelec, D., 1992. Anomalies in intertemporal choice: evidence and an interpretation. Q. J. Econ. 107, 573–597.
Luck, S., 2014. An Introduction to the Event-Related Potential Technique, 2nd ed. MIT Press, Cambridge, MA.
Lukie, C.N., Montazer-Hojat, S., Holroyd, C.B., 2014. Developmental change in the reward positivity: an electrophysiological trajectory of reward processing. Developmental Cognitive Neuroscience 9, 191–199.
MacKillop, J., Amlung, M.T., Few, L.R., Ray, L.A., Sweet, L.W., Munafò, M.R., 2011. Delayed reward discounting and addictive behavior: a meta-analysis. Psychopharmacology 216, 305–321.
Madden, G.J., Raiff, B.R., Lagorio, C.H., Begotka, A., Mueller, A., Hehli, D., Wegener, A., 2004. Delay discounting of potentially real and hypothetical rewards. Part II: between- and within-subject comparisons. Exp. Clin. Psychopharmacol. 12, 251–261.
Manning, J., Hedden, T., Wickens, N., Whitfield-Gabrieli, S., Prelec, D., Gabrieli, J.D., 2014. Personality influences temporal discounting preferences: behavioral and brain evidence. NeuroImage 98, 42–49.
Martin, L.E., Potts, G.F., 2009. Impulsivity in decision-making: an event-related potential investigation. Personal. Individ. Differ. 46, 303–308.
Mazur, J.E., 1987. An adjusting procedure for studying delayed reinforcement. In: Commonds, M.L., Mazur, J.E., Nevin, J.A., Rachlin, H. (Eds.), Quantitative Analyses of Behavior. The Effect of Delay and of Intervening Events on Reinforcement Value. 5 Erlbaum, Hillsdale, NJ.
McClure, S.M., Laibson, D.I., Loewenstein, G., Cohen, J.D., 2004. Separate neural systems value immediate and delayed monetary rewards. Science 306 (5695), 503–507. https://doi.org/10.1126/science.1100907.
McClure, S.M., Ericson, K.M., Laibson, D.I., Loewenstein, G., Cohen, J.D., 2007. Time discounting for primary rewards. J. Neurosci. 27, 5796–5804.
Meckler, C., Allain, S., Carbonnell, L., Hasbroucq, T., Burle, B., Vidal, F., 2011. Expectancy control and response expectancy: a Laplacian ERP study. Psychophysiology 48, 303–311.
Meier, S., Sprenger, C., 2010. Present-biased preferences and credit card borrowing. Am. Econ. J. Appl. Econ. 2, 193–210.
Miltner, W.H., Braun, C.H., Coles, M.G., 1997. Event-related brain potentials following incorrect feedback in a time-estimation task: evidence for a "generic" neural system for error detection. J. Cogn. Neurosci. 9, 788–798.
Myerson, J., Green, L., 1995. Discounting of delayed rewards: models of individual choice. J. Exp. Anal. Behav. 64, 263–276.
Nash, K., Prentice, M., Hirsh, J., McGregor, I., Inzlicht, M., 2014. Muted neural response to distress among securely attached people. Soc. Cogn. Affect. Neurosci. 9, 1239–1245.
O'Donoghue, T., Rabin, M., 1999. Doing it now or later. Am. Econ. Rev. 89, 103–124.
Oswald, F., Sailer, U., 2013. Slow cortical potentials capture decision processes during temporal discounting. Eur. J. Neurosci. 37, 1159–1168.
Pailing, P.E., Segalowitz, S.J., 2004. The effects of uncertainty in error monitoring on associated ERPs. Brain Cogn. 56, 215–233.
Patalano, A.L., Lolli, S.L., Sanislow, C.A., 2018. Gratitude intervention modulates P3 amplitude in a temporal discounting task. Int. J. Psychophysiol. 133, 202–210.
Perrone-McGovern, K., Simon-Dack, S., Esche, A., Thomas, C., Beduna, K., Rider, K., Spurling, A., Matsen, J., 2017. The influence of emotional intelligence and perfectionism on error related negativity: an event related potential study. Personal. Individ. Differ. 111, 65–70.
Pinto, A., Steinglass, J.E., Greene, A.L., Weber, E.U., Simpson, H.B., 2014. Capacity to delay reward differentiates obsessive-compulsive disorder and obsessive-compulsive personality disorder. Biol. Psychiatry 75, 653–659.
Proudfit, G.H., 2015. The reward positivity: from basic research on reward to a biomarker for depression. Psychophysiology 52, 449–459.
Pulcu, E., Trotter, P.D., Thomas, E.J., McFarquhar, M., Juhasz, G., Sahakian, B.J., Deakin, J.F.W., Zahn, R., Anderson, I.M., Elliott, R., 2014. Temporal discounting in major depressive disorder. Psychol. Med. 44, 1825–1834.
Reimers, S., Maylor, E.A., Stewart, N., Chater, N., 2009. Associations between a one-shot delay discounting measure and age, income, education and real-world impulsive behavior. Personal. Individ. Differ. 47, 973–978.
Riesel, A., Weinberg, A., Endrass, T., Meyer, M., Hacjak, G., 2013. The ERN is the ERN is the ERN? Convergent validity of error-related brain activity across different tasks. Biol. Psychol. 93, 377–385.
Samuelson, P., 1937. A note on measurement of utility. Review of Economic Studies 4, 155–161.
Santesso, D.L., Segalowitz, S.J., 2009. The error-related negativity is related to risk-taking and empathy in young men. Psychophysiology 46, 143–152.
Scheffers, M.K., Coles, M.G., 2000. Performance monitoring in a confusing world: error-related brain activity, judgments of response accuracy. and types of errors. Journal of Experimental Psychology: Human Perception and Performance 26, 141–151.
Scheffers, M.K., Coles, M.G.H., Bernstein, P., Gehring, W.J., Donchin, E., 1996. Event-related brain potentials and error-related processing: an analysis of incorrect responses to go and no-go stimuli. Psychophysiology 33, 42–53.
Shackman, A.J., Salomons, T.V., Slagter, H.A., Fox, A.S., Winter, J.J., Davidson, R.J., 2011. The integration of negative affect, pain and cognitive control in the cingulate cortex. Nat. Rev. Neurosci. 12, 154–167.
Tanovic, E., Hajcak, G., Sanislow, C.A., 2017. Rumination is associated with diminished performance monitoring. Emotion 17, 953–964.
Urminsky, O., & Zauberman, G. (2016). The psychology of intertemporal preferences. G. Wu & G. Keren (Eds.), Blackwell Handbook of Judgment and Decision Making (pp. 141–181). Hoboken, NJ: Wiley-Blackwell.
Weinberg, A., Olvet, D.M., Hajcak, G., 2010. Increased error-related brain activity in generalized anxiety disorder. Biol Psychol 85 (3), 472–480. https://doi.org/10.1016/j.biopsycho.2010.09.011.
Woodman, G.F., 2010. A brief introduction to the use of event-related potentials in studies of perception and attention. Attention, Perception, & Psychophysics 72, 2031–2046.
Xia, L., Gu, R., Zhang, D., Luo, W., 2017. Anxious individuals are impulsive decision makers in the delay discounting task: an ERP study. Front. Behav. Neurosci. 11, 5.
Yeung, N., Sanfey, A.G., 2004. Independent coding of reward magnitude and valence in the human brain. J. Neurosci. 24, 6258–6264.
Yu, R., Zhou, X., 2009. To bet or not to bet? The error negativity or error-related negativity associated with risk-taking choices. J. Cogn. Neurosci. 21, 684–696.