Brain and Cognition 90 (2014) 1–7

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Predictability influences whether outcomes are processed in terms of original or relative values

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ARTICLE INFO

Article history:
Accepted 26 April 2014
Available online 3 June 2014

Keywords:
Original value
Relative value
Outcome evaluation
ERP
Neuroeconomics

ABSTRACT

Previous studies have provided insights into the representations of original and relative values and the influence of predictability on decision making. However, whether the predictability of outcomes can influence the processing manner of outcomes (i.e. whether the outcomes are processed in terms of original or relative values) is still unknown. To investigate this issue, we had participants perform a monetary decision task which resulted in two outcomes with the same relative values but different original values in either a predictable or unpredictable condition, while recording event-related potentials (ERP). ERP results showed that the outcome processing in the unpredictable condition elicited more positive deflections in the time window of 300–500 ms (P300) than did those in the predictable condition. More importantly, the outcome with high original value elicited a greater P300 component than did that with low original value in the unpredictable condition even though these two outcomes had the same relative values, while in the predictable condition no significant difference was observed between ERPs elicited by the two outcomes even though their original values were different. These results suggest that the outcomes might be processed in terms of relative values in the predictable condition but original values in the unpredictable condition.

1. Introduction

It is adaptive for creatures to adjust their behaviors according to a rapid evaluation of the outcomes of their actions (Ernst & Paulus, 2005; Holroyd & Coles, 2008). Outcomes can be roughly classified into predictable and unpredictable outcomes according to the context. For example, receiving a fixed salary according to the work performance or getting a traffic fine because of a violation of traffic rules can be regarded as predictable outcomes; winning or losing a lottery can be treated as unpredictable outcomes. The influence of predictability or expectation on decisions as well as the representations of the original and relative values in decision making have been intensely studied (Aron et al., 2004; Berns, McClure, Pagnoni, & Montague, 2001; Cromwell, Hassani, & Schultz, 2005; Dohmen, Falk, Fliessbach, Sunde, & Weber, 2011; Elliott, Agnew, & Deakin, 2008; Fiorillo, Tobler, & Schultz, 2003; Grabenhorst & Rolls, 2009; Holroyd, Larsen, & Cohen, 2004; Ohira et al., 2010; Platt & Padoa-Schioppa, 2009; Polezzi, Lotto, Daum, Sartori, & Rumiati, 2008; Ramnani, Elliott, Athwal, & Passingham, 2004; Schultz, 1998; Tanaka et al., 2006; Vlaev, Chater, Stewart, & Brown, 2011). When evaluating outcomes, the original or/and relative values of the outcomes may be processed (Cromwell et al., 2005; Dohmen et al., 2011; Elliott et al., 2008; Grabenhorst & Rolls, 2009; Holroyd et al., 2004; Platt & Padoa-Schioppa, 2009; Vlaev et al., 2011). Relative values of outcomes refer to the values of the obtained outcomes in comparison to other possible or alternative outcomes (Grabenhorst & Rolls, 2009) and the original values are the values of the obtained outcomes themselves. For example, in a winning or losing 10 Chinese *yuan* (CNY) gamble, the relative value of winning 10 CNY is 20 CNY compared with the potential outcome of losing 10 CNY and the original value of wining 10 CNY is 10 CNY.

In their review of the theories of decision making, Vlaev and his colleagues suggested that some theories such as the expected utility theory and the disappointment theory emphasize the original value in decision making, where other theories such as the inequity aversion theory and the regret theory emphasize the role of the comparative value in decision making (Vlaev et al., 2011). In recent years, a lot of attention has been paid to the brain mechanisms

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http://dx.doi.org/10.1016/j.bandc.2014.04.011
0278-2626/

underlying the representations of the original and relative values in decision making (Cromwell et al., 2005; Dohmen et al., 2011; Elliott et al., 2008; Grabenhorst & Rolls, 2009; Platt & Padoa-Schioppa, 2009). For example, Cromwell and his colleagues found that the activity of the primate striatum was influenced not only by the current reward but also by the other rewards presented in the same experimental block (Cromwell et al., 2005). Other studies on primates distinguished that the original value was encoded by the orbitofrontal cortex (OFC), while the relative value was represented in the parietal cortex (Platt & Padoa-Schioppa, 2009). In the human brain, however, the original and relative values of rewards were shown to be represented separately in the OFC (Elliott et al., 2008; Grabenhorst & Rolls, 2009). Furthermore, human reward regions were associated not only with the original values of incomes but also with their relative values compared with other participants (Dohmen et al., 2011).

Studies of decision-making have revealed the influence of predictability or expectation on decisions as well as the neural basis on which the influence depends. Previous studies that investigated the coding of reward stimuli by single-dopamine-neuron recording suggested that dopamine was specifically connected with uncertainty: dopaminergic activity increased after participants received unpredictable rewards (Fiorillo et al., 2003; Schultz, 1998). For example, by recording the activity of single neurons of monkeys, Fiorillo and his colleagues found that the activation of dopamine neurons after monkeys received rewards increased monotonically with the increased uncertainty of rewards (Fiorillo et al., 2003). Complimentarily, a functional magnetic resonance imaging (fMRI) study on humans revealed that activities in the midbrain area varied with the uncertainty of feedback, which was also correlated with dopaminergic target regions including the ventral striatal, orbital and medial frontal regions (Aron et al., 2004). Other fMRI studies have suggested that some brain regions such as the OFC, dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), cerebellum and striatum were related to decisions involving uncertainty (Ohira et al., 2010; Tanaka et al., 2006). Reward regions including the nucleus accumbens and medial orbitofrontal cortex were most active when the sequence of liquid stimuli orally delivered to subjects was unpredictable (Berns et al., 2001). Unpredictable rewards activated the OFC, frontal pole, parahippocampal cortex and cerebellum (Ramnani et al., 2004). These studies showed that brain regions such as the OFC, DLPFC and cerebellum were correlated with uncertainty in decision making.

The event-related potential (ERP) technique can provide us with neural information of high time resolution (de Haan & Thomas, 2002), which is particularly useful for the detection of the brain's rapid evaluations of the outcomes. Most ERP studies of outcome processing have focused on the valence and magnitude of the outcomes (Goyer, Woldorff, & Huettel, 2008; Gu, Wu, Jiang, & Luo, 2011; Gu et al., 2011; Hajcak, Holroyd, Moser, & Simons, 2005; Holroyd, Pakzad-Vaezi, & Krigolson, 2008; Kamarajan et al., 2009; Sato et al., 2005; Wu & Zhou, 2009; Yeung & Sanfey, 2004). A positive deflection with a latency of roughly 300–600 ms (P300) was highly correlated with outcome evaluations, especially with the valence or the magnitude of the outcomes (Gu, Lei, et al., 2011; Hajcak et al., 2005; Luo, Sun, Mai, Gu, & Zhang, 2011; Sato et al., 2005; Yeung & Sanfey, 2004). The amplitude of P300 was larger when outcome valence was positive than when it was negative (Gu, Lei, et al., 2011; Hajcak et al., 2005). Other studies provided evidence that the amount of money won or lost determined the amplitude of P300 regardless of the positive or negative valence of outcomes (Luo et al., 2011; Sato et al., 2005; Yeung & Sanfey, 2004). Moreover, P300 might reflect the participants' emotional activity (Luo et al., 2011; Sato et al., 2005), their involvement (Luo et al., 2011) or the influence of magnitude expectance on the outcome evaluation (Wu & Zhou, 2009). However, a few ERP studies have focused on unpredictable outcomes (Polezzi et al., 2008) or the original/relative values in outcome processing (Holroyd et al., 2004). According to Polezzi and his colleagues, uncertain monetary outcomes elicited more a negative-going N500 than did certain monetary outcomes (Polezzi et al., 2008). The amplitude of the error related negativity (ERN) was not determined by the original values of the obtained outcomes but rather by the relative values of the presented outcome in comparison with the possible outcomes (Holroyd et al., 2004).

Although prior neural studies have revealed the role of predictability in decision making as well as the neural encoding of the original and relative values, uncertainty remains regarding whether the predictability of outcomes may modulate the processing manner of the outcomes (in original or relative values). In the present study, we investigated how the predictability of the outcomes would influence whether outcomes were processed in terms of original or relative values by combining the ERP technique with a monetary decision-making task in which participants chose to magnify ($\times 10$) or minify ($\times 0.1$) the initial money (+1, −1 CNY). The cues predicting initial money were displayed for 17 ms or 200 ms, which made the monetary outcomes unpredictable or predictable. Due to the aim of our study, we focused on how participants processed the outcomes. In the predictable condition, participants could choose to magnify or minify the initial money exactly based on the initial money. Thus there was no evident reason for a careful participant to magnify his/her losses or minify his/her gains in the predictable conditions. We, therefore, focused on the outcomes of the magnified gains and the minified losses (i.e. the outcomes of +10 CNY and −0.1 CNY) in both predictable and unpredictable conditions. When the obtained outcome was +10 CNY, the initial money must have been +1 CNY, the potential alternative outcome was +0.1 CNY, and thus the relative value of the obtained outcome was +9.9 CNY [(+10) − (+0.1)]. When the obtained outcome was −0.1 CNY, the initial money should have been −1 CNY, the potential alternative outcome was −10 CNY, and thus the relative value of the obtained outcome was also +9.9 CNY [(−0.1) − (−10)]. In the present study, the original/relative values referred to the mathematical original/relative values.

Previous studies using single-dopamine–neuron recording, fMRI, or ERP measurement exhibited distinctive features of brain response when outcomes or decision context differed in predictability (Aron et al., 2004; Fiorillo et al., 2003; Ohira et al., 2010; Polezzi et al., 2008; Ramnani et al., 2004; Schultz, 1998; Tanaka et al., 2006). Furthermore, it has been shown that P300 was highly correlated with outcome processing (Gu, Lei, et al., 2011; Hajcak et al., 2005; Luo et al., 2011; Sato et al., 2005; Yeung & Sanfey, 2004). Thus we hypothesized that the P300 component might reflect the different processing of the unpredictable outcomes and the predictable outcomes. Moreover, in either the predictable or unpredictable condition, if participants focused on the relative values of the outcomes, no difference would be found in the brain potentials elicited by the two obtained outcomes (+10 CNY and −0.1 CNY) because the relative values (relative to the un-obtained outcomes +0.1 and −10 CNY respectively) of the two outcomes were identical (+9.9 CNY). If participants focused on the original values of the obtained outcomes, +10 CNY would evoke a more positive component than −0.1 CNY because both the magnitude and valence of the original value of +10 CNY were higher than those of −0.1 CNY.

2. Materials and methods

2.1. Participants

Eighteen right-handed undergraduates (9 females and 9 males) aged 19–23 years (mean age 21.00 years) from our university