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Neuroimaging Fairness in Economic Decisions: EEG and EROS Analysis in the Ultimatum Game*

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Abstract

This study investigates how the brain processes fairness decisions during the Ultimatum Game by analyzing neural activity (using Event Related Potentials, ERPs, and Event Related Optical Signals) in two groups of participants distinguished by personality and mood profiles. The *proself* group, characterized by positive mood and traits like prudence and forgiveness, was more likely to accept unfair offers. The *prosocial* group, marked by adventurousness and lower modesty, more frequently rejected unfair offers. Neural measurements revealed that proself individuals showed earlier and smaller P200 ERP responses and less right frontal activation during rejection, while prosocial individuals exhibited stronger DLPFC and right temporal junction activity when rejecting unfair offers. These findings indicate that both the timing and location of brain activity during fairness decisions are closely linked to personality traits, and that fast optical signals reliably track these neural dynamics alongside traditional electrophysiological markers.

Keyphrases

Decision making; Ultimatum Game; right frontal lobe; dorsolateral prefrontal cortex; frequency domain functional near-infrared spectroscopy; fast optical neuroimaging.

Introduction

Fairness is a cornerstone of human social interaction and cooperation. Yet, the neurobiological underpinnings of fairness-oriented decision-making remain a rich and evolving field of inquiry. The Ultimatum Game (UG) has emerged as a robust experimental paradigm for studying these processes, as it directly pits self-interest against social norms: a proposer offers a split of a sum of money, and a responder chooses to accept or reject the offer. Rejection results in both parties receiving nothing, making the responder's choice a window into their valuation of fairness versus personal gain (Güth et al. 1982; Fehr and Schmidt 1999).

While behavioral patterns in the UG are well-documented (Camerer and Thaler 1995; Bolton and Ockenfels 2000), the neural and psychological factors that explain individual differences in fairness-related choices remain a rich field of inquiry. Neuroimaging and electrophysiological studies have begun to uncover the brain regions involved in fairness processing, including the dorsolateral prefrontal cortex and anterior insula (Feng et al. 2015; Gabay et al. 2014; Jaquerod et al. 2024). These findings suggest that fairness decisions are shaped not only by cognitive evaluation but also by emotional and personality factors (Andrejević et al. 2022; Bieleke et al. 2017; Miraghaie et al. 2022).

Grounded in neuroeconomics and personality psychology (Fehr and Gächter 2002; Vavra et al. 2018), this study applies a dual-modality neuroimaging approach: EEG to capture temporal dynamics, and event-related optical signals (EROS), based on fast optical neuroimaging (FONI, using frequency-domain functional near-infrared spectroscopy, FD-fNIRS), to locate fast neural activity in cortical space.

Methods

Study Protocol: Twenty-four young adults (mean age = 24.8) were recruited from graduate courses at the University of Lausanne and received course credit for their participation, irrespective of their performance. Prior to the experiment, three validated self-report inventories were administered to assess participants' affective state and personality traits. The Positive and Negative Affect Schedule (PANAS) (Watson et al. 1988) is a 20-item questionnaire measuring positive and negative affective states, where participants rate their feelings using a Likert scale. The Brief Mood Introspection Scale (BMIS) (Mayer and Gaschke 1988) is a 16-item scale that captures current mood states across affective dimensions such as pleasantness and arousal. The HEXACO Personality Inventory (Ashton and Lee 2007) is a comprehensive model of personality assessing six major dimensions, including the Honesty-Humility factor, extending beyond the traditional Big Five.

Experimental Paradigm: In our version of the Ultimatum Game (UG), participants engaged in a structured decision-making task designed to isolate fairness-oriented behavior by eliminating social feedback. Each participant completed a total of 12 blocks, consisting of 3 Proposer blocks and 9 Responder blocks. Each block comprised 24 trials, for a total of 288 trials per participant. The asymmetric distribution of blocks was intentional: given the study's primary focus on fairness-related responses in the Responder role, more trials were allocated to this condition to maximize the yield of behavioral and neurophysiological data, while keeping the total session duration within approximately one hour. During Proposer blocks, participants decided how to split a hypothetical monetary amount between themselves and another anonymous player. In Responder blocks, participants were presented with pre-determined monetary offers and had to decide whether to accept or reject each one, as shown in Fig. 1. Offers were presented with

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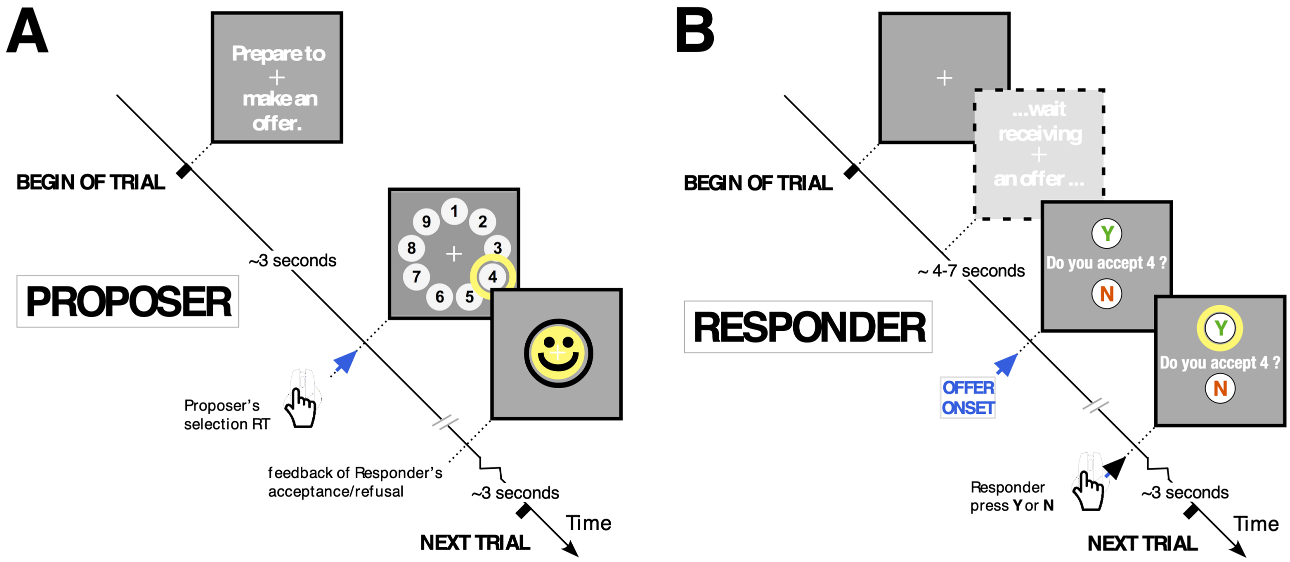

Figure 1: Trial sequences for the Proposer and Responder in the Ultimatum Game. (A) When participants played the role of Proposer, each trial began with a prompt instructing them to prepare an offer, followed by a visual representation showing the potential distribution of shares. After selecting an amount to propose to the Responder, the Proposer received a feedback response, indicated by a smile emoticon if the offer was accepted or a frown emoticon if it was rejected. (B) In Responder trials, participants were alerted with a message, indicating that an offer would be presented. Following this prompt, a screen displaying the amount offered by the Proposer appeared, accompanied by two options prompting the participant to either accept (green "Y") or reject (red "N") the offer.

a simple feedback (accepted/rejected) from a computerized proposer, thereby ensuring that participant responses reflected internalized fairness preferences rather than strategic considerations such as reciprocity or reputation management. Rejections resulted in no monetary gain for either party, consistent with standard UG rules. The order of blocks was pseudo-randomized for each participant, with the constraint that no two Proposer blocks occurred consecutively. Participants initiated each block by pressing the 'ENTER' key, and at the end of each block, a summary message displayed the total earnings accumulated by both players during that segment. A final message at the end of the session summarized the cumulative earnings across all Proposer and Responder trials.

Multimodal Neuroimaging: Electroencephalography (EEG) fast optical neuroimaging (FONI) data were acquired to track neural dynamics associated with each decision. This dual-modality recording allowed for high temporal and spatial resolution in capturing the neurophysiological correlates of fairness-related decisions, as illustrated by Figure 2. EEG data were recorded using a BioSemi ActiveTwo MARK II system (BioSemi B.V., Amsterdam, The Netherlands) at a sampling rate of 1024 Hz. Due to physical constraints imposed by the concurrent EROS acquisition setup, recordings were limited to five active Ag/AgCl scalp electrodes placed at Fz, FCz, Cz, CPz, and Pz, following the 10-20 international system (Klem et al. 1999). Signals were band-pass filtered between 0.05 and 200 Hz and digitally stored for offline processing. The EEG data were re-referenced to the linked mastoids, and ocular movements were monitored using bipolar electrodes positioned around the eyes. Artifacts resulting from blinks or muscle activity were removed using Independent Component Analysis (ICA), implemented via the `runica` function in EEGLAB (Delorme and Makeig 2004). Data were segmented into epochs time-locked to the onset of the decision event, ranging from -200 ms to +600 ms, and baseline-corrected using the 200 ms pre-stimulus interval. Artifact-free epochs were averaged to derive event-related potentials (ERPs) for two trial types: accepted and rejected offers. Peak amplitude and latency measurements for the P200 and P300 components were obtained using the `pop_geterpvalues` function in ERPLAB (Lopez-Calderon and Luck 2014), with peak windows defined based on ERP morphology and temporal parameters observed in the EROS data.

FONI data for event-related optical signals were acquired using two synchronized frequency-domain Imagent oximeters (ISS Inc., Champaign, IL), comprising 28 near-infrared light sources (830 nm) and 8 photomultiplier tube detectors. The sources targeted bilateral frontal and right parietal cortices and were modulated at 110 MHz, while the detectors operated at 110.003125 MHz, producing a 3125 MHz heterodyne signal. Optical data were sampled at 125 Hz (8 ms intervals) across 64 source-detector channels. To reduce signal contamination, sources were time-multiplexed and placed to avoid concurrent activation in the same hemisphere or overlapping detector fields. Channels with source-detector distances < 15 mm or > 60 mm, or those exhibiting phase variability above 160 picoseconds, were excluded based on established noise thresholds (Gratton, Sarno, E. L. Maclin, et al. 2006). Fast Fourier Transform (FFT) was applied to extract phase delay, the primary signal metric due to its superior sensitivity to cortical activity. Preprocessing involved phase wrapping correction, normalization, pulse artifact removal, and band-pass filtering (0.01–10 Hz) (Gratton and Corballis 1995; Wolf et al. 2003). Processed data were averaged by time point, channel, condition, and participant. Electrode positions were digitized using a 3D electromagnetic system (Polhemus 3Space Fastrak) and co-registered to template MRI using nasion and preauricular landmarks. Spatial normalization across participants was performed via Talairach transformation in BioImage Suite.

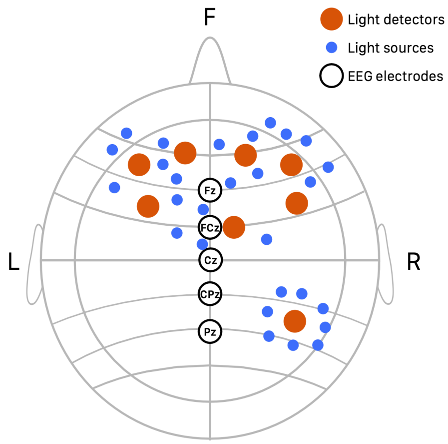

Figure 2: EEG/EROS set up. EEG and EROS data were recorded over bilateral DLPFC and right TPJ, localized by the international 10-20 system. Pink circles along the midline represent the EEG electrodes, blue squares represent the EROS sources and red dots represent the EROS detectors.

Results

Through cluster analysis based on personality traits (assessed via the HEXACO inventory) and emotional states (measured with PANAS and BMIS), we identified two distinct participant groups in terms of compliance with fairness norms: one cluster, termed "proself," was characterized by high levels of sentimentality and prudence; the other, "prosocial," showed lower scores in modesty and forgiveness and rejected unfair offers with greater frequency. The proself group showed lower rejection rates across offer types, suggesting an inclination toward maintaining harmony or minimizing conflict. In contrast, prosocial participants demonstrated a strong aversion to inequality, even at personal cost—behavior that aligns with theories of altruistic punishment and fairness enforcement observed in early UG studies (Güth et al. 1982; Fehr and Schmidt 1999).

These behavioral differences were mirrored neurophysiologically in distinct brain activity patterns. EEG recordings revealed that proself individuals exhibited faster but lower-amplitude P200 responses during offer rejection at the frontal midline (Fz), indicating more rapid but perhaps less emotionally intense evaluation. Prosocial responders displayed enhanced late components, particularly P300, suggesting prolonged and more effortful evaluative processing when facing unfairness.

Simultaneously, FONI revealed spatially precise activations corresponding to these temporal events. Among prosocial responders, rejection of unfair offers was associated with significant activation in Brodmann Area 9 (dorsolateral prefrontal cortex), a region implicated in cognitive control and moral judgment (Gehring and Willoughby 2002). Around 500 ms post-offer, activity also emerged in the right temporal-parietal junction, a region consistently linked to theory of mind and the processing of social norm violations (Gabay et al. 2014).

Discussion

Fairness is a central issue in the Ultimatum Game, where offers are typically evaluated based on their deviation from an equal split. Offers that disproportionately favor the Proposer present Responders with a dilemma: they must decide whether to accept a suboptimal share or to reject the offer, thereby penalizing the Proposer for unfairness at the expense of their own gain (Camerer and Thaler 1995; Fehr and Schmidt 1999).

Previous research has shown that UG Responders are often willing to sacrifice personal benefits in order to punish Proposers who make low offers, indicating a strong preference for fair outcomes (Güth et al. 1982; Pillutla and Murnighan 1996; Fehr and Gächter 2002; Yamagishi et al. 2012; White et al. 2014). Through cluster analysis based on personality traits and emotional states, the participants of our study were categorized in two groups. We observed that participants classified as prosocial rejected unfair (or selfish) offers nearly 90% of the time, compared to approximately 50% for proself participants. Such willingness to prioritize fairness over self-interest highlights the distinction in the UG between prosocial individuals–who are more concerned with the well-being of others and more likely to reject unfair offers–and proself individuals–who prioritize their own interests and are more inclined to accept unfair offers to maximize personal gain, rather than uphold fairness (Bolton and Ockenfels 2000; Hu and Mai 2021; Van Lange et al. 1997; Brethel-Haurwitz et al. 2016; Bieleke et al. 2017; Li et al. 2021). Then, the prosocial group in our sample corresponds to the prosocial individuals described in previous literature, while the proself group aligns with the proself profile.

These findings are further supported by recent research demonstrating the dorsolateral prefrontal cortex's (DLPFC) involvement in processing deviant stimuli, highlighting its role in evaluating the novelty or unexpectedness of stimuli and adjusting future predictions accordingly (Jaquerod et al. 2024). Additionally, electrophysiological markers have been identified that distinguish between fair and selfish individuals during economic decision-making tasks, with fair participants exhibiting distinct ERP components associated with moral decision-making processes (Miraghaie et al. 2022). This aligns with fMRI findings showing that equitable offers activate the brain's reward circuitry, particularly the ventral striatum, reinforcing the idea that fairness is intrinsically valued (Tricomi et al. 2010).

Our results underscore that personality traits—particularly forgiveness, modesty, and adventurousness—not only modulate behavioral responses to unfairness but also shape the timing and amplitude of neural coding signals during fairness-related decisions (Andrejević et al. 2022). The parallel between these activations and classical descriptions of cognitive-emotional conflict underscores the complementary roles of emotion and deliberation in fairness-related decisions. Previous studies have demonstrated that people are willing to incur personal losses to punish unfairness, often driven by brain circuits involving both medial and lateral prefrontal regions (Fehr and Gächter 2002).

The use of EROS, which offers sub-second spatial localization of cortical dynamics, adds a unique dimension to this investigation. Its sensitivity to rapid changes enabled the researchers to isolate neural signatures that may otherwise be blurred in hemodynamic-based imaging modalities (Gratton, Sarno, E. Maclin, et al. 2000). These results demonstrate the utility of combining temporal and spatial resolution in the study of decision neuroscience.

Conclusion

In sum, this study highlights how individual differences in personality influence not only economic behavior but also the neurocognitive strategies underlying it. Prosocial individuals respond more forcefully and with specific prefrontal recruitment when faced with inequality, while proself individuals appear to employ quicker, possibly more adaptive processing strategies. These findings may offer useful insights into both everyday human interactions and broader societal debates around equity, cooperation, and the enforcement of social norms.

Citation

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Contributions

All authors contributed equally to the paper.

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