Development of the Striatum-mediated Reward Prediction Error Processing from Age Three to Twelve Years

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Abstract

Reward prediction error (RPE), a type of neural signal that encodes discrepancy between expectation and actual outcome, is a crucial component of human learning supported by the striatal dopaminergic reward system. This study analyzes a large open source dataset from a functional magnetic resonance imaging (fMRI) study to examine the developmental trajectory of the processing of RPE. In this study, we identified five novel events in the experimental stimulus of the original study. These events are characterized by the unique "anticipation-surprise" narrative structure which is similar to the classical conditioning paradigms commonly used in the studies of RPE. With those events as predictors, a voxel-wise general linear model (GLM) analysis was conducted for each age group in the dataset (3, 4, 5, 7, 8-12 years old, and adult group, with n = 17, 14, 34, 23, 34, and 33 respectively). The results of the GLM analyses show noticeable striatal activation in all age groups except 3 and 4-year-old. The study also finds that children ages 8-12 years old show exaggerated striatal activity compared to the other age groups. The results corroborate the view that the development of the striatal RPE processing follows a quadratic trend with inverse U-shape, and suggest that the enhanced RPE activity can be seen in as early as late schooler. The results also demonstrate the effectiveness of the anticipation-surprise narrative in eliciting RPE-related activity in younger children and affords a novel insight into the development of reward processing mechanisms in early childhood.

Method

The dataset is from the study by Richardson, Lisandrelli, Riobueno-Naylor, et al. (2018) and is made available on Openfmri (https://www.openfmri.org/dataset/ds000228/). The data were collected from children (n=122, 3-12 years) and adults (n=33) watching a short animated film (*Partly Cloudy* by Pixar, duration: 5-6 minute) while undergoing fMRI. The entire film is broken down into 168 TRs with each TR lasting 2 second. T1-weighted structural images were collected in 176 interleaved sagittal slices with 1mm isotropic voxels. The gradient-echo EPI sequences were collected in 32 interleaved near-axial slices with 2mm isotropic voxels. The participants were not asked to perform any task during scanning, and thus the dataset is not task-specific.

Functional images were registered to the first image of the run, which was registered to each participant's anatomical image, and each participant's anatomical image was normalized to the Montreal Neurological Institute (MNI) template. Registration of each individual's brain to the MNI template was visually inspected. All data were smoothed using a 5mm Gaussian kernel before any analysis.

For each subject, motion artifact timepoints were identified via the ART toolbox and five PCA noise components were generated using CompCor, which were used in later analysis as nuisance regressors.

Data were analyzed using Nilearn and Nistat python brain imaging processing modules, which differ from those used in the original study (Matlab and SPM). The impact of this departure was gauged in a separate analysis (not presented here), where parts of the results in the original study were reproduced in good fidelity using Nilearn and Nistat, with marginal differences that can be attributed to the algorithmic nuances between different toolkits.

A standard general linear model (GLM) approach was used for statistical analysis. Potential confounds are accounted for by including nuisance regressors and signal drift components into the model. Five sequential anticipation-surprise events were identified in the movie; each contains one anticipatory cue followed by a surprising event. We postulate that this kind of events, with its structural similarity with the classical conditioning paradigm (Fig.1), will elicit RPE signal. In summary, the model contains the following regressors: five anticipatory cues, five surprising events, and controlling variables (motion artifact, PCA noise components, and signal drift components). After model estimation, a whole brain statistical map was calculated based on the contrasts of *1st surprising event and 2nd-5th anticipatory events > 1st anticipatory event and 2nd-5th surprising events*. To obtain the group-level result, individual statistical maps were put into an one-sample t-test linear model. The significance of activations in the resulted group map was thresholded at false discovery rate (FDR) of .05 at the whole brain level.

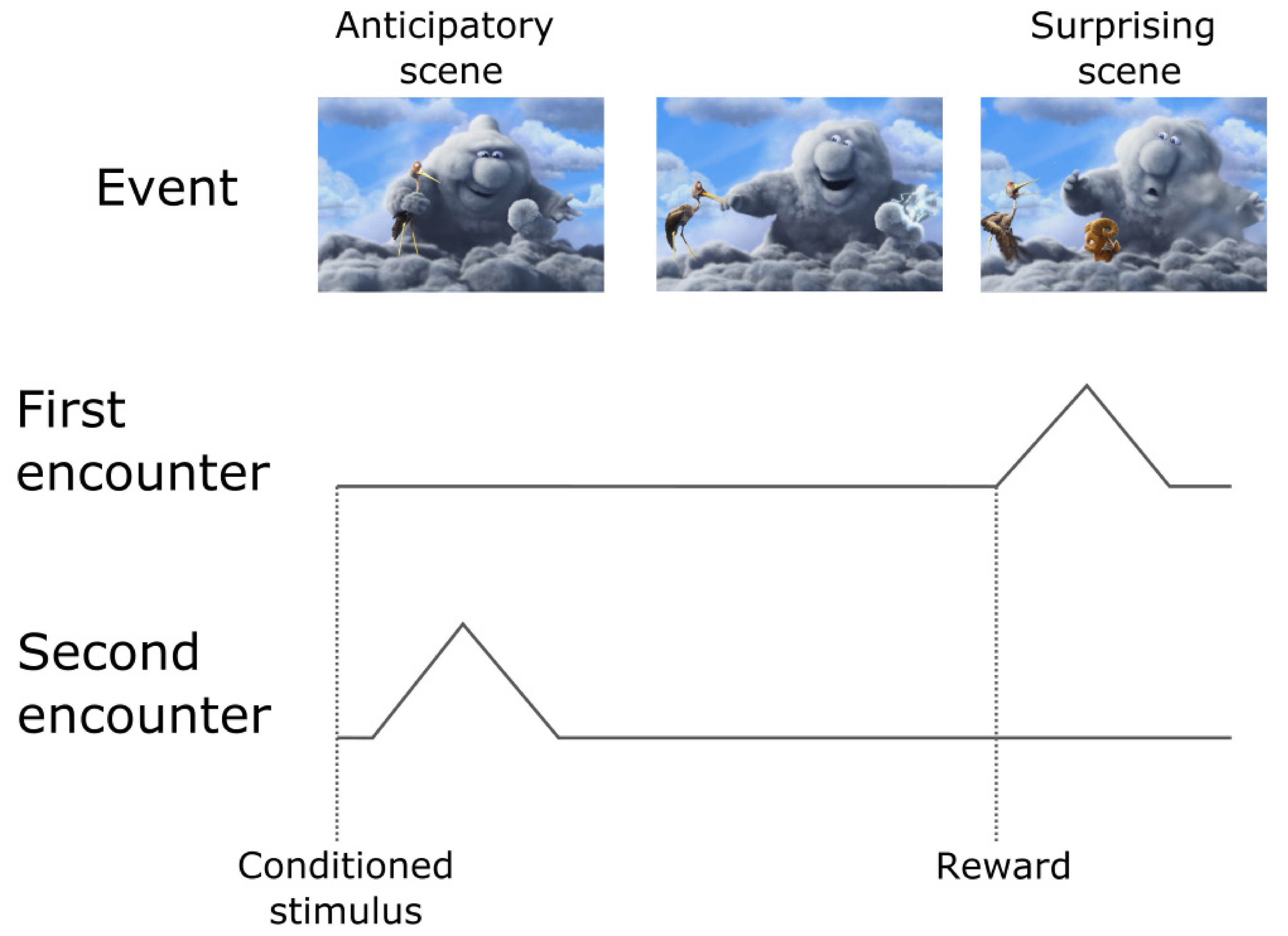

Fig. 1. Diagram of anticipation-surprise event and the conjectural RPE signal it elicits. In the stimulus, an anticipation-surprise event features a scene with anticipatory cue that leads to a surprising result, which viewer will find rewardingly amusing. This is structurally similar to the classical conditioning paradigm and should elicit similar RPE signals.

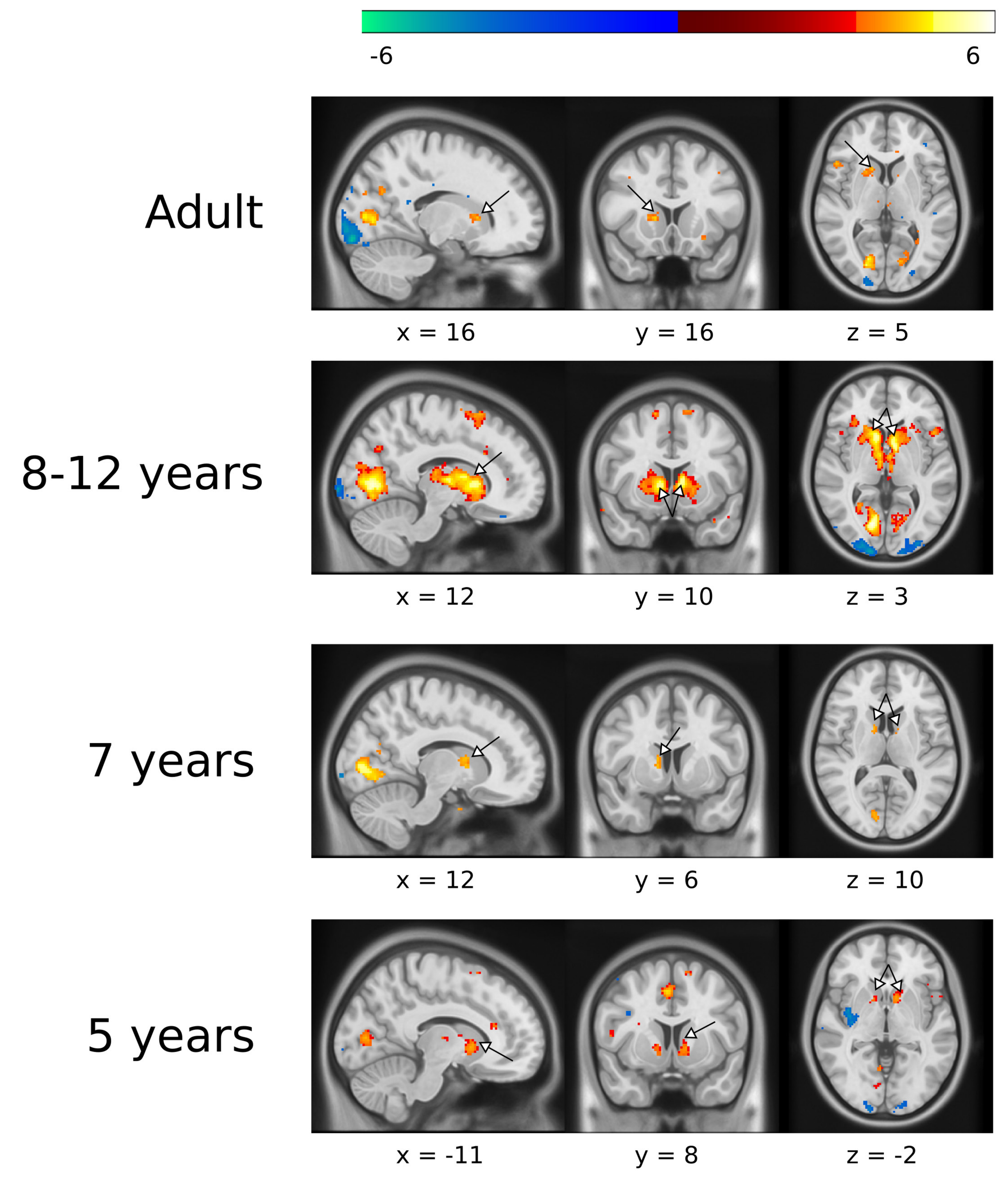

Fig. 2. Statistical maps reveals significant activations (FDR = .05) in uni- and bilateral caudate (arrowed) when viewing a series of anticipation-surprise events in movie, indicating heightened RPE processing activities during those events. Late schoolers (8-12 years) show exaggerated striatal activities. 4 years old show less significant striatal activities (not shown, detectable at FDR = .1) while 3 years old show no activities.

Conclusion

The result corroborates the theory of the hyper-responsiveness of striatal system during adolescence (Galvan, 2010), but dates the onset to an earlier stage, from mid-early adolescence (around age 15) reported in previous findings to late schooler (age 8 to 12, see Fig.2). This study also detects striatum-mediated RPE activities in much ealier ages (7, 5, and arguably 4 years old), which are rarely reported in previous RPE studies, if at all (for example, see Cohen, Asarnow, Sabb, et al., 2010).

We suspect that the reason why the study fared well in younger children is in its use of naturalistic stimulus and ecologically valid event, which have been shown to promote more complex multimodal intergration and have higher test–retest reliability (Sonkusare, Breakspear, Guo, 2019). There has not been many studies on the development of RPE processing that utilize more naturalistic stimuli in the experiments. This study serves to fill the lacuna as the interest in ecologically valid paradigms grows in the field. The study's success also highlights the intricate frontostriatal interaction between reward processing and higher cognitive functions like theory of mind and reading comprehension in a real world setting.