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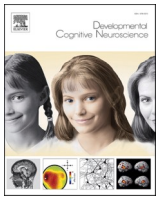

Neural processes of reward and punishment processing in childhood and adolescence: An event-related potential study on age differences

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ABSTRACT

Reward and punishment processing are subject to substantial developmental changes during youth. However, little is known about the neurophysiological correlates that are associated with these developmental changes, particularly with regard to both anticipatory and outcome processing stages. Thus, the aim of this study was to address this research gap in a sample of typically developing children and adolescents.

Fifty-four children and adolescents (8–18 years) performed a Monetary Incentive Delay Task comprising a monetary reward and punishment condition. Using event-related brain potential recordings, the cue-P3 and the stimulus-preceding negativity (SPN) were analyzed during the anticipation phase, while the Reward Positivity and the feedback-P3 were analyzed during the outcome phase.

When anticipating monetary loss or no gain, SPN amplitude in the right hemisphere decreased with age. Moreover, exploratory analyses revealed a decrease in feedback-P3 amplitudes in response to monetary loss with increasing age. No other group differences were observed.

Age-related changes in the SPN and fP3 component suggest that sensitivity to negative outcomes decreases from childhood to late adolescence, supporting the notion that adolescence is associated with reduced harm-avoidance. Longitudinal research including young adults is needed to substantiate our findings and its clinical implications regarding disturbed developmental trajectories in psychiatric populations.

1. Introduction

Throughout childhood and adolescence, responsiveness to reward and punishment are subject to substantial changes. In particular, the transition into adolescence is characterized by heightened seeking of rewards and pleasurable experiences and reduced harm-avoidance (see Casey et al., 2008; Ernst et al., 2006; Somerville et al., 2010 for a review and discussion), often resulting in high-risk behavior, such as alcohol and drug use as well as risky sexual behavior (Dahl, 2004).

Incentive processing is typically divided into anticipatory and outcome phases (Glazer et al., 2018; Novak and Foti, 2015). While anticipation is described as the motivation to approach and receive rewards ("wanting"), the outcome reflects "liking", i.e. hedonic impact of the incentive (Berridge et al., 2009; Glazer et al., 2018). Event-related potential (ERP) studies are particularly well-suited to examine different stages of "wanting" and "liking" due to the high temporal resolution of electroencephalography (Glazer et al., 2018).

Regarding the anticipatory processing stage, the stimulus-preceding negativity (SPN) and the cue-P300 (cP3) are often examined ERP components, whereas the feedback-P300 (fP3) and Reward Positivity (RewP) are commonly examined during the outcome stage. The SPN is a slow-wave potential, has its dominance in the right hemisphere and is usually measured 0−200 ms before feedback onset. The component reflects an index of anticipatory attention preceding relevant feedback and increases in negativity until feedback is provided (Brunia et al., 2011; Glazer et al., 2018).

The cP3/fP3 component peaks about 300−600 ms post-stimulus, is largest at centro-parietal sites (San Martín, 2012) and is increased for reward and punishment compared to neutral stimuli (Glazer et al., 2018). Although exhibiting a similar localization and temporal window,

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studies demonstrate that these are two distinct processes (Glazer et al., 2018). The cP3 is evident after cue onset and reflects attention allocation to stimuli predicting reward and punishment, thus stimulating incentive pursuing (Novak and Foti, 2015). The fP3 is elicited after feedback to behavioral choices, involves updating of the information context and is considered to reflect integration of relevant information in the working memory (Donchin, 1981; Glazer et al., 2018; Novak and Foti, 2015; Polich, 2007).

The RewP has its maximum at fronto-central sites at about 250−350 ms after positive and negative feedback (with a higher deflection after positive vs. negative feedback) and is discussed as an index of reward-related neural activity and linked to performance-monitoring (Glazer et al., 2018; Proudfit, 2015). It is usually conceptualized as a difference wave and calculated by subtracting neural activity of negative from positive feedback (Krigolson, 2018; Proudfit, 2015)[2] . In contrast to the fP3, the RewP is not modulated by magnitude and is sensitive to evaluation of the own performance (Glazer et al., 2018).

To our knowledge, ERP studies on development of incentive processing from childhood to adolescence exclusively focused on outcome components (Crowley et al., 2013; Ferdinand et al., 2016; Hämmerer et al., 2011; Kujawa et al., 2017), particularly on RewP/FRN. While some studies reported a decrease in RewP/FRN amplitudes from childhood to adolescence (e.g. Crowley et al., 2013; Ferdinand et al., 2016; Hämmerer et al., 2011; Pincham et al., 2015), others did not find an association between age and amplitude (Bowers et al., 2018; Bress et al., 2012; Lukie et al., 2014). The finding of the decrease in amplitudes can be interpreted as a higher reactivity of the performance monitoring system to external feedback in children versus adolescents (Ferdinand et al., 2016). Importantly, taking the calculation of the components into account is crucial for interpretation of the data. Some studies examined ERP components to gains and losses separately, while others calculated difference waves or peak-to-peak amplitudes of gain vs. loss or gain vs. no-gain, respectively. For example, Hämmerer et al. (2011) found a decrease in RewP/FRN amplitude to gains and losses with increasing age when separately considering these two outcomes. However, the difference score was smaller in children compared to adolescents. Moreover, a comprehensive study in children and adolescents (Burani et al., 2019) based on a cross-sectional and longitudinal design demonstrated that RewP/FRN amplitudes to gains increased longitudinally, which was not the case for losses. Moreover, this increase was only evident in younger participants. The authors suggested that age-related increases in the reward-related activity might be relatively specific for the late childhood and early adolescent period. In summary, the divergent findings on developmental differences in this component might at least partially be driven by methodological differences between the studies, including the calculation of this component.

Concerning the fP3, two studies investigated differences between children and adolescents during incentive processing. The first study (Lukie et al., 2014) demonstrated longer overall fP3 latencies in children compared to adolescents to rewards and non-rewards, which is consistent with research showing that children exhibit prolonged latencies in many ERPs related to cognitive processes (Taylor and Baldeweg, 2002). The second study found comparable fP3 amplitudes across age groups, while only adolescents exhibited larger fP3 amplitudes for unexpected versus expected feedback. The results might reflect that adolescents are better able to update their memory representation after unexpected feedback (Ferdinand et al., 2016).

While these previous studies provide important insights into age-related differences, more research is needed for several reasons: First, most prior work examined only one ERP component. Multicomponent analysis is crucial as the examination of one single component may lead to a confounded result by other components, which are in temporal proximity to the component of interest (Glazer et al., 2018). Moreover, to our knowledge no study assessed age-related changes of anticipatory ERP components from childhood to adolescence. However, examining anticipatory and outcome processing stages is essential as studies suggest that reward anticipation and reward outcome underlie different developmental trajectories (Hoogendam et al., 2013; Van Leijenhorst et al., 2010). Generally speaking, imaging studies suggest that during the outcome phase neural activity in subcortical regions, including the ventral striatum, is increased in adolescents compared to children and adults (Schreuders et al., 2018). However, data on age-related differences in the ventral striatum during anticipation of rewards have been inconclusive and results seem to depend on different variables such as the likelihood of getting the reward (for a review see Shulman et al., 2016). Furthermore, responses to reward and punishment are thought to draw partially on different neurobiological systems. According to the "adolescent triadic model of motivated behavior" the "propensity for risk-/reward-seeking behavior of adolescents partly originates from predetermined ontogenic changes in three neural systems that support (1) reward-related (approach) behavior, (2) harm avoidance, and (3) regulation of both approach and avoidance systems "(Ernst et al., 2006, p. 309). This emphasizes the importance of separately assessing reward and punishment processing in youth, which has rarely been done.

Adding to the previous points, findings from developmental studies on reward and punishment processing can reveal first starting points for the development or adaptation of clinical or educational interventions (e.g. Coelho et al., 2015) that aim at reducing undesireable, maladaptive behavior and implementing adaptive behavior. More precisely, insight into age-related differences in incentive processing can be helpful to tailor behavioral interventions such as token economy or response cost to different age groups in youth.

Thus, the aim of our study was to assess differences in reward and punishment processing in children compared to adolescents. Adopting a multicompetent approach, we chose to examine the cP3 and SPN as anticipatory, and the fP3 and RewP as outcome components, respectively. This is the first ERP study to investigate age-related changes in anticipatory incentive processing from childhood to adolescence. As neural activity of reward anticipation increases from childhood to young adulthood (Hoogendam et al., 2013) and adolescence is characterized by a greater dominance of the reward compared to the harm-avoidant system (Ernst et al., 2006), we expected an increase in mean amplitudes of SPN and cP3 from childhood to adolescence during reward anticipation. Concerning the RewP, we expected a decrease in amplitudes from childhood to adolescence in response to both, reward and punishment (Crowley et al., 2013; Ferdinand et al., 2016; Pincham et al., 2015). Regarding the fP3 component, we expected a reduction in fP3-latency form childhood to adolescence in response to monetary rewards (Lukie et al., 2014). Former studies have found associations between inhibition and approach behavior and ERP components related to reward and punishment processing (Balconi and Crivelli, 2010; Boksem et al., 2008; Bress and Hajcak, 2013), including correlations between self-reported reward responsiveness and RewP/FRN amplitude in young adults (Bress and Hajcak, 2013). Building on these results, we also exploratively examined relationships between inhibition and approach behavior and the ERP components investigated.

2. Method

2.1. Participants

This study forms part of a larger project that investigated reward and

[2] In the past, this component has often been conceptualized as Feedback-Related Negativity (FRN), which is usually calculated by subtracting neural activity of positive feedback from neural activity of negative feedback, resulting in fronto-central negativity after losses (San Martín, 2012). According to recent studies, the neural activity following a feedback should be conceptualized as a positive deflection (RewP), rather than as a negativity (FRN) (Krigolson, 2018; Proudfit, 2015). The present work follows this more recent RewP conceptualization.

punishment processing to different kinds of incentives in both healthy and depressed adolescents (Greimel et al., 2018; Landes et al., 2018). Fifty-four typically developing (TD) children and adolescents (38 females, 16 males) between 8–18 years of age ($M = 13.55$, $SD = 2.91$) were included in the study. Only participants with IQs ≥ 85 ($M = 110.11$, $SD = 11.42$) were included in the study. Age did not correlate with sex, handedness ($n = 4$ sinistral) or IQ (all $ps \geq .188$). We chose to include children from the age of 8 years onwards since the concept of money is fully understood by this age (Grunberg and Anthony, 1980).

Participants were recruited via flyers or from a contact list containing names of families who were interested in participating in research projects within our department. Experienced clinical psychologists screened all participants in order to exclude current or former psychiatric disorders by administering the Kinder-DIPS, which is a well-established, semi-structured diagnostic interview (Schneider et al., 2009). Additionally, the German version of the Child Behavior Checklist (CBCL/4–18; Achenbach, 1993) was used to screen for psychopathological symptoms based on a dimensional measure. Participants were only included if they scored below the clinically relevant CBCL total cut-off score (T-Score ≤ 60).

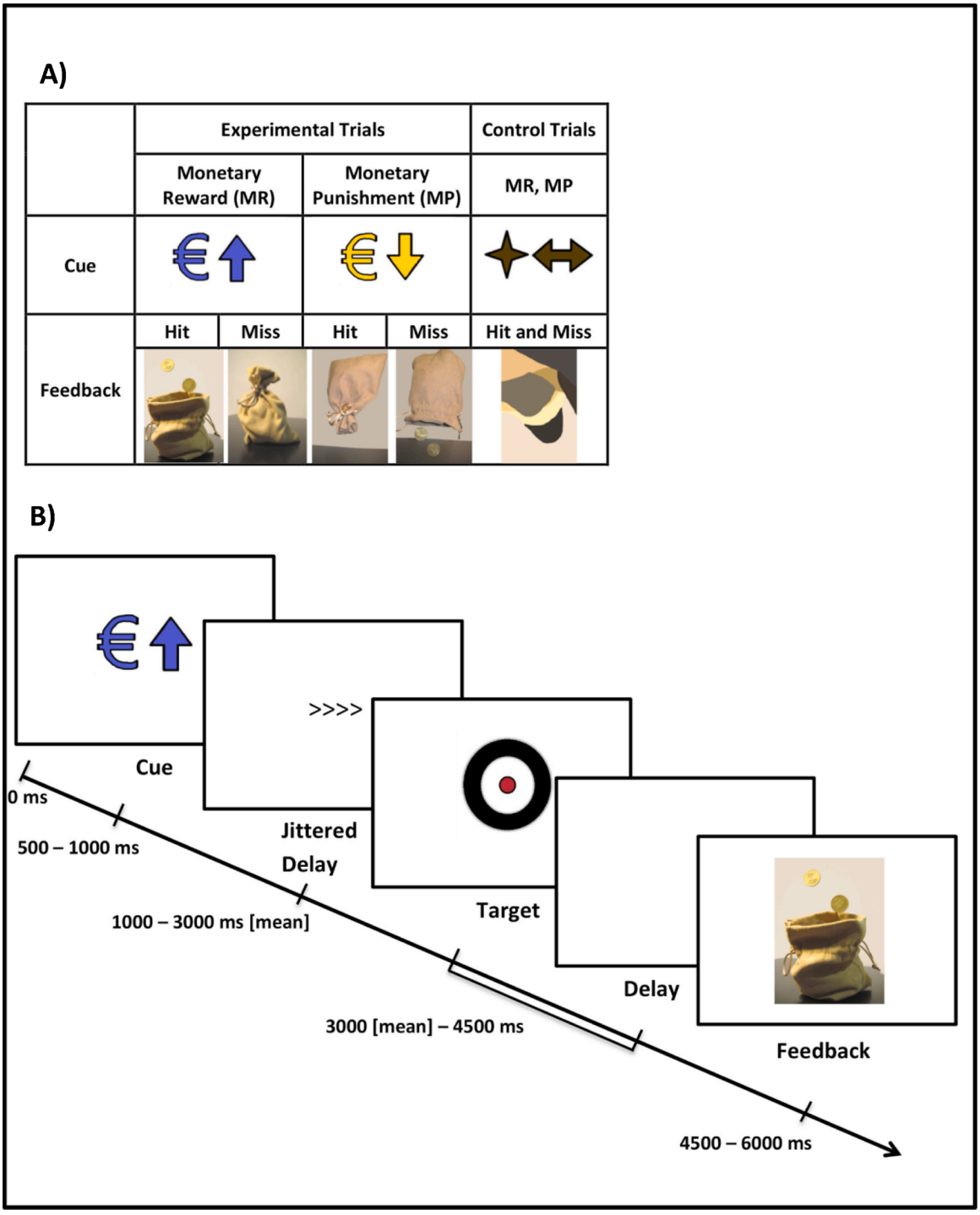

Fig. 1. A) MIDT design and stimuli (cue / feedback) of the experimental and control trials. B) MIDT trial structure (example: Monetary reward condition, positive feedback).

We applied the BIS/BAS scales (Carver and White, 1994; German version by Strobel et al., 2001; modified as parental report by Blair et al., 2004) to assess individual differences in personality traits that reflect the sensitivity of two self-regulatory systems based on four scales. The BIS scale relates to the identification of goal-conflict and the inhibition of ongoing behavior (Wacker et al., 2010), and the three BAS scales (BAS fun, BAS drive, BAS reward) are related to approach motivation (Carver and White, 1994). In more detail, the BAS drive scale is related to an ambition to pursue goals, the BAS fun scale to a desire to receive rewards and the BAS reward to positive reactions towards anticipated or received rewards, respectively (Carver and White, 1994). In the present sample, the mean scores were as follows: BIS ($M = 17.89$, $SD = 2.48$); BAS drive scale ($M = 11.89$, $SD = 2.09$); BAS fun scale ($M = 10.62$, $SD = 1.87$) and BAS reward ($M = 15.75$, $SD = 1.82$) (for an exploratory investigation of linear and quadratic age-related changes in these scales, see supplemental material S4). Higher scores represent higher levels of the respective attribute being measured.

The study was approved by the institutional review board of the Medical Faculty of the Hospital of the Ludwig-Maximilians- University (LMU) Munich and was performed in accordance with the latest version of the Declaration of Helsinki and national legislation. All participants were informed in detail about the experimental procedures and study aims. Informed, written consent (parents; adolescents aged 18 years) and assent (children; adolescents < 18 years) was obtained for all participants. All participants were reimbursed with vouchers.

2.2. Experimental setup and procedure

In the present study, the Monetary Incentive Delay Task (MIDT; Knutson et al., 2001, 2000) was applied. The task is a well-established paradigm to investigate both anticipatory and outcome stages of performance-contingent incentive processing. The trial structure and timing of this paradigm are illustrated in Fig. 1 and were based on prior reports (e.g. Broyd et al., 2012). The MIDT comprised two conditions, a monetary reward (MR condition) and a monetary punishment condition (MP condition), which were presented block-wise. The order of the presentation was counter-balanced. Each condition block comprised 80 experimental trials, as well as 40 control trials serving as a baseline condition. Each of the 80 condition-specific experimental trials offered two possible outcomes which were dependent on the participant's reaction to a cued target symbol (MR condition: "reward" vs. "no-reward" / MP condition: "punishment" vs. "no-punishment"). Participants were instructed to press the mouse button in response to the target with the index finger of the dominant hand as fast and as precisely as possible. If the participant's response to the target appeared in time ("hit"), a relatively positive feedback was delivered (MR condition: "reward" / MP condition: "no-punishment"). In case of a late response (i.e., a response when the target symbol had already disappeared from screen) a relatively negative feedback (MR condition: "no-reward" / MP condition: "punishment") was delivered. Similarly, in experimental trials, anticipatory reactions (i.e., responses before the target symbol appeared on screen) and omissions were followed by a relatively negative feedback.

Each trial started with the presentation of a cue symbol (500 ms) that signaled whether this was a control trial or an experimental trial. The inter-stimulus interval between cue and target was jittered (1750 ms – 2250 ms; mean: 2000 ms) in order to prevent automated responses. Target duration, and thus the response window for a "hit", was set individually based on an online response algorithm (see next two paragraphs), aiming at an individual hit ratio of ~50 % (see Foti and Hajcak, 2009; Santesso et al., 2012). At 1500 ms after target onset, outcomes were presented on screen for 1500 ms, followed by an inter-trial interval (500 ms).

Aligning all participants to an accuracy rate – and thus positive feedback rate – of ~50 % results in approximately the same frequency of positive and negative feedback across all participants and has been proven optimal in regard of motivational value (Martens and White, 1975). The online response algorithm linked the specific reaction within a trial to the actual feedback presented, thus increasing task credibility. Importantly, a manipulation check at the end of the experiment confirmed that all participants perceived the feedback within each trial as performance-contingent. The average hit rate in experimental trials was 46.20 ± 5.54 % in MR trials and 47.59 ± 5.25 % in MP trials (thus approximating the targeted 50 %).

The online response algorithm (for a similar approach, see e.g., Kohls et al., 2013) individually adjusted the response window for each trial based on the reaction times (RTs) of the two previous experimental trials. Initial target duration for each condition was based on the individual's RTs within a condition-specific practice session (19 trials), which preceded each block and helped participants to familiarize with the task. During the experiment, the target duration, and thus the response window, equaled the mean RT of the two previous experimental trials. In case of one invalid response (omission / anticipation), the new target duration equaled the remaining valid previous response. If both previous trials were invalid, the response window remained unchanged. This algorithm also defined the target duration for control trials, although the calculations were exclusively based on the two previous experimental trials.

Before each experimental block, extensive visual and verbal task instructions were given. Hereby, participants were also informed that each monetary feedback stimuli (MR condition: "reward" / "no-reward"; MP condition: "punishment" / "no-punishment") represented the gain / no-gain (MR condition) or loss / no-loss (MP condition) of real money (0.20 €). Participants received a starting value of 8 € and were told that a better performance would result in a higher total win. At the end of the testing session, the bonus of each participant was rounded up to a bonus of 10 € (for a similar approach, see Broyd et al., 2012; Kohls et al., 2011). Response collection and stimulus presentation was controlled by the software E-prime 2.0 (Psychology Software Tools, Pittsburgh, PA; Schneider et al., 2012).

2.3. Stimuli

Cue stimuli (control and experimental condition) were designed with Adobe Photoshop 7.0 and consisted of an array of a condition-specific symbol and an arrow (see Fig. 1). The feedback stimuli of the MR and MP condition were designed to suit the themes of monetary reward ("reward" outcome vs. "no-reward" outcome) and monetary punishment ("punishment" outcome vs. "no-punishment" outcome). Altogether, 40 slightly varying photographs of money bags were presented (10 for each outcome type; for exemplary stimuli, see Fig. 1). The feedback stimuli of the control condition consisted of 10 slightly varying mosaics. The stimuli in the control condition and in both experimental conditions were comparable in regard of luminescence. All stimuli were presented on a 17-inch Dell monitor, placed 70 cm in front of the participant.

2.4. EEG recording and processing

During the experiment, EEG was recorded using an Electrical Geodesic Inc.−128-channel system with a sampling rate of 500 Hz. The impedance was kept below 50 kΩ during recording. Cz was used as the online reference electrode (see Fig. 2).

Further processing steps were performed with Brainvision Analyzer (Brain Products GmbH, Gilching, Germany). After visual inspection of the data and offline filtering with a 0.53 (time constant 0.3) to 30 Hz band-pass (Butterworth zero phase, 12 dB/Oct) and 50 Hz notch filter, independent component analysis was run to remove electro-ocular (EOG) artefacts. Subsequently, all electrodes were re-referenced to the averaged mastoids (Electrode 57LM/100RM, see Fig. 2). Amplitudes exceeding ± 100 μV, bursts of electromyographic activity (maximal allowed voltage step: 50 μV/ms, max-min: 100 μV) and any activity

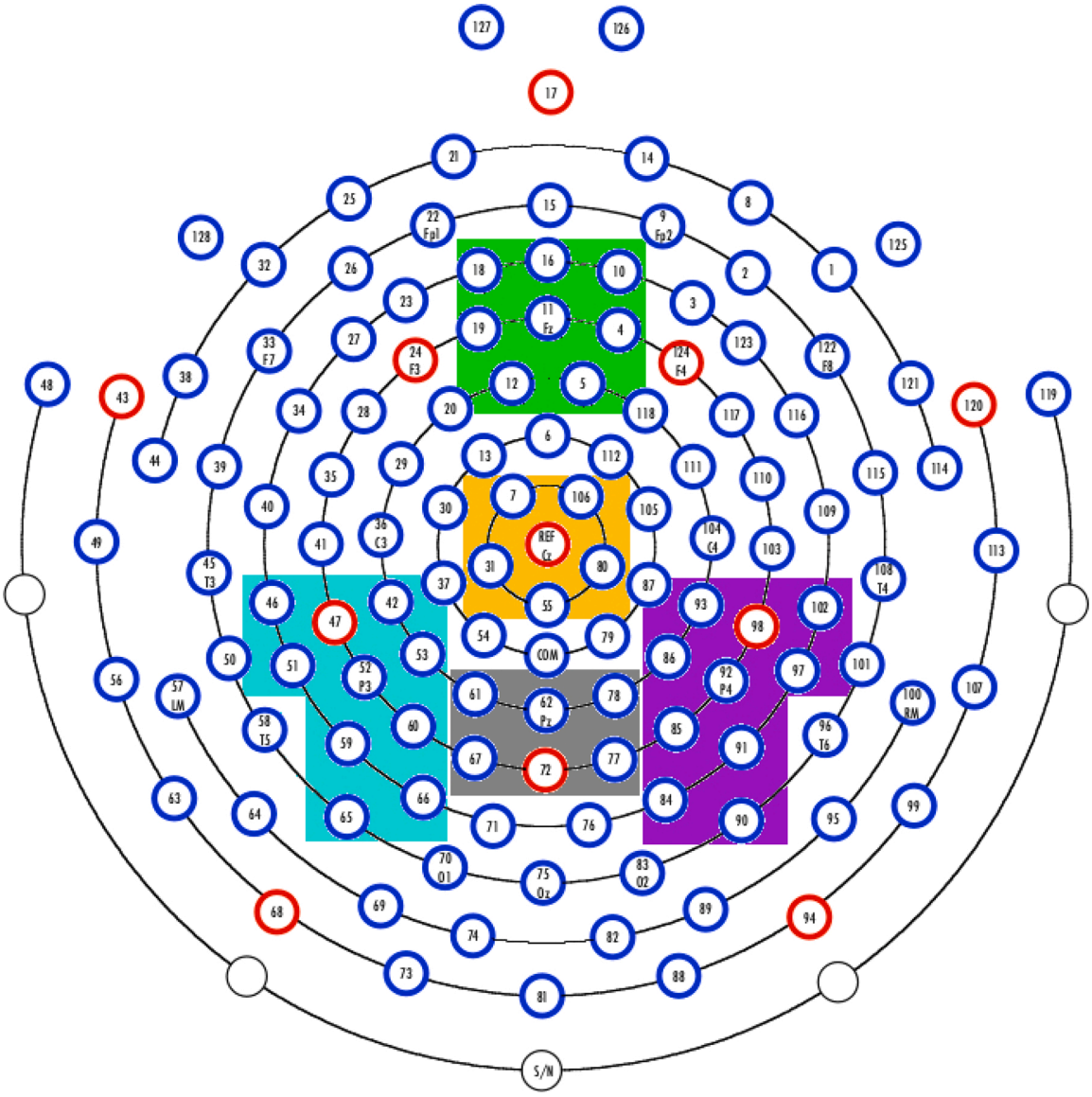

Fig. 2. Illustration of the 128-channel arrangement and electrode position taken from Electrical Geodesic Inc. Black square: Parietal ROI for the cP3 and fP3 analyses, spanning electrodes 61,62[Pz],67,72,77&78; Orange square: Central ROI for the **Δ**RewP analyses, spanning electrodes 7,31,55,80,106,129[Cz]; Green square: Frontal ROI for the **Δ**RewP analyses, spanning electrodes 4,5,10,11[Fz],12,16,18,19; Turquoise shape: Left centro-parietal ROI for the SPN analyses, spanning electrodes 42,46,47,51,52,53,59,60,65,66; Lilac shape: Right centro-parietal ROI for the SPN analyses, spanning electrodes 84,85,86,90,91,92,93,97,98,102.

lower than 0.5 μV in intervals of 100 ms were defined as artefacts and excluded from further processing.

2.5. Data analysis

2.5.1. Behavioral data

RTs of the experimental trials were entered into a mixed-model ANCOVA with age as covariate and block type (MR / MP) as within-subjects factor. To validate motivational speed effects depending on which trial (experimental / control) was presented, RTs between experimental and control trials were compared using paired samples t-tests (separately for the MR and MP condition).

2.5.2. ERP data

Positive feedback trials (i.e., trials with positive outcome valence; "reward" in the MR condition and "no-punishment" in the MP condition) were defined as trials with button presses within the presentation duration of the target. Negative feedback trials (i.e., trials with negative outcome valence; "no-reward" in the MR condition and "punishment" in the MP condition) were defined as trials with late responses (i.e., responses after the target had disappeared). Trials with anticipatory or missed reactions were not included in further analysis.

The continuous EEG was segmented into epochs (stimulus-locked ERPs). For the cP3, fP3 and RewP, the data were segmented into epochs (-200 ms to 1000 ms related to the cue / feedback onset), with the 200 ms pre-stimulus interval used for baseline correction. For the cP3, ERPs were averaged separately for each condition (MR / MP). Regarding the fP3 and RewP, segments were averaged separately for negative and positive feedback trials for each condition and each participant. For the analysis of the RewP, we computed a RewP difference wave (= ΔRewP; Foti and Hajcak, 2009; Novak and Foti, 2015) by subtracting mean amplitudes from negative from positive feedback trials (MR: "reward" – "no-reward"; MP: "no-punishment" – "punishment"). Visual inspection of the topography maps (see supplemental material S7) suggested that the RewP was reliably elicited in the MP condition at frontal cites extending to central cites. However, for the difference wave in the MR condition, no substantial positivity was evident at the frontal or central sites. Therefore, the analyses of the RewP was restricted to the MP

condition. Segments for the SPN were defined from −600 ms to 100 ms relative to the feedback onset with the signal between −600 ms and -400 ms serving as baseline. For the SPN, ERPs were averaged for the four outcome types („reward", „no-reward", „punishment", „no-punishment").

Based on visual inspection of the ERP data and on previous literature, the ROIs (region of interest) for the four ERP components were defined as follows: According to relevant P3 literature, which reports highest P3 amplitudes over centro-parietal regions (Cox et al., 2015; Glazer et al., 2018; Novak and Foti, 2015), the ROIs for the fP3 and cP3 were defined around the electrode Pz, spanning six electrodes (61,62[Pz],67,72,77, 78, see Fig. 2 for the location of ROIs). For the fronto-central ΔRewP (Crowley et al., 2013; Novak and Foti, 2015), we defined a frontal and a central ROI (see Fig. 2): The frontal ROI was defined around the electrode Fz (spanning the electrodes 4,5,10,11[Fz],12,16,18,19), and the central ROI around the electrode Cz (spanning the electrodes 7,31,55, 80,106,129[Cz]). The SPN has previously been shown to be strongest over right lateralized, central and parietal regions (Catena et al., 2012; Kotani et al., 2003). We thus defined two lateralized centro-parietal ROIs. The left centro-parietal ROI included the electrodes 42,46,47,51, 52,53,59,60,65,66; the right centro-parietal ROI included the electrodes 84,85,86,90,91,92,93,97,98,102.

With regard to all components, a minimum of ≥ 20 artefact-free trials per condition / outcome type was necessary for each ROI electrode to be accepted for further analysis. All 54 participants included in the final sample (see "participants") met this criterion. Regarding the cP3 and ΔRewP, there were on average 76 (cP3) / 69 (ΔRewP) trials per condition (MR / MP) to be included in the final analysis. Regarding the SPN and the fP3, there were on average 33 (SPN) / 32 (fP3) trials for each of the four outcome types (reward / no reward / punishment / no punishment) to be included in the final analysis.

ERPs from single electrodes were averaged for statistical analysis within each ROI. To determine individual mean amplitudes for each component, the particular time window was set based on visual inspection of the grand averages and on previous reports: The cP3 was scored as the mean amplitude from 180 ms to 350 ms after cue onset and the fP3 as the mean amplitude from 200 ms to 380 ms after feedback onset (Broyd et al., 2012; Foti and Hajcak, 2009). The ΔRewP was assessed as the mean amplitude from 260 ms to 360 ms after feedback onset (Bress et al., 2012; Lukie et al., 2014).We do not report RewP latencies due to calculation of the difference wave ΔRewP. For the SPN, mean activity values during the last 200 ms before feedback onset were exported for statistical analysis (Glazer et al., 2018; Poli et al., 2007). CP3 and fP3 peak latencies were measured within the interval of 200 ms to 350 ms (cP3) and 200 ms to 400 ms (fP3) after stimulus onset (Goldstein et al., 2006), respectively, and were based on local (±10 data points) instead of absolute peaks (Luck, 2005).

CP3 mean amplitudes and cP3 peak latencies were each analyzed based on a mixed-model ANCOVA with age as covariate and block type (reward / punishment) as within-subjects factor. FP3 mean amplitudes and fP3 peak latencies were each analyzed using a 2 (block type: reward / punishment) x 2 (outcome valence: positive / negative) mixed-model ANCOVA with age as covariate and block type and outcome valence as within-subjects factors. ΔRewP mean values were analyzed based on a 2-way (ROI: frontal / central) mixed-model ANCOVA with age as covariate, and ROI as within-subjects factors. Finally, SPN mean amplitudes were analyzed using a 2 (block type: reward / punishment) x 2 (outcome valence: positive / negative) x 2 (ROI: left / right) mixed-model ANCOVA with age as covariate, and block type, outcome valence, and ROI as within-subjects factors. Explorative analyses of the effects of sex can be found in the supplement (S6).

Control trials were not included in the final ERP analyses, as the P3 components for control trials were characteristically different from those for informative feedback trials (see Santesso et al., 2012 for similar ERP observations), with peaks emerging much earlier for control trials. In regard of the SPN, control trials were not included in further ERP analyses, as it has been reported that this component is only elicited in the prospect of informative feedback (Böcker et al., 1994; Foti and Hajcak, 2012). However, exploratory analyses of ERPs of control vs. experimental trials were conducted. Details can be found in the supplement (S5).

For the cP3, fP3, ΔRewP, and SPN, further post-hoc correlation analyses with age were conducted if ANCOVAs revealed a significant interaction. As the focus of the present study is on age differences, significant interaction effects are only reported if they involve age.

Brain-behavior relationships were investigated in case of significant effects of age on ERP parameters (this approach was chosen to restrict the number of analyses and thus the risk of false positive results). For this aim, correlational analyses were conducted between the respective ERP parameters and (1) behavioral inhibition tendencies (BIS scale; Cronbach's alpha = .77, Vervoort et al., 2019) as well as (2) behavioral approach tendencies (BAS scales) related to incentive processing. In regard of the BAS scales, we focused only on the BAS drive scale to restrict further the number of analyses. This decision was built on the rationale that previous research in developmental samples (1) links between the BAS drive scale and incentive processing (Luking et al., 2016), and (2) better psychometric properties for the BAS drive scale based on confirmatory factor analyses (Pagliaccio et al., 2016; Vervoort et al., 2019) and results on internal consistency (Cronbach's alpha of BAS drive = .86, BAS fun = .57, BAS reward = .72, Vervoort et al., 2019).

Statistical analyses of the ERP data and behavioural data were conducted with IBM SPSS Statistics 24. For all analyses the significance level was set to alpha = .05 (two-tailed). Greenhouse-Geisser's correction was applied to all ANOVAs when violations of the sphericity assumption (Mauchly's test) had to be corrected. Effect size was indicated by partial η^2 (classification of effect sizes η_p^2: .01 = small effect; .06 = medium effect; .16 = large effect; Ellis (2010)).

3. Results

3.1. Reaction time data

The covariate age significantly influenced RTs ($F(1,52) = 27.47$; $p \leq .001$; $\eta_p^2 = .35$), with faster RTs with increasing age across both conditions (MR, MP). There was no significant main effect of block type ($F(1,52) = 0.07$; $p = .799$; $\eta_p^2 = .001$) on RTs. Likewise, the interaction of age and block type was not significant ($F(1,52) = 0.15$; $p = .701$; $\eta_p^2 = .003$). Confirming the motivational value of the informative feedback in experimental trials, paired sample t-tests demonstrated that RTs between experimental and control trials differed significantly for both block types (all $ps \leq .001$) with significantly shorter RTs for experimental (MR: $M = 249.52$, $SD = 49.04$; MP: $M = 251.54$, $SD = 45.56$) compared to control (MR control: $M = 273.3$, $SD = 57.48$: MP control: $M = 274.83$, $SD = 56.04$) trials.

3.2. ERP data

Means for the mean amplitudes of the cP3, fP3, ΔRewP and SPN as well as for the cP3 and fP3 peak latencies are summarized in Table 1. Mean amplitudes for the SPN and the fP3 are depicted in Figs. 3 and 4, respectively. For visualization purposes in the graphs, participants were devided into a younger age group comprising children (8–12 years; n = 25), and an older age group comprising adolescents (13–18 years; n = 29).

3.2.1. Anticipation phase

3.2.1.1. Cue-P3. For cP3 mean amplitudes, there was no significant main effect of age ($F(1,52) = .01$; $p = .923$; $\eta_p^2 < .001$). There was a significant main effect of block type ($F(1,52) = 14.62$; $p < .001$; $\eta_p^2 = .22$)

Table 1
Means and standard deviations (in brackets) of event-related potential parameters.

Reward		*Punishment*	
Cue-P3			
Cue-P3 mean amplitude MR	3.99 (2.53)	Cue-P3 mean amplitude MP	2.8 (2.22)
Cue-P3 peak latency MR	264.65 (29.96)	Cue-P3 peak latency MP	263.43 (30.71)
SPN			
SPN mean amplitude MR reward – right ROI	−1.84 (2.25)	SPN mean amplitude MP no-punishment – right ROI	−1.23 (2.25)
SPN mean amplitude MR no-reward – right ROI	−1.55 (2.26)	SPN mean amplitude MP punishment – right ROI	1.79 (2.82)
SPN mean amplitude MR reward – left ROI	−1.18 (1.98)	SPN mean amplitude MP no-punishment – left ROI	−.48 (2.28)
SPN mean amplitude MR no-reward – left ROI	−.06 (2.22)	SPN mean amplitude MP punishment – left ROI	−.37 (1.84)
Feedback-P3			
Feedback-P3 mean amplitude MR reward	12.73 (6.9)	Feedback-P3 mean amplitude MP no-punishment	9.35 (5.05)
Feedback-P3 mean amplitude MR no-reward	9.53 (6.34)	Feedback-P3 mean amplitude MP punishment	9.47 (5.15)
Feedback-P3 peak latency MR reward	295.65 (38.71)	Feedback-P3 peak latency MP no-punishment	289.34 (35.71)
Feedback-P3 peak latency MR no-reward	277.22 (37.24)	Feedback-P3 peak latency MP punishment	304.41 (35.04)
ΔRewP			
		ΔRewP mean amplitude MP – central ROI	.79 (4.15)
		ΔRewP mean amplitude MP – frontal ROI	1.99 (4.48)

Notes: Amplitude in μV; latency in ms. Abbreviations: MR = monetary reward; MP = monetary punishment; RewP = Reward Positivity (difference wave).

such that mean amplitudes were higher for the MR (3.99 ± 2.52 μV) than for the MP condition (2.80 ± 2.2 μV). The interaction between age and block type was significant ($F(1,52) = 8.74$; $p = .005$; $\eta_p^2 = .14$). However, post-hoc correlation analyses did not reveal a significant relationship between age and cP3 mean amplitude in MR ($r = -0.17$, $p = .222$) or in MP ($r = .17$, $p = .228$) blocks. Scatter plots of the correlation can be found in the supplement (S1). For cP3 peak latency, we found no significant main effects (all $ps \geq .42$) and no significant interaction with age ($F(1,52) = .8$; $p = .374$; $\eta_p^2 = .02$).

3.2.1.2. SPN. For SPN mean amplitudes (see Fig. 3), there was no significant main effect of age ($F(1,52) = 1.69$; $p = .199$; $\eta_p^2 = .03$). A significant main effect of ROI was revealed ($F(1,52) = 6.85$; $p = .012$; $\eta_p^2 = .12$); amplitudes were significantly higher over the right (-1.61 ± 1.73 μV) compared to the left ROI (-.52 ± 1.51μV). The main effect of outcome valence ($F(1,52) = .91$; $p = .346$; $\eta_p^2 = .02$) and the main effect of block type ($F(1,52) = .43$; $p = .517$; $\eta_p^2 = .01$) were not significant. There was a significant three-fold interaction of age with ROI and outcome valence ($F(1,52) = 4.75$; $p = .034$; $\eta_p^2 = .08$). Correlation analyses revealed a significant relationship between age and SPN mean amplitudes for negative outcome valences in the right ROI ($r = .30$, $p = .026$), with higher SPN amplitudes in younger participants (for scatter plots, see supplement S2, see also Fig. 3; for visualization purposes, the mean amplitudes are separately depicted for a younger and older age group). Post-hoc analyses for negative outcome type in the left ROI or for positive outcome type in both ROIs revealed no significant correlations (all $ps \geq .431$). No further interactions involving the covariate age were significant (all $ps \geq .113$).

3.2.2. Outcome phase

3.2.2.1. Feedback-P3. The main effect of age on fP3 mean amplitudes (Fig. 4) was significant ($F(1,52) = 4.9$; $p = .031$; $\eta_p^2 = .09$), with lower amplitudes with increasing age across conditions and outcome valences. Main effects of block type ($F(1,52) = .72$; $p = .399$; $\eta_p^2 = .01$) and valence $F(1,52) = 0.2$; $p = .653$; $\eta_p^2 = .00$) were not significant. A marginally significant three-fold interaction of age with block type and outcome valence ($F(1,52) = 3.18$; $p = .081$; $\eta_p^2 = .06$) was revealed. Exploratory correlation analyses to follow up this trend revealed a significant correlation between age and fP3 mean amplitudes to negative outcomes within the MP condition (i.e. punishment; $r = -0.36$; $p = .008$) (for scatter plots see supplement S3). Correlations of age and fP3 mean amplitudes to positive outcomes within the MP and MR conditions and negative outcomes within MR conditions failed to be significant (all $ps \geq .063$). No interaction involving age reached significance (all $ps \geq .125$). Regarding fP3 peak latencies, no significant main effects of age ($F(1,52) = .04$; $p = .837$; $\eta_p^2 = .00$), block type ($F(1,52) = .12$; $p = .734$; $\eta_p^2 = .00$) and valence ($F(1,52) = 2.28$; $p = .137$; $\eta_p^2 = .04$) were revealed. There was no significant interaction involving the factor age (all $ps \geq .102$).

3.2.2.2. ΔRewP. Regarding ΔRewP mean amplitudes, no main effects of ROI ($F(1,52) = 3.92$; $p = .053$; $\eta_p^2 = .07$) and age ($F(1,52) = 3.14$; $p = .082$; $\eta_p^2 = .06$) were revealed, albeit the RewP marginally increased with age. The interaction of age and ROI did not reach significance ($F(1,52) = 1.85$; $p = .18$; $\eta_p^2 = .03$).

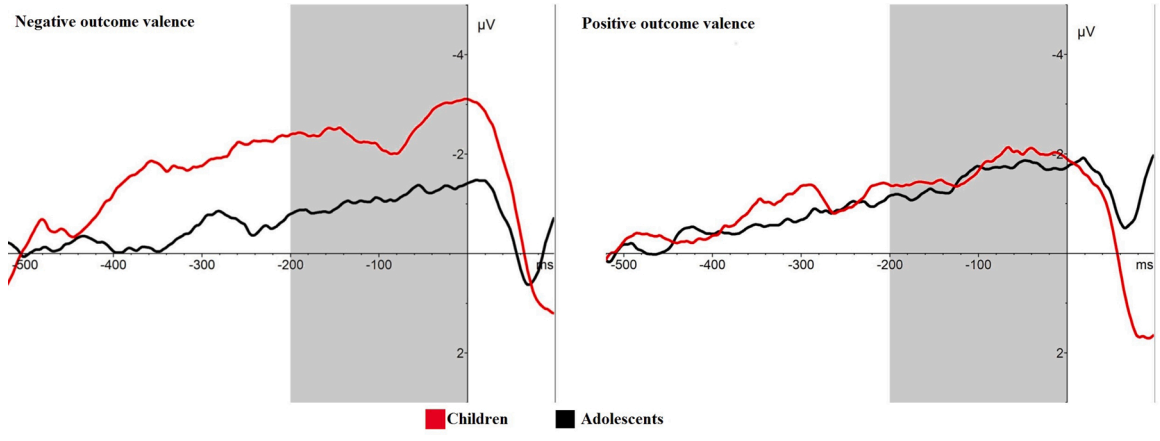

Fig. 3. Stimulus-locked event-related potentials (SPN) preceding incentive delivery for the children group (8-12 years; n = 25; red) and adolescent group (13-18 years; n = 29; black) averaged across the monetary reward and punishment condition at electrode site 92 of the right-hemispheric ROI. Negative outcome valences comprise no-reward and punishment and positive outcome valences comprise no-punishment and reward. For visualization purposes, amplitudes of children and adolescents are depicted separately.

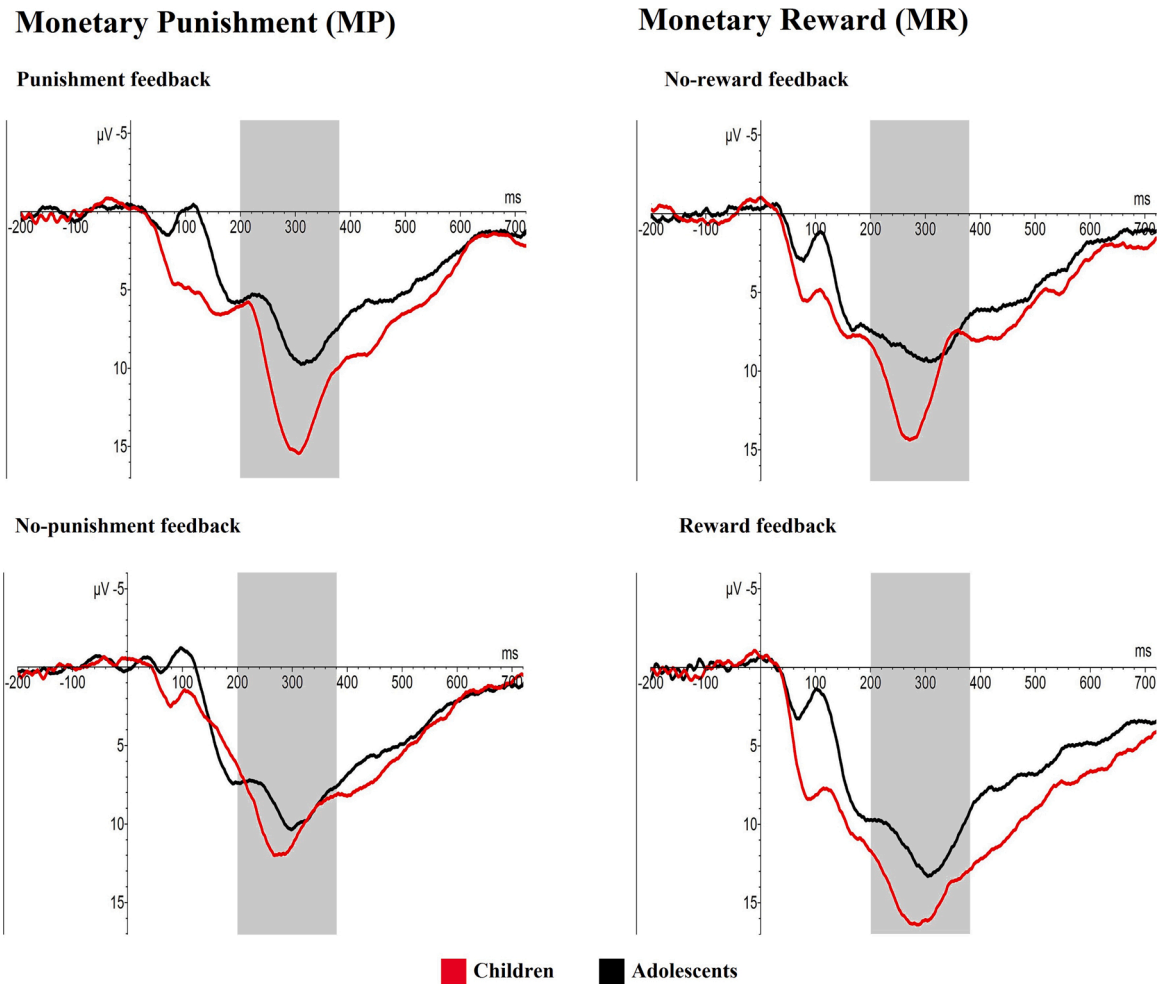

Fig. 4. Stimulus-locked event-related potentials (feedback-P3, fP3) to feedback for the children group (8-12 years; n = 25; red) and adolescent group (13-18 years, n = 29; black) at electrode site 62 (Pz).

3.3. Brain-behavior relationships

Correlation analyses between the BIS / BAS drive scales and the SPN mean amplitude to negative feedback over the right ROI did not reveal any significant relationships. Similarly, correlational analyses between these sclaes and the fP3 mean amplitudes to monetary loss was non-significant (all *ps* $\geq$ .276).

3.4. Exploratory analysis of quadratic relationships

In addition to the analysies described, we exploratively examined the possibility of quadratic age-related changes in ERP parameters. Therefore, linear and quadratic regression curve fitting analyses were conducted for the investigated ERP parameters in the respective experimental conditions and ROIs. The results demonstrated that the quadratic models were always inferior compared to linear models.

3.5. Exploratory analysis of the control condition

Results of an exploratory analysis comparing mean amplitudes of ERPs (cP3, SPN and fP3) in the experimental conditions to the control conditions can be found in the supplement (S5). In brief, results show that for the two ERP components for which age-related changes were revealed (fP3; SPN in the right hemisphere) significantly larger mean amplitudes in the experimental conditions versus the control conditions were evident (all *ps* $\leq$ .026).

4. Discussion

In the current study, we examined the neurophysiological underpinnings of differences in monetary reward and punishment processing from childhood to late adolescence. During incentive anticipation, the SPN amplitude in the right hemisphere decreased with age when anticipating monetary loss or the absence of monetary gain. Moreover, in the outcome stage, explorative analyses suggested diminished fP3 amplitudes to monetary losses with increasing age. No age-related changes were observed in the cP3 and RewP components and in fP3 latency.

The SPN is suggested to reflect a "broad index of anticipatory attention" (Glazer et al., 2018) and is increased when motivationally relevant feedback is anticipated (Brunia et al., 2011). In line with most study results, we found a dominance of the SPN in the centro-parietal ROI of the right hemisphere, as the right anterior insula is discussed to be the neural generator of the SPN (for overviews see Brunia et al., 2011; Glazer et al., 2018). The insula is part of the neural performance monitoring network, which undergoes developmental changes in youth (for a review see Tamnes et al., 2013). The results of a decrease of the SPN from childhood to adolescence for negative outcome valences (i.e. "no reward" in the MR condition and "punishment" in the MP condition) can be interpreted as a lower motivational relevance for cues signalizing negative feedback in older participants compared to younger ones or, in other words, as a higher "wanting" (Berridge et al., 2009) to avoid negatively valenced outcomes in younger participants. In accordance with this explanation, self-report data demonstrate that the fear of

punishment (e.g., the fear of being punished by the mother) is highest in childhood and decreases over the course of adolescence (Westenberg et al., 2007).

Another explanation for our findings relates to the "uncertainty hypothesis", suggesting that the SPN is increased when the feedback outcome is perceived as unpredictable (Catena et al., 2012). In the context of our study, a comparable SPN in children and adolescents to positive outcome valences (i.e., participants responded to the target in time) might reflect that the outcome was similarly predictable for all ages. A decrease in SPN for negative outcome valences from childhood to adolescence might reflect that negative outcome is less predictable for children.

Regarding the cP3 as the second anticipatory component that was examined in our study, we found higher cP3 amplitudes for cues signalizing reward vs. punishment trials across all ages. Similar to our findings, other studies demonstrated a higher cP3 amplitude after cues signalizing the possibility to win money compared to no incentive or monetary loss in adolescents and young adults (Broyd et al., 2012; Santesso et al., 2012). Together with our results, these findings might suggest an increased attention allocation to trials signaling potential monetary rewards across childhood, adolescence and young adulthood.

Concerning the outcome processing stages, our explorative analyses revealed a reduction in fP3 amplitudes to negative outcomes in the MP condition with increasing age. As the P3 component is largest after stimuli with motivational saliency (Nieuwenhuis et al., 2005), our findings suggest a lower motivational salience for negative feedback with increasing age, or, put differently, a higher "disliking" of negative feedback in younger participants. Considering the "adolescent triadic model of motivated behavior", our results support the notion that adolescence is a phase characterized by a greater dominance of the reward compared to the harm-avoidant system (Ernst et al., 2006). Moreover, our findings are corroborated by imaging and behavioral studies demonstrating a lower sensitivity to punishment and negative feedback stimuli in adolescence (e.g., Humphreys et al., 2016; Luking et al., 2016; van den Bos et al., 2012). Similar to our findings, a longitudinal study demonstrated a higher fP3 amplitude after punishment (vs. rewards) in children, which the authors interpreted as greater neural sensitivity to punishment in this age group (Harms et al., 2014). However, our findings for the fP3 should be interpreted with caution, since the three-way interaction with age which was then followed up reached only marginal significance.

Our result of comparable ΔRewP across ages is in line with some previous reports, which also found no age-related changes in this index of reward-related neural activity (Proudfit, 2015) during youth (Larson et al., 2011; Lukie et al., 2014). However, other studies demonstrate an decrease in the RewP/FRN amplitude from childhood to adolescence/adulthood (Crowley et al., 2013; Ferdinand et al., 2016; Pincham et al., 2015). These equivocal results may be attributed to methodological differences between the studies, such as differences in the way the RewP is calculated and the paradigms applied (e.g. gambling tasks vs. probabilistic reinforcement learning tasks vs. incentive delay tasks with performance contingent feedback).

Moreover, it needs to be discussed that the RewP was only reliably elicited in MP trials, but not in the MR trials. This result might well be attributed to methodological reasons. In contrast to previous work on age-related changes, our experimental design included a separate MR and MP condition. Consequently, the RewP difference wave in our study was computed by subtracting negative from positive feedback trials in both the MR and MP condition (i.e., MR: "reward"-"no reward"; MP: "no-punishment"-"punishment"). This approach has the important advantage that neurophysiological processes of reward versus punishment can be decomposed in a fine-graded manner (Novak and Foti, 2015). Future developmental studies assessing the RewP in the context of MIDT should examine whether our pattern of results can be replicted when the experimental design differentialtes between positive and negative outcomes in both reward and punishment conditions.

4.1. General discussion, limitations and conclusions

When taking our findings on the anticipatory and outcome phase together, the results suggest that the sensitivity to negative outcomes/punishment decreases from childhood to adolescence. These findings can be brought in line with research showing that fear of punishment diminishes form childhood to adolescence (Westenberg et al., 2004, 2007). If replicated in longitudinal studies, our results on normative differences in incentive processing provide an important basis for more clinically oriented research investigating disturbances in the developmental trajectories of reward and punishment processing. During the transition phase from childhood to adolescence, there is an increase of several psychiatric conditions (Chau et al., 2004; Le Grange and Lock, 2011; Paus et al., 2008), which are characterized by abnormal reward and punishment processing (Dichter et al., 2012). In future longitudinal studies, it would be important to investigate whether disturbances in age-related changes of punishment sensitivity from childhood to adolescence might be a vulnerability factor for psychopathology later in development. For example, given robust findings on a reduced punishment sensitivity in individuals who are prone to oppositional or deviant behavior (Matthys et al., 2013), future studies should examine whether decreased sensitivity to punishment cues in early childhood might be a risk factor for violence or other rule-breaking behavior. Moreover, depression is characterized by an increased sensitivity for negative cues and a reduced ability to suppress this kind of information (Pizzagalli et al., 2011). Thus, it seems worthwhile to examine possible relationships between disturbed developmental trajectories in punishment sensitivity and risk of youth depression.

Although neural data suggested a decrease of punishment sensitivity from childhood to adolescence, additional analyses did not reveal age-related changes in a behavioral measure of inhibition as assessed by the BIS scale. However, comparable BIS scores across age are not contradictory to the reported differences in the neural data, since neurobiological data can be more sensitive than behavior (Wilkinson and Halligan, 2004). Moreover, the BIS scale contains several questions comprising social punishment sensitivity, which was not operationalized in the present study.

Consistent with other MIDT studies (e.g. Pizzagalli et al., 2009), our behavioral data points towards speed effects in the experimental compared to the control conditions that most likely can be attributed to the informational and motivational content of the experimental stimuli presented. This notion is further supported by our finding of larger SPN in the right hemisphere and fP3 components in the control versus experimental condition (see also Franken et al., 2011). Taken together, behavioral and ERP data prove validity of the applied stimuli and the experimental setup.

Our study is the first to address neurophysiological underpinnings of both anticipatory and outcome reward and punishment components in typically developing children and adolescents. However, to be able to draw more comprehensive conclusions, it would be important to additionally include adults in follow-up studies (cf. Hämmerer et al., 2011) since maturation of several reward-related brain structures continues well into early adulthood (Casey, 2015; Casey et al., 2008). Another limitation of our study is the cross-sectional design, as developmental changes are better assessed longitudinally. Finally, our study population included about twice as many females than males and sex has been shown to influence neural correlates of reward and punishment processing (Crowley et al., 2013; Greimel et al., 2018). In this context it should be noted that sex distribution did not vary with age in the present sample. As we only included a relatively small group of boys, a detailed investigation of how sex impacts on age-related changes in neural incentive processing was beyond the scope of our study. Our explorative analysis of the effects of sex indicated that sex might influence ERP components of reward and punishment processing. Further developmental studies with larger sample sizes should therefore examine systematically how sex influences on incentive-related ERPs in youth

(Crowley et al., 2013). Despite these limitations, our findings extend previous research on incentive processing in youth and provide important new insights into the neurophysiological mechanisms underlying developmental differences in reward and punishment processing in childhood versus adolescence.

4.2. Conclusion

Here, we examined the cP3, SPN as anticipatory ERP components and the fP3 and RewP as outcome ERP components in children and adolescents within one single study. Our results suggest a decrease in sensitivity to negative feedback from childhood to adolescence, which was evident in both anticipatory and outcome processing stages. Future longitudinal studies are needed to investigate whether disturbances in developmental processes of reward and punishment processing might be a risk factor for the development of psychiatric diseases in adolescence, which are associated with disturbed incentive processing.

Data statement

To adhere to principles of open science and to facilitate further use of aggregated data in meta-analytical approaches, we will consider making raw data available to other researchers if this can be achieved along with protecting sensitive information of the participants, such as socio-demographic information.

Since participants could possibly be identified by making our raw data publicly available, ethical principles of protecting participant confidentiality would be breached. Aggregated group data can be made available on request.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.dcn.2020.100896.

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