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Feedback processing in children and adolescents: Is there a sensitivity for processing rewarding feedback?

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ABSTRACT

Developmental studies indicate that children rely more on external feedback than adults. Some of these studies claim that they additionally show higher sensitivity toward positive feedback, while others find they preferably use negative feedback for learning. However, these studies typically did not disentangle feedback valence and expectancy, which might contribute to the controversial results. The present study aimed at examining the neurophysiological correlates of feedback processing in children (8–10 years) and adolescents (12–14 years) in a time estimation paradigm that allows separating the contribution of valence and expectancy. Our results show that in the feedback-related negativity (FRN), an event-related potential (ERP) reflecting the fast initial processing of feedback stimuli, children and adolescents did not differentiate between unexpected positive and negative feedback. Thus, they did not show higher sensitivity to positive feedback. The FRN did also not differentiate between expected and unexpected feedback, as found for adults. In contrast, in a later processing stage mirrored in the P300 component of the ERP, children and adolescents processed the feedback's unexpectedness. Interestingly, adolescents with better behavioral adaptation (high-performers) also had a more frontal P300 expectancy effect. Thus, the recruitment of additional frontal brain regions might lead to better learning from feedback in adolescents.

1. Introduction

The ability to process external feedback is important in order to flexibly optimize our behavior, avoid harmful stimuli or situations, and seek out rewarding ones. It is especially important during development because children constantly encounter situations in their daily lives where they receive corrective feedback from parents or teachers. The ability to process and evaluate feedback develops during childhood and adolescence and is closely related to the maturation of the mediofrontal cortex, especially the anterior cingulate cortex (ACC), and the midbrain dopamine system (e.g., Casey et al., 2008; Fareri et al., 2008; Galvan, 2010; Hämmerer and Eppinger, 2012; Luciana et al., 2012; Somerville and Casey, 2010). It is not only crucial for the development of children's cognitive skills, e.g., their learning abilities, but also for self-regulation (e.g., Smith et al., 2013). However, the neuronal basis of feedback processing and its course of development are not yet well understood. An open question that is of high interest from a developmental as well as from an applied perspective is whether the sensitivity to positive and negative feedback is changing during childhood and adolescence. For instance, an increased responsiveness to positive, rewarding stimuli is often suggested to explain adolescent risk-taking (e.g., Casey et al., 2008; Ernst, 2014). The present study approaches this question by examining feedback processing after positive and negative feedback in children (8–10 years) and adolescents (12–14 years) by means of event-related potentials (ERPs).

Feedback processing can be examined online by means of the feedback-related negativity (FRN), an ERP component which is measured over fronto-central brain areas approximately 200–300 ms after subjects receive feedback and whose likely generator lies in the ACC (e.g., Gehring and Willoughby, 2002; Ferdinand and Opitz, 2014; Gehring et al., 2012; Holroyd and Coles, 2002; Miltner et al., 1997). It has been suggested that the FRN is elicited by decreases in dopamine activity when events occur that are classified as "worse than expected" and that its role is to train the ACC to adjust behavior (Holroyd and Coles, 2002). In line with this, studies show an FRN for negative feedback that increases with learning (e.g., Holroyd and Coles, 2002; Nieuwenhuis et al., 2002; Cohen et al., 2007; Opitz et al., 2011). However, recent findings indicate that positive feedback might also play a crucial role in behavioral adaptation and that it elicits a feedback positivity in the

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ERP (e.g., Eppinger et al., 2008; Holroyd et al., 2008; Potts et al., 2006). An alternative view proposes that the ACC is constantly predicting the likely outcomes of actions and signaling unexpected violations of these predictions (Alexander and Brown, 2011). Consistent with this, imaging studies have found larger ACC activation after unexpected events, signaling the need for increased control (Braver et al., 2001; Aarts et al., 2008; Jessup et al., 2010). There is currently no consensus about which aspects of the feedback, e.g., its valence or its unexpectedness, primarily drive learning. One reason for this discordance might be that as a consequence of the learning process, feedback valence and expectancy are oftentimes confounded. At the beginning of learning, positive and negative feedback should be equally unexpected. However, with the progress of learning, positive feedback will become more and more expected, while negative feedback will become unexpected. There are very few ERP studies that explicitly aimed at avoiding this confound during learning. They found that unexpected positive and unexpected negative feedback elicited an FRN in adult samples (Ferdinand et al., 2012; Oliveira et al., 2007).

To our knowledge there have been no similar attempts in developmental studies. However, the developing brain underlies a multitude of maturational changes which should, among other things, result in age-related changes in feedback processing well into early adulthood. According to recent developmental models, these changes should be particularly pronounced during adolescence, when an imbalance between brain systems responsible for cognitive control and those processing motivational or reward information results in mainly reward-driven behavior (e.g., Casey and Jones, 2010; Crone and Dahl, 2012; Ernst, 2014; Galvan, 2010). However, there are only a handful of electrophysiological studies examining feedback processing in children and adolescents to evaluate these theoretical considerations (for a review see Ferdinand and Kray (2014)). For example, it has been found that the FRN decreases with increasing age (Eppinger et al., 2009; Hämmerer et al., 2010; Zottoli and Grose-Fifer, 2012). This was interpreted as children showing a stronger reaction to external feedback as compared with adults, because external feedback plays a greater role in children's behavioral control while their internal control and monitoring processes are not yet fully developed (Crone et al., 2006). Additionally, relative to adolescents and younger adults, children's FRN amplitude usually differentiates less well between positive and negative feedback (Hämmerer et al., 2010; Mai et al., 2011; Zottoli and Grose-Fifer, 2012). This suggests that although they respond stronger to feedback in general, their monitoring system does not yet differentiate between these different outcomes. In line with the finding that children usually need longer to learn from feedback (e.g., Crone et al., 2006; Hämmerer et al., 2010), this indicates that they are less able to use the information conveyed by the feedback to change their behavior accordingly.

As for the question of whether children preferentially process positive or negative feedback, findings are less homogeneous. Eppinger et al. (2009) found a larger FRN after negative feedback for 10–12 year-old children as compared to young adults, whereas no age differences were obtained in the ERP after positive feedback in a probabilistic learning task. They inferred that children are more sensitive to negative feedback than adults. Similarly, Hämmerer et al. (2010) inferred a negativity bias in children's feedback processing because they showed less efficient behavioral adaptation after positive feedback (i.e., children showed more random behavior than adults). In contrast, Zottoli and Grose-Fifer (2012) compared feedback processing in adolescent (14–17 years) and young adult (22–26 years) males using a gambling task with unpredictable gains and losses. They found that the FRN in both age groups was larger for low than high gains, but this differentiation was not present for low and high losses. Although the authors suggested this might be due to the fact that their participants processed a low reward as a negative outcome, it could also hint towards a greater sensitivity or differentiation for rewards.

However, earlier studies are not well suited to answer the question of whether children preferentially process positive or negative feedback because the results are most probably influenced by differences in feedback expectancy (cf. Ferdinand et al., 2012). Earlier studies either used learning or gambling paradigms. Learning paradigms have the problem mentioned above that feedback expectancy and valence are confounded. In gambling, feedback is not behaviorally relevant and irrational expectancies (e.g., the gamblers' fallacy) can occur. Taken together, although models of brain maturation imply that the brain systems responsible for cognitive control and reward processing mature with different developmental trajectories, the respective impact of positive vs. negative feedback during learning and whether it changes during development is still an open question.

Therefore the goal of the present study was to examine the relative influence of valence and expectancy in feedback processing in children and adolescents using a paradigm including behaviorally-relevant feedback. For this purpose, we used a child-friendly version of a time estimation task in which positive and negative feedback were equally unexpected and were contrasted with expected feedback. This paradigm has proven useful in studies of adults by showing that positive and negative feedback can elicit a FRN of the same size when they are both unexpected (Ferdinand et al., 2012). Importantly, this FRN was larger than that after expected feedback (cf. Oliveira et al., 2007). Another finding of those studies was that unexpected positive feedback elicited a larger P300 than unexpected negative feedback, which was attributed to working memory updating after unexpected task-relevant events (for a review see Polich (2004, 2007)). It was concluded that in adults, the FRN is sensitive to learning-relevant expectancy violations and is not biased toward the processing of either positive or negative feedback. In contrast, the P300 is also sensitive to the feedback's valence.

In the present study, we were interested in whether children's and adolescents' ERPs would differentiate between positive and negative feedback if expectancy effects were kept equal between conditions. On the basis of earlier findings and the developmental considerations reported above, our hypotheses were that (a) children would have larger FRNs and (b) would show less differentiation between expected and unexpected feedback in their FRNs than adolescents. We also hypothesized that (c) adolescents would be more sensitive to positive feedback (in FRN and P300) because of an overactive reward system in combination with not yet fully developed cognitive control.

2. Material and methods

2.1. Participants

Twenty-three children (8–10 years) and 24 adolescents (12–14) took part in this study and received 24€ for their participation. Informed consent was signed by their legal guardians. All were healthy, right-handed, and had a normal or a corrected to normal vision. Three children were excluded, one because of motivational problems in sticking to the task and two because the adaptive mechanism did not succeed in generating the feedback frequencies as intended (trial numbers for negative feedback were 5 and 11, respectively). The effective sample consisted of 20 children (mean age = 9.8 years, SD = 0.8, 12 female) and 24 adolescents (mean age = 13.5 years, SD = 1.0, 14 female).

In order to assess the cognitive abilities of the two samples, all participants performed the Digit-Symbol Substitution Test (DSST; Wechsler, 2008) as a marker of perceptual speed, the Digit-Backwards Span Test (DBST; Wechsler, 2008) as a marker of working memory capacity, and a modified computer version of the Spot-a-Word Test (MWT-B, Lehrl, 1977) as a marker of verbal knowledge. In all tests, adolescents performed better than children (see Table 1) and all participants

Table 1
Results of psychometric tests (means and standard deviations; *$p<.05$, **$p<.01$, two-tailed).

	Age group		t-Value
	Children	Adolescents	(df=42)
DSST (correct items) (SD)	35.0 (12.5)	52.0 (12.0)	4.58**
Digit Backwards Span (SD)	4.2 (0.9)	5.1 (0.8)	3.51**
MWT-B (correct items) (SD)	10.5 (4.1)	13.3 (4.0)	2.27**
Parental Education (years) (SD)	15.8 (3.6)	14.4 (6.8)	< 1

Note: DSST=Digit Symbol Substitution Test (Wechsler, 2008); MWT-B=Spot-a-Word Test, Version B (Lehrl, 1977).

performed well within the normal range of their age groups. Also, parents' educational levels were comparably high (see Table 1) with 61.4% of them having at least a high-school diploma.

2.2. Task, stimuli, and procedure

After parents gave informed consent for their child's participation in the study, they filled out a short demographic questionnaire. Then participants performed the cognitive tests (DSST, DBST, MWT-B). After fitting of the electrode cap, they performed a time estimation task (adapted from Ferdinand et al. (2012)). They were instructed to press a response key exactly 2.5 s after a fixation cross vanished from the screen. Five seconds after the disappearance of the fixation cross, they received positive, intermediate, or negative feedback about their accuracy in form of a blue, yellow, or purple rectangle. The assignment of colors to feedback was counterbalanced across subjects. There were variable presentation times for the fixation cross (250, 500, or 750 ms) and inter-trial interval (750, 1000, 1250 ms) to prevent rhythmic responses. The experimental task consisted of one practice block with 20 trials and 15 experimental blocks with 20 trials each. An adaptive mechanism ensured that the frequency of positive and negative feedback was kept low and unexpected (at ~20%, respectively) and the frequency of intermediate feedback was high and thus expected (at ~60%).

The instruction was given in form of a cover story. All participants were told that they should test a new security system to protect Scrooge McDuck's Money from the Beagle Boys. Depending on their performance, they would either catch them ("excellent" feedback) or they would steal money ("bad" feedback). A colored time line explained the meaning of the feedback in relation to the subjects' performance. If their estimation was close to 2.5 s they would receive an "excellent" feedback (Beagle Boys caught). If they pressed the button very early or very late, they would get "bad" feedback (Beagle Boys stole money). Most of the time they would receive "ok" feedback (Beagle Boys escaped but did not steal money). Participants were instructed to catch the Beagle Boys as often as possible and to avoid them stealing money.

Before the experiment, a practice block was administered. During this practice block, negative feedback was given if the participant's response was slower than 3200 ms or faster than 1800 ms. Positive feedback occurred between 2350 ms and 2650 ms. For response times from 1800 to 2350 ms or from 2650 to 3200 ms intermediate feedback was given. In the following experimental trials, outer time windows were adjusted every 20 trials by adding (to the upper time limit) and subtracting (to the lower time limit) 75 ms whenever negative feedback occurred in less than 20% of the last 20 trials and overall or by subtracting (to the upper time limit) and adding (to the lower time limit) whenever negative feedback occurred in more than 20% of the last 20 trials or overall. The inner time window (2350–3200 ms) was adjusted analogously by adding or subtracting 15 ms whenever positive feedback occurred in more or less than 20% of the last 20 trials or overall.

2.3. EEG recording

The task was performed in an electrically shielded chamber. During the task, EEG was recorded from 26 Ag/AgCl electrodes embedded in an elastic cap (EasyCap, Brain Products, Germany) and recording locations were based on the extended 10–20 System (Jasper, 1958). EEG was amplified from DC to 100 Hz at a sampling rate of 500 Hz using Brain Vision Recorder (Brain Products, Germany). An additional electrode on the left mastoid served as reference, the ground electrode was placed at AFz. To control for eye movements, EOG was recorded from four electrodes at the outer ocular canthi and right suborbital and supraorbital ridges. Impedances were kept below 20 kΩ. Off-line processing of EEG data was conducted using the eeprobe software package (ANT Software: 〈www.antneuro.com/products〉). Data were bandpass filtered from 0.5 to 30 Hz off-line and re-referenced to linked mastoids. Eye movements were corrected by a linear regression approach (Gratton et al., 1983), recording epochs with other artifacts were rejected whenever the standard deviation in a 200 ms interval exceeded 30 μV in any EOG channel. For the analysis of feedback-locked ERPs, epochs of 100 ms before to 700 ms after feedback presentation were extracted and baseline-corrected with respect to 100 ms pre-feedback recording interval.

2.4. Statistical analyses

Analyses of behavioral data included mean feedback frequencies and estimation times. To examine the change of these dependent measures over the course of the experiment, the 300 experimental trials were subdivided into 6 bins. Trials with timeout were excluded from analyses of the behavioral and EEG data. Time estimation performance was additionally analyzed by measuring the absolute time difference between estimation time and target time (2.5 s). Additionally, the ability to adapt behavior after the feedback was measured by calculating each participant's probability of generating a better time estimation (one that is closer to the target time) after having received negative feedback in the previous trial. In this calculation, over-adaptation (i.e., generating an overestimation after having generated an underestimation in the previous trial or vice versa), was not assessed as an improvement: If a participant received negative feedback because the time estimation was too slow, the feedback in the next trial was counted as better if it was positive or intermediate feedback from the too-slow range (analogously for the too-fast range). To examine whether this ability for behavioral adaptation on the single trial level was related to the electrophysiological correlates of feedback processing, this probability was calculated for each participant and a median split was used to group participants into those with a high and those with a low probability to adapt their behavior after negative feedback. Analyses of EEG data were based on feedback-locked ERPs. Time windows for the FRN and the P300 were selected according to prior studies and visual inspection of the ERP. To reduce component overlap (cf. Holroyd et al., 2006; Ferdinand et al., 2012), the FRN was defined as the peak-to-peak difference between the positivity in a 200–280 ms time window and the following negativity in a 280–380 ms time window after feedback presentation at electrode FCz where it usually is found to be maximal (e.g., Gehring and Willoughby, 2002). The P300 was defined as the mean amplitude between 400 ms and 500 ms after feedback presentation. To additionally analyze topographical differences between the age groups (cf. Thomas and Nelson, 1996; Ferdinand et al., 2012), the P300 was measured at electrodes FCz, Cz, CPz, and Pz.

Behavioral and ERP data were analyzed using repeated measures analyses of variance (ANOVAs) with an alpha level of.05. Greenhouse–Geisser correction for non-sphericity was applied whenever appropriate and epsilon-corrected p-values are reported together with uncorrected degrees of freedom. To examine the effects of feedback expectancy (expected intermediate vs. unexpected positive and negative feedback) and feedback valence (unexpected positive vs. unexpected negative feedback) which have been previously reported for adult samples, a-priori defined orthogonal contrasts were included in the analyses. To avoid unnecessary comparisons, electrode sites in the P300 analysis were subsumed in the factor Anterior/Posterior and repeated contrasts, i.e., FCz vs. Cz, Cz vs. CPz, and CPz vs. Pz, were defined a-priori. For reasons of clarity, only main effects and interactions including the experimental factors of interest, i.e., Age Group, Feedback Expectancy, and Feedback Valence, will be reported.

3. Results

3.1. Behavioral results

Manipulation check: An ANOVA with the factors Feedback Type (positive, negative, intermediate), Bin (1–6), and Age Group (children, adolescents) on feedback frequency revealed a main effect for Feedback Type ($F(2,84)=543.07$, $p<.01$, $\eta^2_p=.93$). Intermediate feedback was more frequent ($M=56.99\%$, $SD=.10$) than positive or negative feedback ($F(1,42)=1017.19$, $p<.01$, $\eta^2_p=.96$), while positive and negative feedback were both infrequent ($M=20.6\%$, $SD=.11$ and $M=21.8\%$, $SD=.10$, respectively) and did not differ from each other ($p>.32$). There were no further main effects or interactions (all p-values $>.37$). These results show that the adaptive mechanism worked as intended and that in the following, positive and negative feedback can be compared without the confounding influence of differing feedback frequencies.

Estimation performance: Both age groups did fairly well in estimating the target time (children: $M=2279$ ms, $SD=674$ ms; adolescents: $M=2407$ ms, $SD=603$ ms). Time estimation performance was analyzed by measuring the absolute time difference between the estimation time and the target time (Fig. 1). An ANOVA with the within-subjects factor Bin (1–6) and the between-subjects factor Age Group (children, adolescents) revealed a

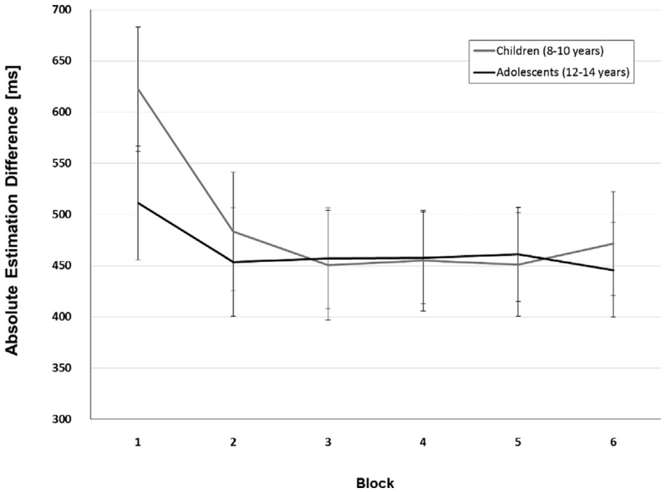


Fig. 1. Absolute differences between estimation and target time over the course of the experiment (bars denote standard errors of the mean): both age groups generate more precise time estimations over the course of the experiment.

quadratic trend for Bin ($F(1,42)=4.76$, $p<.05$, $\eta^2_{part}=.10$) with time differences getting smaller over the course of the experiment. Additionally, the probability of generating a time estimation that was closer to the target time after having received negative feedback was compared between the age groups. A *t*-test for independent samples showed that this probability did not differ between the two age groups ($p=.63$, two-tailed; children: $M=.53$, $SD=.10$; adolescents: $M=.51$, $SD=.08$).

3.2. EEG data

Peak-to-peak FRN: The ANOVA with the factors Age Group (children, adolescents) and the two planned contrasts reflecting Feedback Expectancy (intermediate vs. unexpected feedback) and Feedback Valence (unexpected positive vs. unexpected negative) revealed that children displayed larger peak-to-peak FRNs than adolescents ($F(1,42)=14.23$, $p<.01$, $\eta^2_{part}=.25$). Feedback Expectancy was marginally not significant ($F(1,42)=2.9$, $p=.09$, $\eta^2_{part}=.07$). The interactions between Feedback Expectancy and Age Group and between Feedback Valence and Age Group failed to reach significance (all *p*-values $>.26$; Figs. 2 and 3).

P300 mean amplitude: The ANOVA with the factors Age Group (children, adolescents), Anterior/Posterior (FCz, Cz, CPz, Pz), and the two planned contrasts reflecting Feedback Expectancy and Feedback Valence resulted in a main effect of Feedback Expectancy ($F(1,42)=19.0$ $p<.01$, $\eta^2_{part}=.31$), interactions between Age Group and Feedback Expectancy ($F(1,42)=7.1$, $p<.05$, $\eta^2_{part}=.15$), Age Group and Anterior/Posterior ($F(1,42)=11.8$, $p<.01$, $\eta^2_{part}=.22$ at electrodes CPz vs. Pz), Feedback Expectancy and Anterior/Posterior ($F(1,42)=5.9$, $p<.05$, $\eta^2_{part}=.12$ at electrodes CPz vs. Pz), and Feedback Valence and Anterior/Posterior ($F(1,42)=4.2$, $p<.05$, $\eta^2_{part}=.09$ at electrodes FCz vs. Cz) were found (see Figs. 2 and 4).

Further analyses revealed that the interaction between Age Group and Feedback Expectancy was due to a significant effect of Expectancy for adolescents ($F(1,23)=39.6$, $p<.01$, $\eta^2_{part}=.63$) but not for children ($p=.34$). The interaction between Expectancy and Anterior/Posterior (electrode locations CPz and Pz) was found to be due to a more pronounced expectancy effect over parietal electrodes as can be inferred from the effect sizes (CPz: $F(1,43)=19.8$, $p<.01$, $\eta^2_{part}=.32$; Pz: $F(1,43)=30.4$, $p<.01$, $\eta^2_{part}=.41$). However, because the Expectancy effect was significant for adolescents only, we additionally examined the Expectancy effect at electrodes CPz and Pz separately for children and adolescents in a post-hoc fashion. These analyses revealed that while adolescents had a more broadly distributed expectancy effect, i.e., it was significant for both electrodes (CPz: $F(1,23)=43.0$, $p<.01$, $\eta^2_{part}=.65$; Pz: $F(1,23)=43.1$, $p<.01$, $\eta^2_{part}=.65$), for children, the effect was present only at Pz ($F(1,19)=4.4$, $p<.05$, $\eta^2_{part}=.19$). The interaction of Age Group and Anterior/Posterior was not analyzed further because it is not relevant for the question of interest. To further examine the Feedback Valence effect, positive vs. negative feedback was analyzed at FCz and Cz separately, but neither electrode showed a significant Valence effect (both *p*-values $>.17$).

In studies on feedback processing, the P300 usually has a parietal focus. This was also the case for the P300 in our earlier study examining younger adults (cf. Ferdinand et al., 2012). However, the analysis above indicates, that the P300 expectancy effect seems to be more broadly distributed over the scalp in adolescents. This could indicate that additional frontal brain areas can be accessed in adolescence to evaluate the feedback in our task. Therefore, to examine whether the ability to adapt one's behavior after unexpected negative feedback was related to the size and topographical distribution of the P300 expectancy effect, an ANOVA with factors Performance Adaptation (high, low) and Anterior/Posterior (FCz, Cz, CPz, Pz) was conducted with the size of the P300 expectancy effect as dependent variable. Because the expectancy effect was significant for adolescents only, this exploratory analysis was conducted only for this age group. It revealed a significant interaction between Performance Adaptation and Anterior/Posterior ($F(1,22)=5.7$, $p<.05$, $\eta^2_{part}=.21$ at electrodes FCz vs. Cz). Further comparisons demonstrated that this effect was due to the fact that adolescents with a high probability of adapting their time estimations after unexpected negative feedback (high-performers) had a larger P300 expectancy effect at FCz ($F(1,22)=4.7$, $p<.05$, $\eta^2_{part}=.18$) than those with a low probability of behavioral adaptation (low-performers; see Fig. 5). Additionally, to corroborate that the frontal shift of the P300 in adolescents was related to prefrontal functioning, we analyzed correlations of P300 amplitude at FCz with the performance on the DSST and Digit Backwards Span. We found that higher values on the DSST (higher fluid intelligence) were associated with a larger P300 amplitude after unexpected feedback at frontal electrode sites indicating a smaller difference between expected und unexpected feedback conditions ($r(22)=.51$, $p<.05$).

4. Discussion

The main goal of our study was to examine whether children and adolescents differ in how they process the valence and expectancy of feedback. For this purpose, we conducted a child-friendly version of a time estimation task with an adaptive mechanism controlling feedback probabilities. This adaptive mechanism succeeded in generating frequent intermediate feedback (about 60%) and infrequent positive and negative feedback (about 20%, respectively). Thus positive and negative feedback should have been perceived as equally unexpected and could be examined without the confounding influence of expectancy differences, which is difficult to accomplish in many learning paradigms. Our behavioral data showed that children as well as adolescents learned to produce better time estimations over the course of the experiment. This means that the feedback was useful to adapt their behavior.

In the electrophysiological data, we found that children generated a larger peak-to-peak FRN than adolescents. Interestingly, this effect seems to be independent of the feedback's valence and its expectancy. This is in line with earlier ERP findings and has been interpreted as children's monitoring system reacting more strongly to external feedback than that of adolescents or adults (e.g., Eppinger et al., 2009; Hämmerer et al., 2010; Zottoli and

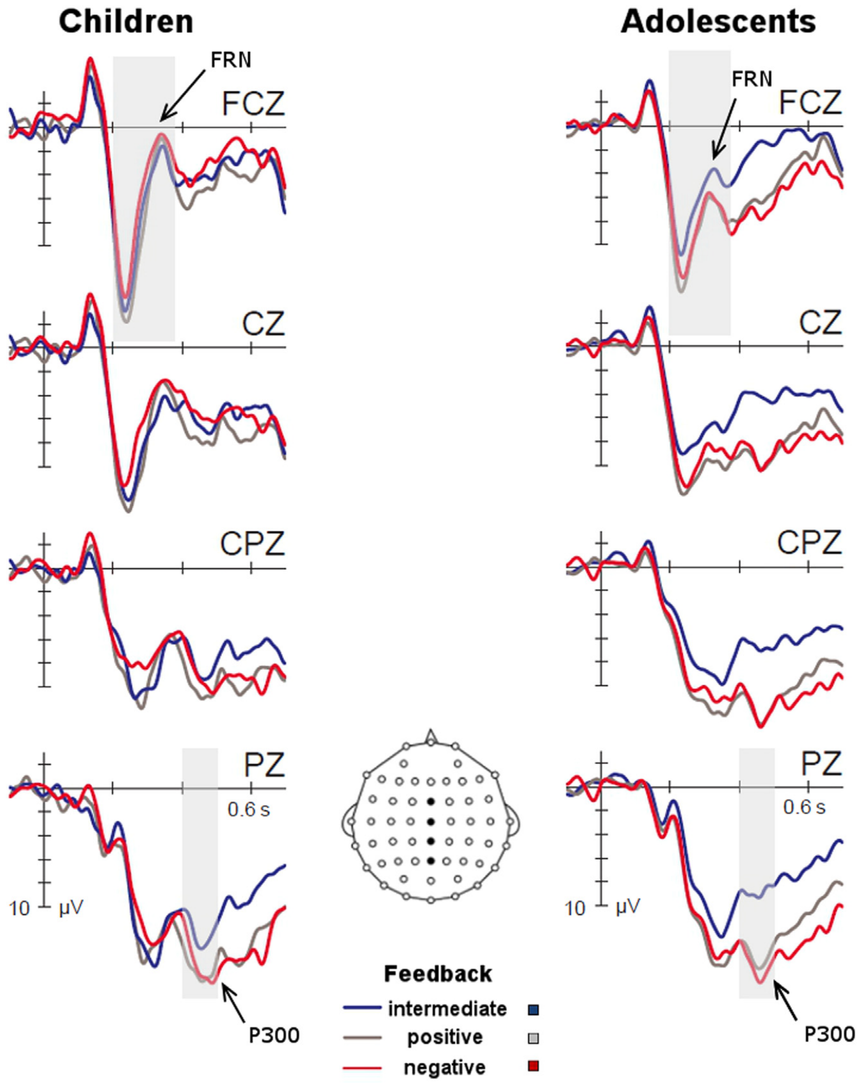


Fig. 2. Feedback-locked ERPs for the two age groups at midline electrodes FCz, Cz, Cpz, and Pz (negative voltages are plotted upwards).

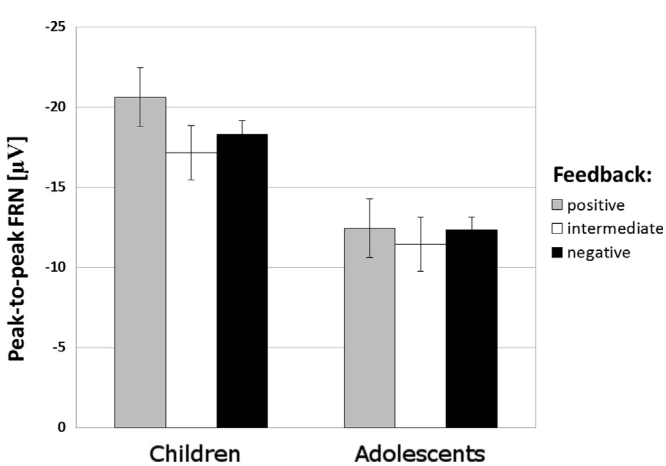
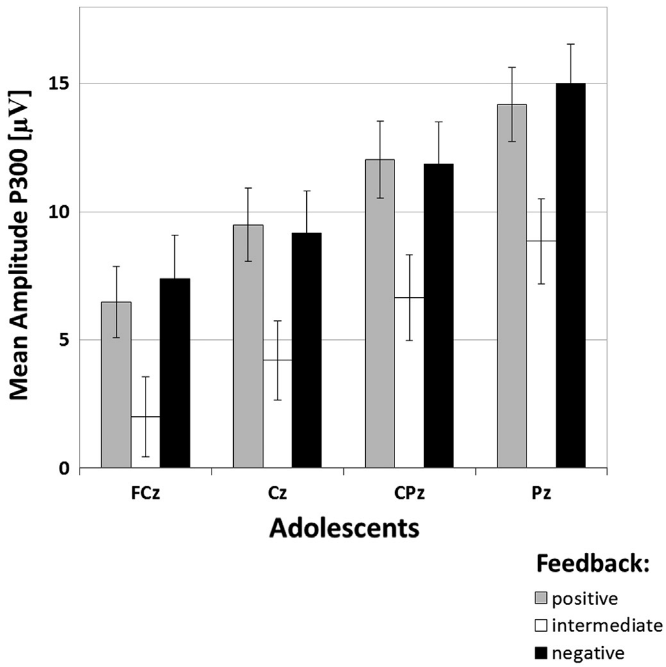


Fig. 3. Bar graphs of the peak-to-peak FRN for both age groups at electrode FCz (bars denote standard errors of the mean): Children's and adolescents' FRN did not differentiate between expected and unexpected feedback.

Grose-Fifer, 2012). Corroborating the idea that this is an effect specific to the monitoring processes reflected in the FRN is the fact that children do not show larger ERP components in general, e.g., the P300 in the present experiment was not larger for children than adolescents. It is also in line with fMRI findings demonstrating a linear decrease in ACC activation with increasing age (van Leijenhorst et al., 2010a). Together, these arguments speak in favor of a disengagement from external feedback with increasing age, which might be due an increasing reliance on internal representations of the environment (see also Crone et al. (2006) and Ferdinand and Kray (2014)).

Surprisingly, we found that children's as well as adolescents' FRN failed to differentiate between expected and unexpected feedback. This is in contrast to our hypothesis that children's FRN would differentiate less between these feedback conditions than adolescents' FRN. Adolescents neither showed a more adult-like pattern (i.e., a larger FRN for unexpected feedback; cf. Ferdinand et al., 2012) nor a bias towards stronger processing of positive feedback, as would be assumed based on an overactive reward system. Alternatively, it might be the case that the activation of the (possibly overactive) reward system is not processed in the ACC in adolescents and thus not visible in the FRN. This alternative idea would fit nicely with results from fMRI studies showing an inverted U-shaped pattern of reward-related activation in the striatum with a peak in adolescence (e.g., Cohen et al., 2010; Ernst et al., 2005; van Leijenhorst et al., 2010a, 2010b). Either way, this indicates that the mechanisms of cognitive control represented by the FRN are not yet fully implemented in 12–14 year-olds (Crone



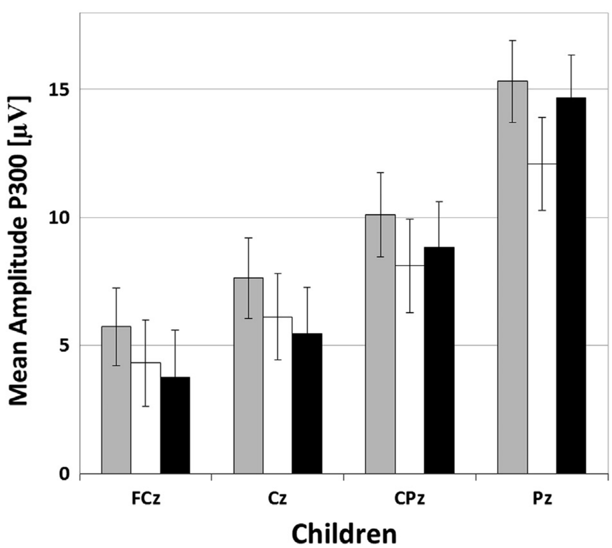


Fig. 4. Bar graphs of P300 mean amplitude for both age groups at midline electrodes FCz, Cz, Cpz, and Pz (bars denote standard errors of the mean): Children's and adolescents P300 was larger for unexpected than expected feedback. This effect is more pronounced and more broadly distributed over the scalp in adolescents.

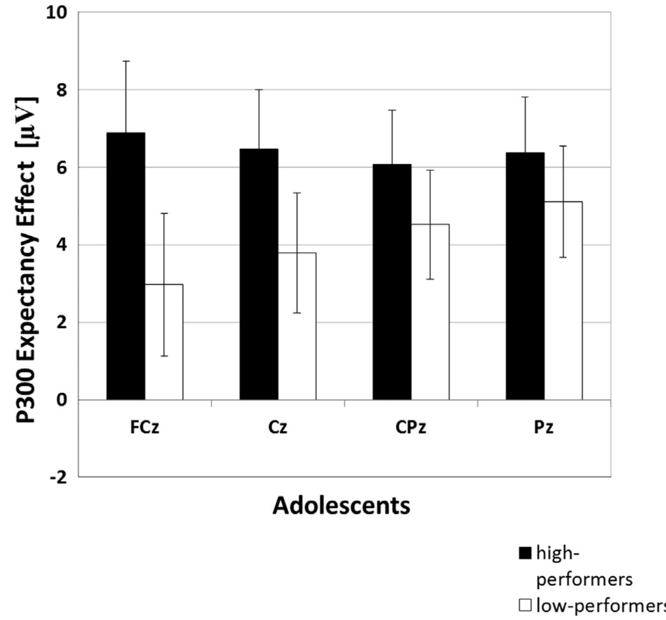


Fig. 5. Bar graphs for the P300 expectancy effect for high and low-performing adolescents at midline electrodes FCz, Cz, Cpz, and Pz (bars denote standard errors of the mean): Adolescents with a low ability to adapt their time estimations after negative feedback show a smaller P300 expectancy effect at frontal electrode sites.

and Dahl, 2012; Ernst, 2014). Our findings also fit nicely with a study by Crone and van der Molen (2004) who examined four age groups (6–9, 10–12, 13–15 and 18–25 years) in the Iowa gambling task and found an increase in the sensitivity to future consequences with age, regardless of whether consequences were rewards or punishments. They concluded that young children fail to anticipate future outcomes because of their not yet fully developed ventromedial prefrontal cortex that exerts enhanced cognitive control with increasing age. At first sight, our FRN results seem at odds with earlier studies reporting that children's FRN does not differentiate between positive and negative feedback as well as adolescents' FRN. One explanation for this could be that these studies used only two types of feedback (positive and negative). Three types of feedback might be harder to represent in working memory. However, this does not fit in with the finding that both age groups were able to learn from the feedback, i.e., it must have been meaningful to them.

In contrast to the FRN results, an effect of expectancy was found for the P300 which was larger after unexpected positive and negative feedback than after expected feedback. This effect was more pronounced and had a broader scalp distribution for adolescents. This means that in children aged 8–10 years, the ability to process the feedback's unexpectedness and to update their working memory representations (Donchin and Coles, 1988; Polich, 2004, 2007) is still developing. In our task, this would include to keep the representation of the produced time estimation in working memory and update it after unexpected feedback. In adolescents, these processes seem to work more efficiently or are more consistently applied. However, adolescents do also not yet display the mature pattern of results. First, using the same task with young adults, it has been found that positive feedback elicits a larger P300 than negative feedback of the same frequency. This has been interpreted as a relevance effect that occurs in addition to the expectancy effect. Positive feedback might be evaluated as more task-relevant because it signals that the intended goal (precise time estimation) has been achieved and that the executed action needs to be exactly replicated for future success (Ferdinand et al., 2012; Mecklinger et al., 1994; Ruchkin et al., 1990). In older adults, probably due to limited working memory resources, the expectancy effect in the P300 is even abandoned in favor of the more important relevance effect (Ferdinand and Kray, 2013; Nieuwenhuis, 2011). Second, adolescents' P300 expectancy effect seems to be distributed more broadly over the scalp than that of children. The evidence concerning P300 topography changes during childhood is scarce and the few existing studies using the oddball paradigm find inconsistent results (e.g., Oades et al., 1997; Stige et al., 2007; Thomas and Nelson, 1996; Yordanova and Kolev, 1997; van der Stelt et al., 1998). However, our paradigm is likely to be more complex than the oddball paradigm because in the adult P300 not only effects of stimulus frequency but also task relevance were found. Our results suggest that the cognitive processes indicated by the expectancy effects seem to mature later during development than the simple frequency processing in oddball paradigms. Additionally, its development seems to be related to a frontal shift during adolescence, which could mean that additional frontal areas can be accessed in adolescence to evaluate the feedback in our task (similar to the compensatory frontal shifts usually found for older adults). Corroborating this idea is the finding that this frontal shift is related to adolescents' performance: Adolescents with better adaptation in their time estimations after unexpected negative feedback (high-performers) also had a larger frontal P300 expectancy effect than those with worse behavioral adaptation (low-performers). This is corroborated by the finding that in adolescents, higher fluid intelligence was associated with a larger P300 amplitude after expected feedback at frontal electrode sites indicating a smaller expectancy effect. However, this is a post-hoc interpretation. Additionally, inferences on the neuronal origin of an ERP component based on the topographical distribution should be treated with caution. Therefore, investigating the localization of feedback processing using methods better suited for localization of function (e.g., fMRI) seems a promising and necessary endeavor for future research. Together, the P300 data from the present study with the results from the two studies mentioned above paint an interesting life-span pattern of the role of the P300 in feedback processing: the expectancy effect develops first before the more strategic relevance effect occurs in young adulthood. This relevance effect is then preserved in older age in contrast to the expectancy effect. They also show that improvements in using the feedback for behavioral adaptation go hand in hand with topographical changes in P300 in adolescence, which are likely to reflect the fact that increasing recruitment of frontal areas is possible during adolescence before the adult pattern of processing can be established.

A possible limitation of our study is that we cannot fully exclude that motivational effects may have had an influence on the missing differentiation between feedback types in children's or adolescents' FRN. Nevertheless, we think this unlikely because both age groups actually learned to generate more precise time estimations over the course of the experiment and showed an effect of expectancy in the P300. A lack of motivation would probably not be specific for the monitoring processes reflected in the FRN. Additionally, we cannot exclude the possibility that the emotional salience of positive and negative feedback stimuli might have influenced our results because positive and negative feedback stimuli are both presented infrequently. However, we think that expectancy is the most parsimonious explanation for our data and that it is unclear whether positive and negative feedback would actually result in a comparable emotional salience in our study design. In a similar vein, although our participants probably perceive a remaining temporal uncertainty even after having learned to produce better time estimations (which could lead to continued signaling of the ACC that cognitive control is necessary and thus to a large FRN), we think it unlikely that this uncertainty would be equal in all three feedback conditions. A general limitation of the present paradigm is that we cannot differentiate between the role of expectancy violations and informative value for learning from feedback. When we take a look at the discussion of whether the valence or expectancy of a feedback stimulus elicits the FRN, we find that valence seems to be processed over expectancy in gambling paradigms (negative feedback elicits the FRN), while it is the other way around in learning paradigms (unexpected feedback elicits the FRN). These seemingly contradictory findings could probably be reconciled, by taking the informative value of feedback into account: during gambling, the valence (win or loss) is the only informative aspect of the feedback stimulus because there is no information included about how to adapt behavior to be more successful. In contrast, in learning situations the feedback's unexpectedness carries information about how to adapt behavior. This implies that expectancy or valence might be means to manipulate the informative value in different paradigms, while the underlying mechanism is probably concerned with how useful the feedback is for the individual under the given circumstances, i.e., the informative value in a given situation determines the behavioral relevance of the feedback. This idea is consistent with studies showing that activity in the error monitoring system is critically dependent on learning-relevance (e.g., Crone et al., 2008; Ferdinand et al., 2015; Holroyd et al., 2009; van den Bos et al., 2009). Notwithstanding, empirical tests of these ideas in other paradigms would be desirable. Another drawback of the present study is that the age at which an adult pattern of feedback processing is reached and whether some stages of feedback processing mature earlier than others remain unclear. Also, it is possible that a positivity bias could emerge in older adolescents. Future studies should address this question by examining more age groups from early to late adolescence and to young adulthood or even using a longitudinal design.

Taken together, the present results clearly show that different stages of feedback processing are important for behavioral adaptation. In the fast initial processing of feedback stimuli as reflected in the FRN, children and adolescents did not differentiate between unexpected positive and unexpected negative feedback, i.e. they did not show a higher sensitivity to positive feedback. They also did not yet differentiate unexpected from expected feedback. However, the later processing stage mirrored in the P300 component of the ERP demonstrates that children do evaluate the unexpectedness of feedback events and use this information to update their working memory. Thus, children and adolescents use information about the unexpectedness of events but they do so in a later processing stage than adults. Interestingly, adolescents with better behavioral adaptation after unexpected negative feedback (high-performers) also displayed a more frontal distribution of the P300 expectancy effect than those with worse behavioral adaptation (low-performers). This might indicate that in adolescents, the additional recruitment of frontal brain regions is possible which leads to improved learning from feedback.

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