

A DEVELOPMENTAL EXAMINATION OF FEEDBACK PROCESSING DURING
DECLARATIVE LEARNING

by

JAMES C. BORDERS

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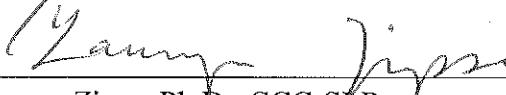
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Approved:



Yael Arbel, Ph.D., CCC-SLP
Thesis Advisor



Lauryn Zipse, Ph.D., CCC-SLP
Second Reader



Sofia Vallila-Rohter, Ph.D., CCC-SLP
Third Reader

MGH INSTITUTE OF HEALTH PROFESSIONS

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Feedback processing during declarative learning

ABSTRACT

The present study examined developmental differences in feedback processing of declarative learning between children and young adults using event-related potentials (ERPs). A visual feedback-based two-choice paired associate learning task was utilized, which required participants to learn associations between visually presented non-objects. Though children and adults demonstrated similar learning outcomes at comparable rates, children exhibited distinct patterns of feedback processing. Temporal Principal Component Analysis (PCA) was utilized to examine two feedback related ERP components, the feedback-related negativity (FRN) and the fronto-central positivity (FCP). Neurophysiologically, the amplitude of the FRN following negative feedback was not different between children and adults in the initial stage of learning. Additionally, children did not demonstrate the learning-related decrease in the FRN amplitude to positive feedback seen in adults. The FCP amplitude was found to be overall larger in adults when compared with children. Moreover, a learning-related increase in the FCP elicited by negative feedback was found in adults but not in children. Taken together, these findings propose that although children and adults demonstrate similar learning outcomes, children exhibit different electrophysiological patterns in the FRN and FCP that reflect differences in the processing of feedback in a declarative learning task.

INTRODUCTION

As children are exposed to a variety of information in their environment, they must use feedback to monitor and adjust performance. In this sense, the utilization of external feedback is integral to development as it provides the learner with an evaluation of their performance that guides the modification of learning strategies in real-time. Feedback processing, specifically error detection, monitoring, and subsequent behavioral modifications, is considered to be a distinct component of executive functions (Anderson, 2002). After age five, children develop these executive functions rapidly through adolescence into adulthood (Best, Miller, & Jones, 2009).

Behavioral research has shown that the ability to use executive functions to optimize performance improves with age. In various learning paradigms, including the Wisconsin Card Sorting Task (Chelune & Baer, 1996) and the Dimensional Change Card Sort (Frye, Zelazo, & Parfai, 1995), young children exhibit an inflexibility in adjusting rule-based strategies despite receiving feedback (Chelune & Thompson, 1987; Riccio et al., 1994; Welsh, Pennington, & Groisser, 1991; Zelazo, Frye, & Rapus, 1996; Zelazo, 2006). Though this inflexibility resolves around age five, children continue to require more trials and time to learn (Hammerer, Li, Mullen, & Lindenberger, 2010) and often fail to utilize feedback to enhance future behavior (Bohlmann & Fenson, 2005; Zelazo et al., 1996). Furthermore, children make more errors following negative feedback (van Duivenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008). Crone, Jennings, and Van der Molen (2004) investigated the role of feedback processing in children's poor performance on these tasks. They examined heart rate following response-dependent and noninformative feedback, as slowed heart rate following feedback is thought to reflect the extent to which feedback is utilized to adjust behavior. Compared to adults, children's

Feedback processing during declarative learning

heart rate slowed following both response-dependent and noninformative feedback, demonstrating difficulty assessing the validity of feedback (Crone et al., 2004). Thus, it has been postulated that children's performance in feedback-based tasks results from difficulty assessing the relevance of feedback to optimize future behavior.

The anterior cingulate cortex (ACC) plays a critical role in completing these types of learning tasks, as it is involved in performance monitoring, reinforcement learning, and reward and feedback processing. Research has shown that the ACC is still developing in early adolescence (Crone, Zanolie, Leijenhorst, Westenberg, & Rombouts, 2008). Additionally, structural and functional developmental changes of the ACC have been linked to age-related improvements in feedback processing and cognition (Velanova, Wheeler, & Luna, 2008). Neuroanatomically, the ACC is involved in the cortico-striatal circuit, which mediates feedback processing and executive functioning (Alexander, Delong, & Strick, 1986). In this way, the striatum interacts with the frontal cortex. These two structures are anatomically distinct but topographically related, in that the cortex sends stronger signals to specific regions of the striatum in a complex, GABA-mediated feedback loop. Clinical populations with an impaired cortico-striatal system, such as Parkinson's disease, demonstrate impaired learning in feedback-based tasks (Sholamy, Myers, Onlaor, & Gluck, 2004).

The dorsal ACC is thought to be involved in a generic error-processing system that detects and utilizes errors to enhance task performance (Holroyd & Coles, 2002). Specifically, a negative reinforcement-learning signal from the mesencephalic dopamine system is conveyed to the frontal cortex leading to disinhibition of the ACC, resulting in the generation of an error signal (Holroyd & Coles, 2002). This signal is proposed to reflect a negative prediction error that is generated when an action violates the expected outcome. Thus, the examination of an

Feedback processing during declarative learning

electrophysiological signature of this neural structure provides valuable insight into developmental changes in executive functions, namely feedback processing.

An event-related potential (ERP) embedded in electroencephalogram (EEG) activity and elicited by performance feedback, namely the feedback-related negativity (FRN), is reportedly generated from the dorsal ACC via this error-processing system. The FRN, which has been elicited in numerous learning paradigms in adults, is maximal at fronto-central electrodes between 200 and 300 ms after the onset of negative feedback (Miltner, Braun, & Coles, 2004). The FRN is elicited when the information about the accuracy of one's performance is unknown until it is communicated by external feedback. Examining developmental changes in the FRN is integral to our understanding of the developmental trajectory of specific components of executive functions, namely error detection and monitoring, as it is generated by a system that is known to undergo structural and functional changes during childhood.

The FRN is followed by a positivity, referred to as the Fronto-Central Positivity (FCP), which reaches its maximal peak at approximately 300 to 400 ms after the presentation of feedback. Although it has been postulated that error awareness affects the FCP (Wessel, Danielmeier, & Ullsperger, 2011), the study of the FCP has been limited, and its functional significance is still largely undetermined. To our knowledge, developmental research has not examined the FCP in children during feedback-based tasks or its utility as an indicator of error awareness during the learning process.

There is growing interest in the examination of developmental changes in feedback processing using ERPs. Eppinger, Mock, and Kray (2009) examined the FRN in 10 – 12 year old children and 19 – 24 year old adults performing a probabilistic learning task in which the validity of feedback was manipulated. When feedback was valid, children demonstrated larger FRNs to

Feedback processing during declarative learning

negative feedback and a similar FRN to positive feedback when compared to adults. When the FRN was examined in bins of seventy-five trials, adults exhibited a learning-related decrease in the FRN to positive feedback, whereas no such changes were observed in children. Using a similar probabilistic learning task with the same age group, Groen and colleagues (2007) did not observe an FRN to negative feedback in children. They proposed that their feedback stimuli (i.e. green and red squares) might not have been motivationally salient enough for the children. In a reinforcement learning task examining developmental changes across the lifespan, from 9 to 75 years of age, the amplitude of the FRN to negative feedback was found to decrease with age. Moreover, while adults and adolescents demonstrated larger differences in FRNs to positive and negative feedback, the FRN amplitude in children showed smaller differences between feedback type (Hammerer et al., 2010). Crowley and colleagues (2013) employed a non-learning reward versus non-reward task in 10 – 17 year old children that replicated age-related decreases in the FRN, as well as similar amplitudes across reward type. Similar findings were found in preschool-aged children (Mai et al., 2011) and adolescents (Zotoli & Grose-Fifer, 2012) in gambling tasks. In a recent study comparing 8 – 10 year old children and 12 – 14 year old adolescents, a time estimation task was employed to attempt to reduce the effect of feedback valence and expectancy on the FRN and found similar FRN amplitudes between positive and negative feedback in both children and adolescents (Ferdinand, Becker, Kray, & Gehring, 2016). Taken together, several results from the aforementioned studies suggest larger FRNs in childhood, which decrease in adulthood, though the pattern has not been well established. Additionally, the relative differentiation between positive and negative feedback remains unclear. While Eppinger and colleagues (2009) found overall increased FRN amplitudes to negative compared to positive feedback in children compared to adults, others have reported less differentiation between

Feedback processing during declarative learning

feedback types in children, as well as larger differences in the amplitude of the FRN to positive and negative feedback in adolescents and adults (Crowley et al., 2013; Ferdinand et al., 2016; Hä默er et al., 2010; Mai et al., 2011; Zottoli & Grose-Fifer, 2012). Furthermore, few studies have investigated learning-related changes in the FRN. Eppinger and colleagues (2009) found a learning-related decrease in the FRN to positive feedback in adults but not in children. Groen and colleagues (2007) did not observe a discernible FRN among children but found learning-related decreases in other positive components, the P2 and P3.

Lack of consensus in current research is driven, in part, by the variety of ERP analysis procedures employed. For example, in some studies the FRN was defined separately for positive and negative feedback with peak-to-peak measures (Eppinger et al., 2009; Ferdinand et al., 2016), whereas others use difference waves (Hammerer et al., 2010). Peak-to-peak measures are common in the ERP literature and involve measuring the FRN from its maximal to minimal point. However, given that the FCP has been shown to be a distinct component, this method is actually measuring the combination of two separate components, the FRN and the FCP. Difference waves provide a single value of the FRN by subtracting the FRN amplitude of positive feedback from negative feedback. Thus, one is unable to examine changes in the FRN to positive feedback and make comparisons to negative feedback.

Despite the temporal precision of ERP methodology, latency measures remain underreported in developmental research. The latency of several ERP components, specifically the P300 (Courchesne, 1978; Friedman, Putnam, & Sutton, 1990; Johnstone, Barry, Anderson, & Coyle, 1996), has been shown to decrease with age. This decrease in latency has been suggested to reflect potential age differences in processing efficiency. More recently, longer FRN latencies

Feedback processing during declarative learning

have been shown in preschool-aged (Mai et al., 2011), in young children (Crowley et al., 2013), and adolescents (Zottoli & Grose-Fifer, 2011).

Since feedback plays an integral role in learning, examining the underlying neural processes of feedback processing in children is imperative. Though several examinations of the FRN in children purport to examine learning-related changes, probabilistic and reinforcement-learning paradigms are often employed (Eppinger et al., 2009; Hammerer et al., 2011; Groen, Wijers, Mulder, Minderaa, & Althaus, 2007). In these paradigms, the learner is required to associate a response with a stimulus and provided feedback that is not consistently valid. In this sense, any differences found between groups might reflect, to a certain extent, one's ability to ignore invalid feedback instead of differences in extracting relevant information from feedback to enhance task performance.

Feedback based declarative learning is common in the environment of school age children, as they must form associations with various material from the curriculum while receiving feedback from both their teacher and peers. An examination of feedback processing in a declarative learning task in which children need to learn to make an association between pairs of stimuli will add to the growing knowledge of learning and information processing in children. Given that research is beginning to report developmental differences in latency, methods that hone in on a narrow timeframe with grouped data lend themselves to a type II error. The present study uses a feedback-based paired associate task that required the learner to map stimulus pairs via trial and error. To account for the variance across participants and within-subject variability in children's latency, we corrected for latency jitter and employed a temporal principal component analysis (PCA). In this sense, developmental differences in the FRN were examined

Feedback processing during declarative learning

during declarative learning, with subsequent analyses accounting for the variance of overlapping components and latency differences.

Specific Aims

The present study aims to examine developmental differences in ERP correlates of feedback processing to better understand the development of EFs, specifically the role of feedback processing during declarative learning. We applied a nonlinguistic feedback-based paired associate task where children and adults inferred stimulus pairs via trial and error across six rounds.

Our research questions and hypotheses were as follows:

1. How does the FRN to negative feedback differ overall between children and adults?

Given recent research demonstrating a decrease in the FRN with age, we hypothesized that the amplitude of the FRN would be larger in children compared to adults.

2. How does the amplitude towards positive and negative feedback differ within and between groups? We anticipated similar amplitudes to positive and negative feedback in children, and learning related decreases in the FRN to positive feedback in adults, which was demonstrated in a recent study by Eppinger and colleagues (2009).

3. How does the latency of the FRN differ between adults and children? Given emerging research suggesting longer FRN latencies in children, we expected to see a similar pattern compared to adults.

4. How does the pattern of FCP amplitude differ between adults and children? We anticipated greater FCP amplitudes overall in adults that reflects increased conscious processing. We also anticipated greater amplitudes following negative feedback as learning progresses,

Feedback processing during declarative learning

reflecting increased attentional resources. Consequently, we anticipated smaller FCP amplitudes overall in children, as well as similar amplitudes between positive and negative feedback.

METHODS

Participants

Thirty adults between 19-38 years of age (mean age = 24.77 years, $SD = 4.13$, 18 female, 23 right-handed) and thirteen children between 8-12 years of age (mean age = 10.10 years, $SD = 1.19$, 4 female, 12 right-handed) participated in the study. Six adults were initially excluded due to an insufficient number of clean trials, resulting in an effective sample size of twenty-four adults and thirteen children. Participants with a history of head injury, neurological deficits, learning disabilities, ADHD/ADD, and psychological or psychiatric disorders were excluded from the study. According to self-report, participants had a history of typical development, with English as their predominant language. In order to assess language and cognition, the Clinical Evaluation of Language Fundamentals (CELF-5; Wiig, Semel, & Secord, 2013) and the Kaufman Assessment Battery for Children (KABC-II; Kaufman & Kaufman, 2004), were administered to children. All children were found to fall within the average range for language and cognition. All subjects and parents of the children gave informed consent and were provided monetary compensation.

Assessment	Mean	Standard Deviation (SD)
CELF-5	112.84	18.59
KABC-II	113.60	16.05

Table 1. Mean scores and SDs for language (CELF-5) and cognitive (KABC-II) assessments in children.

Stimuli and Task

A visual feedback based paired associate learning task was used. Two different sets of stimuli were used for adults and children (see Appendix A). Adults were visually presented three unique non-objects (see Figure 1; Kroll & Potter, 1984), whereas children were presented with an alien creature and two unique non-objects (see Figure 2; Gupta et al., 2004). Adults were told

Feedback processing during declarative learning

to infer the stimulus pairs via trial and error. Children were provided a narrative about aliens within which their task was defined as choosing the correct tool that belonged to each alien via trial and error. All participants were required to learn six visual stimulus pairs across six rounds in two separate blocks for a total of twelve unique items, and were told to infer the correct response via trial and error. In the first round, the presentation of feedback was standardized to establish a 50% baseline error rate across participants. Valid feedback was provided in subsequent rounds based on the participant's performance. Feedback was visually presented in the form of red x-marks for incorrect responses and green checkmarks for correct responses. When the response deadline (3000 ms) was exceeded, three hyphens appeared on the screen, indicating that the participant needed to respond faster. In the sixth round, participants were tested on their ability to pair the visual stimuli and were not provided feedback. Instead, they were asked to rate their confidence on a scale of 1 (confident) to 4 (not confident). In each block, adults completed 30 training trials, whereas children completed 54 trials. All participants completed six testing trials in each block, for a total of twelve testing trials. In the entire experiment, adults completed a total of 60 training trials, and children completed 108 training trials.

Feedback processing during declarative learning

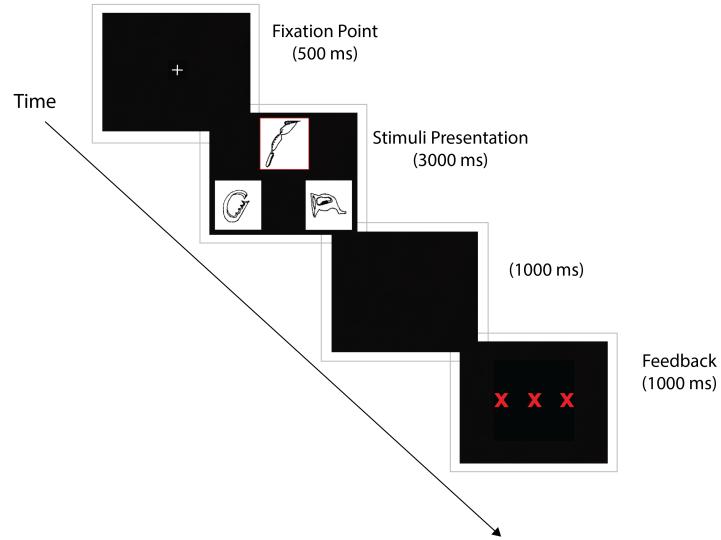


Figure 1. Schematic diagram of the nonlinguistic learning paradigm for adults.

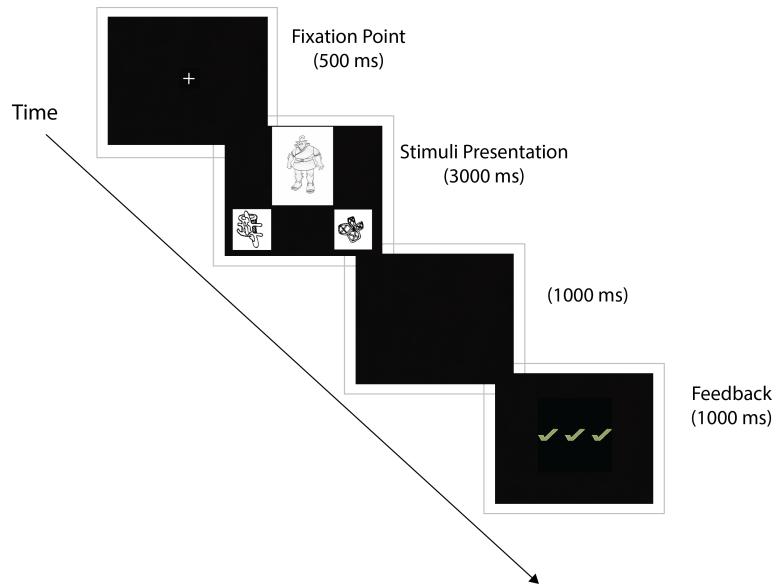


Figure 2. Schematic diagram of the nonlinguistic learning paradigm for children.

Data Recording

All tasks were designed and presented using the software E-Prime (PST Inc., Pittsburgh, PA). The EGI System was used to acquire and analyze dense-array EEG activity (EGI Inc., Eugene, OR) from 32 Ag/AgCl electrodes at a sampling rate of 1000 Hz.

Data Analysis

Behavioral Analysis. Responses that exceeded the response deadline (3000 ms) were excluded from analysis. Responses were averaged across all six trials per round in adults and twelve trials per round in children, and reported as percent (%) correct. As fourteen children is a relatively small sample group, Cohen's effect size (η^2 ; Cohen, 1992) was reported to ensure results were reliable and are interpreted as small (.20), medium (.50), and large (.80).

EEG Analysis. EEG activity was offline filtered with a 0.1 Hz-30 Hz band pass filter. The filtered data were segmented to isolate EEG activity 200 ms before and 800 ms after the onset of feedback. Rounds were collapsed into three blocks (round 1, rounds 2 & 3, and rounds 4 & 5), creating six categories (two feedback types & 3 rounds). Segmented data underwent artifact detection, followed by a trial-by-trial visual examination of the data to further exclude bad segments. Artifact free segments were averaged, and re-referenced to average reference. A pre-feedback epoch (-200ms to -100 ms) was used for baseline correction.

Individual participant's waveforms were examined for differences in FRN latency, within a 150 - 400 ms time-window. Given subsequent analyses showing age differences in the latency of the FRN and variation between individual children's waveforms (see FRN Latency analyses), children's latencies at the FCz site, where FRN is known to be maximal (Yeung & Sanfey, 2004) were individually adjusted for each condition (feedback, round) to align with the FRN in the adult grand average waveform observed to peak at 237 ms (see Figure 7).

Temporal Principal Component of Analysis (PCA) computes the covariance across time points in all subjects and conditions, separating overlapping ERP components into temporal factors. The appropriate temporal factor, depending on its timing and relevance to a particular component, is then identified. Factor scores for each condition are then computed, resulting in a

Feedback processing during declarative learning

measurement of activity in the ERP component. In the present study, two separate temporal PCAs were performed. First, the adults' data from the FCz site were entered into a temporal PCA. This data set included both learners and non-learners, but excluded participants who did not have enough clean trials. Thus, the effective sample size for the adult PCA was 24. In a separate PCA, both the adults' data and the children's latency corrected data from the same electrode were entered into a temporal Principal Component Analysis (PCA) (Spencer, Dien, & Donchin, 2001). Non-learners who did not reach 70% accuracy in the final testing round were excluded, as well as participants without enough clean trials. This included 8 adults and 6 children, resulting in an effective sample size of 22 adults and 8 children.

ANOVAs were performed with the temporal scores as the dependent variable, and all analyses were reported with the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959). Follow-up pairwise comparisons of significant main effects were performed with the Bonferroni correction (Dunn, 1961). Post-hoc tests examining significant interaction effects were performed with the Benjamini-Hochberg procedure, which controls for the false discovery rate (Yoav & Hochberg, 1995). In this procedure, each p-value is ranked in ascending order, and then compared to its Benjamini-Hochberg critical value (see Equation 1). Any comparison in which the p-value is less than the Benjamini-Hochberg critical value is deemed significant.

$$(i/m)Q$$

Equation 1. Equation illustrating the Benjamini-Hochberg critical value. (i = rank; m = number of comparisons; Q = predetermined false discovery rate)

RESULTS

Behavioral Data

Accuracy. A mixed ANOVA with the between factor Group (adults, children) and the within factor Rounds (rounds 1 – 5) was used to analyze accuracy scores. Analyses indicated a main effect of Rounds, $F(4, 38) = 36.10, p < .0001, \eta^2 = .47$, was found (see Figure 3). To further investigate the main effect of Rounds, pairwise comparisons were performed and indicated significant differences between rounds 1 and 2, and rounds 2 and 3 (p 's $< .006$), which reflected an increase in accuracy scores in initial rounds across age groups, which plateaued in the last two training rounds (see Figure 3). No Group differences in accuracy, $F(1, 41) = .87, p = .35, \eta^2 = .02$, or interaction between Group and Rounds, $F(4, 38) = .64, p = .63$, were found. To investigate accuracy in leaners, individual scores that did not reach 70% accuracy in the final round were excluded. A mixed ANOVA with the between factor Group and the within factor Rounds was employed with this effective sample (22 adults, 11 children). The analysis indicated a main effect of Rounds, $F(4, 29) = 38.14, p < .0001, \eta^2 = .56$. Follow-up pairwise comparisons were performed and indicated significant differences between rounds 1, 2, and 3 (p 's $< .01$), but comparisons between rounds 3, 4, and 5 were non-significant. This reflected a linear increase in accuracy scores in the first three rounds, which plateaued in rounds 4 and 5. No Group differences in accuracy, $F(1, 30) = .09, p = .76$, or interaction between Group and Rounds, $F(4, 27) = .154, p = .96$, were found.

Learning Rate. To examine participants' rates of learning, children's scores were binned into five rounds so that the exposure to stimuli was standardized across groups (see Figure 4). A mixed ANOVA with the between factor Group and the within factor Rounds indicated a main effect of Rounds, $F(4, 38) = 31.38, p < .0001, \eta^2 = .43$. Follow-up pairwise comparisons showed

Feedback processing during declarative learning

significant differences between rounds 1, 2, & 3, and between rounds 4 and 5 (p 's $< .02$), which reflected an increase in accuracy scores across rounds in both age groups. A between-subjects effect of Group approached significance, $F(1, 41) = 3.01, p = .09, \eta^2 = .06$, which reflected a trend of higher accuracy scores in adults. No interaction between Group and Rounds, $F(4, 38) = 1.33, p = .26$, was found.

Reaction Time. A mixed ANOVA with the between factor Group and the within factor Rounds was used to analyze reaction time data (see Figure 5). The analysis showed significant differences across rounds, $F(4, 38) = 16.65, p < .0001, \eta^2 = .28$. Follow-up pairwise comparisons showed significant differences between round 1 & 4, and 5, as well as round 2 & 3, 4, and 5 (p 's $< .05$), suggesting that reaction time decreased after the first two rounds of training. No Group differences in reaction time, $F(1, 41) = 2.80, p = .10$, or interaction between Group and Rounds, $F(4, 38) = .12, p = .28$, were found. To investigate reaction time in leaners, non-learners were excluded and a mixed ANOVA with the between factor Group and the within factor Rounds was employed. The analysis indicated a significant main effect of Rounds, $F(4, 27) = 27.63, p < .0001$. Follow-up pairwise comparisons showed significant differences between rounds 1 & 3, 4, and 5, as well as round 2 & 3, 4, and 5 (p 's $< .05$), which reflected a decrease in reaction time in initial rounds and a subsequent increase in the final training rounds. No Group differences in reaction time, $F(1, 30) = 1.06, p = .30$, or interaction between Group and Rounds, $F(4, 27) = .69, p = .59$, were found. To examine differences in reaction time across similar exposure to stimuli, children's scores were grouped into bins (see Figure 6). A mixed ANOVA with the between factor Group and the within factor Rounds indicated a main effect of Rounds, $F(4, 38) = 16.18, p < .0001, \eta^2 = .28$. Follow-up pairwise comparisons showed significant

Feedback processing during declarative learning

differences between rounds 1 & 4, rounds 2 and 3, 4, & 5, and between rounds 4 & 5 (p 's $< .04$), which reflected an overall decrease in reaction times across rounds in all groups.

Confidence Ratings. A one-way ANOVA indicated no differences in self-reported confidence in responses between age groups, $F(1, 41) = 2.22, p = .14$ (see Figure 7).

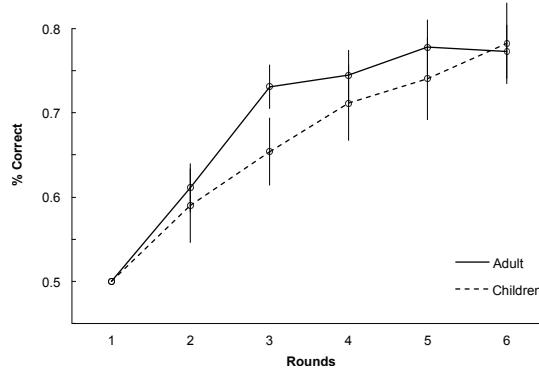


Figure 3. Accuracy scores (% correct) across six rounds in all children and adults. Error bars represent Standard Error of the Mean (SEM).

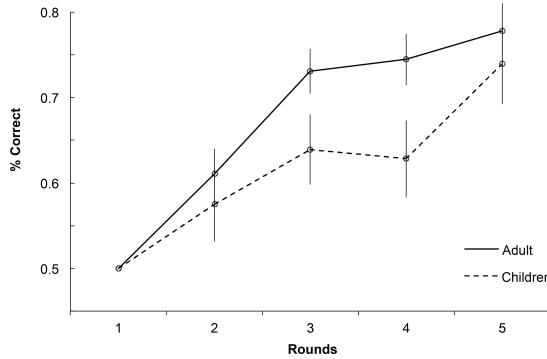


Figure 4. Accuracy scores (% correct) after being placed into bins. Error bars represent Standard Error of the Mean (SEM).

Feedback processing during declarative learning

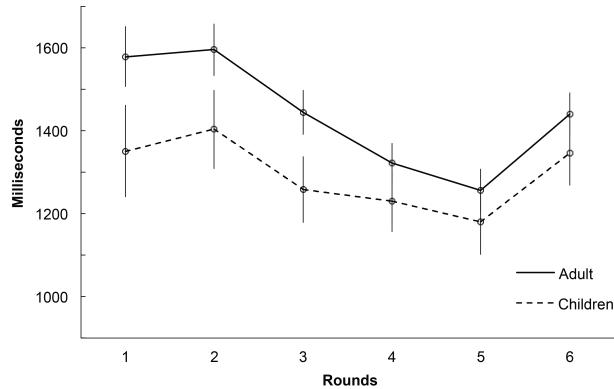


Figure 5. Reaction times (ms) across six rounds in children and adults. Error bars represent SEM.

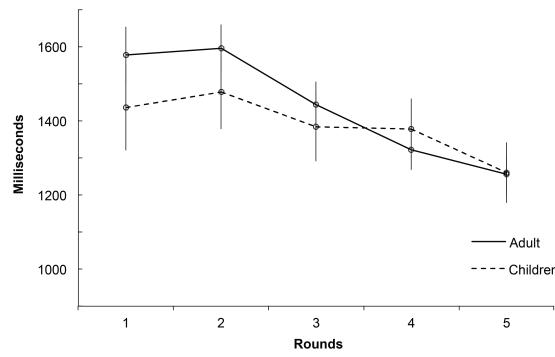


Figure 6. Reaction times (ms) after being placed into bins. Error bars represent SEM.

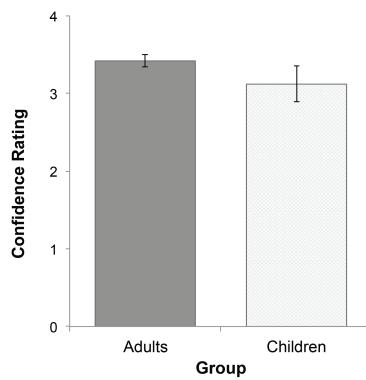


Figure 7. Confidence ratings in children and adults. Error bars represent SEM.

ERP Data

Feedback-Related Negativity. Visual inspection of the grand-averaged data (see Figure 9) suggested larger FRN amplitudes to negative feedback compared to positive feedback in all rounds in adults, whereas only round 1 showed a larger FRN to negative than positive feedback in children. In both age groups, the FRN to both positive and negative feedback appears to decrease, particularly between round 1 and subsequent rounds (see Figure 8). First, a temporal PCA of adult data was performed, which provided an in-depth examination of ERP patterns in adults. Two temporal factors pertaining to the FRN (TF3) and FCP (TF2) were identified at approximately 250 ms and 400 ms, respectively (see Figure 10). Next, a temporal PCA of both adult and children post-latency adjusted data was performed. Two temporal factors pertaining to the FRN (TF3) and FCP (TF1) were identified at approximately 225 ms and 350 ms, respectively (see Figure 11).

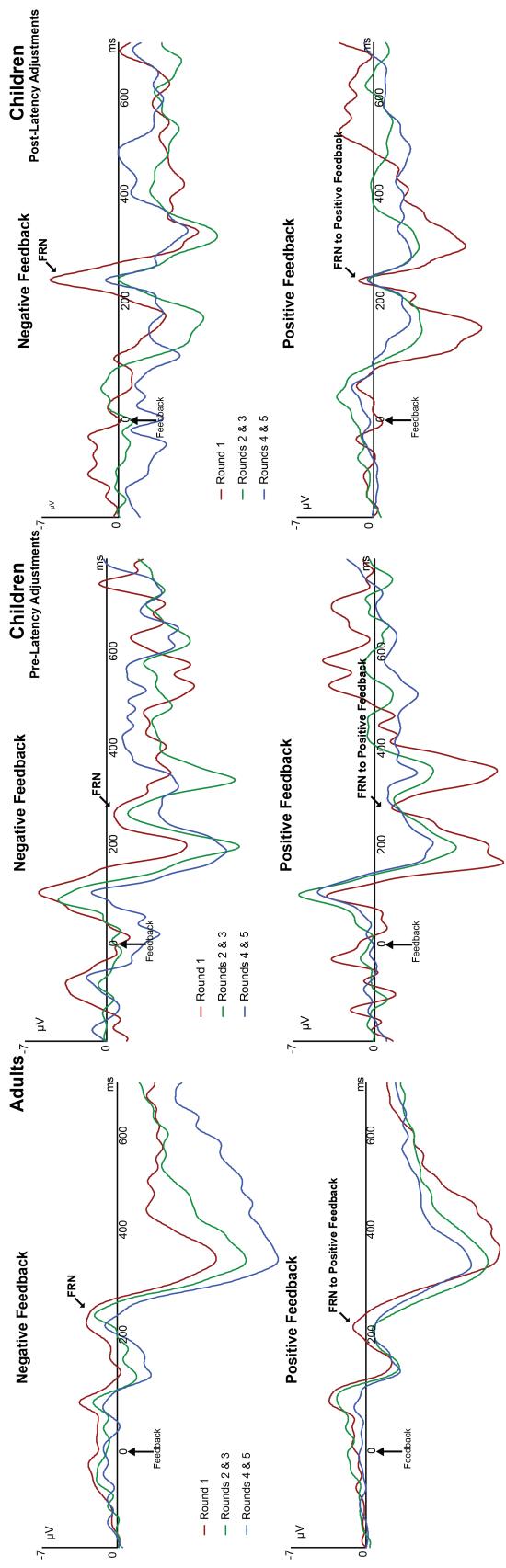


Figure 8. Grand average at electrode FCz to positive and negative feedback in adults and children.

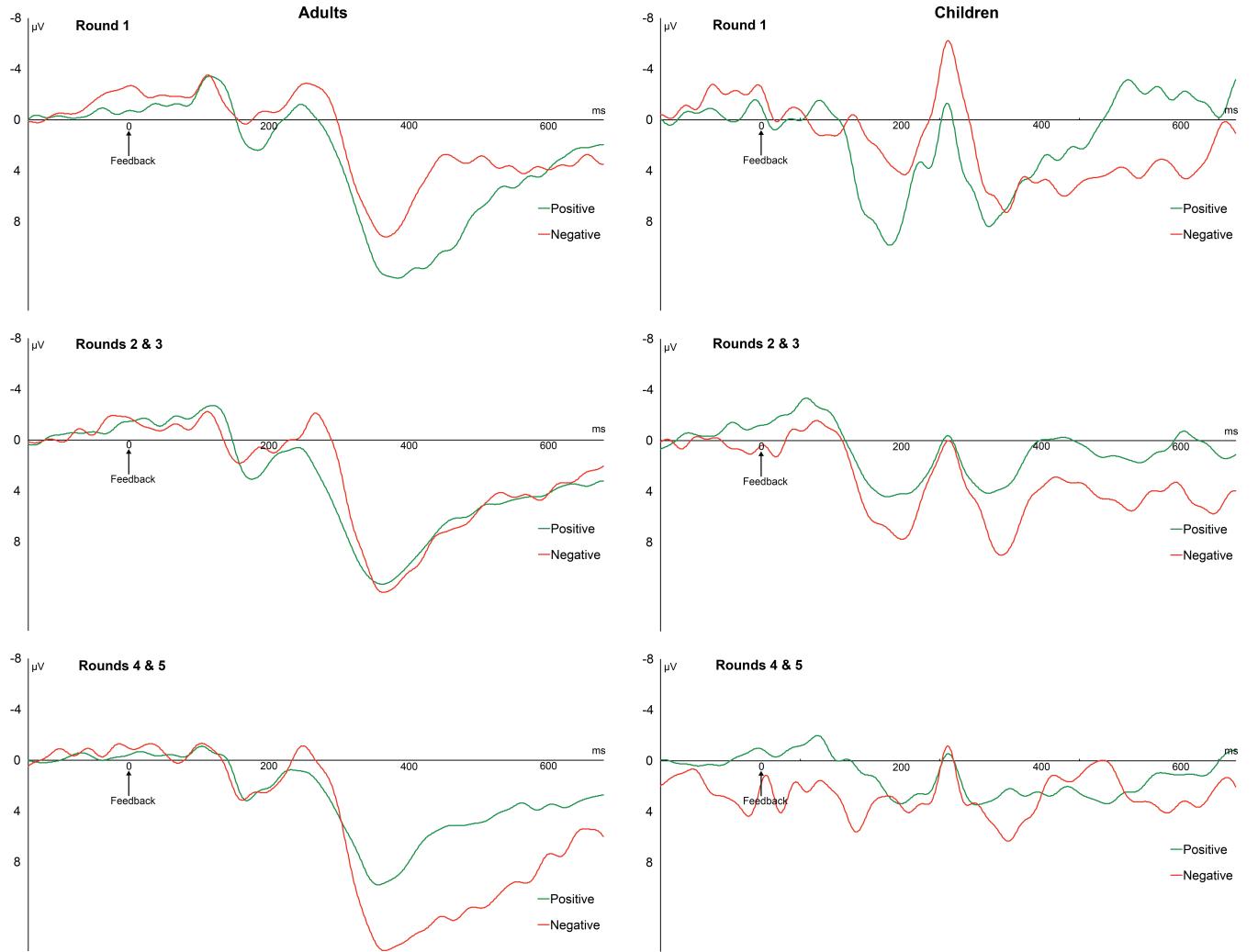


Figure 9. Grand average at electrode FCz to positive and negative feedback across rounds in adults and children.

Feedback processing during declarative learning

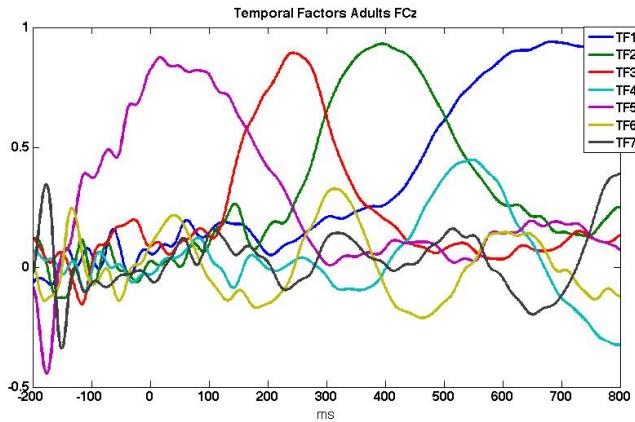


Figure 10. Factor loadings from the adult temporal PCA for the FRN and FCP. Temporal factor 3 (TF3; red) corresponds to the FRN and factor 2 (TF2; green) to the FCP.

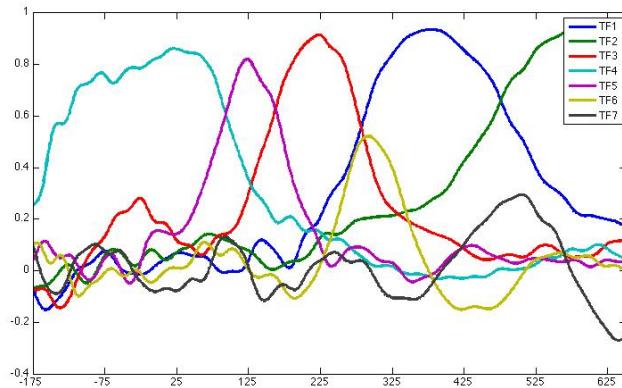


Figure 11. Factor loadings from the combined (children and adults) temporal PCA for the FRN and FCP. Temporal factor 3 (TF3; red) corresponds to the FRN and factor 1 (TF1; blue) to the FCP.

FRN Amplitude. To first determine whether a typical pattern of the FRN was found in adults, a within-subjects ANOVA was performed with the factors Round and Feedback. The FRN temporal factor scores from the adult PCA was entered as the dependent variable. Analyses indicated a main effect of Feedback, $F(1, 23) = 19.10, p < .0001, \eta^2 = .45$, which reflected more negative amplitudes following negative feedback. A Round and Feedback interaction effect

Feedback processing during declarative learning

approached significance, $F(2, 46) = 3.00, p = .06, \eta^2 = .11$ (see Figure 12). Exploratory follow-up paired t-tests with a Benjamini-Hochberg correction revealed significant differences between positive and negative feedback in rounds 2 & 3 ($p < .007$) and 4 & 5 ($p < .01$), as well as significant differences between round 1 and rounds 2 & 3 following positive feedback ($p < .02$). No main effect of Round was found, $F(2, 46) = 1.95, p = .15$.

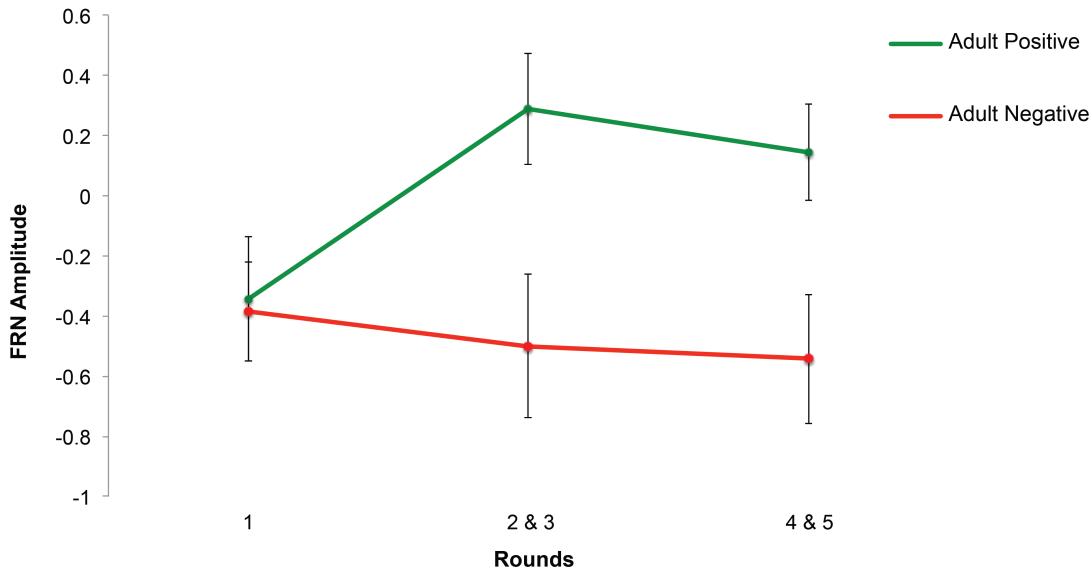


Figure 12. Main effect of feedback in the FRN. Error bars represent SEM.

To examine group differences and potential main and interaction effects, a repeated measures mixed ANOVA with the within-subject factors Round (round 1, 2 & 3, 4 & 5) and Feedback (positive, negative), and a between-subject factor of Group (adult, children) was performed. The FRN temporal factor scores from the combined PCA were entered as the dependent variable. The analysis indicated a significant main effect of Feedback, $F(1, 30) = 15.64, p < .0001, \eta^2 = .34$, which reflected significantly more negative amplitudes following negative feedback across both age groups (see Figure 13). Results showed a between-subjects effect of Group, $F(1, 30) = 7.95, p = .008, \eta^2 = .20$, which reflected more negative amplitudes in

Feedback processing during declarative learning

adults overall. No interaction effects between Feedback and Round, $F(2, 60) = 1.50, p = .23$, Feedback and Group, $F(1, 30) = .17, p = .83$, or three-way interaction effects between Feedback, Round, and Group, $F(2, 60) = 2.15, p = .12$, were found.

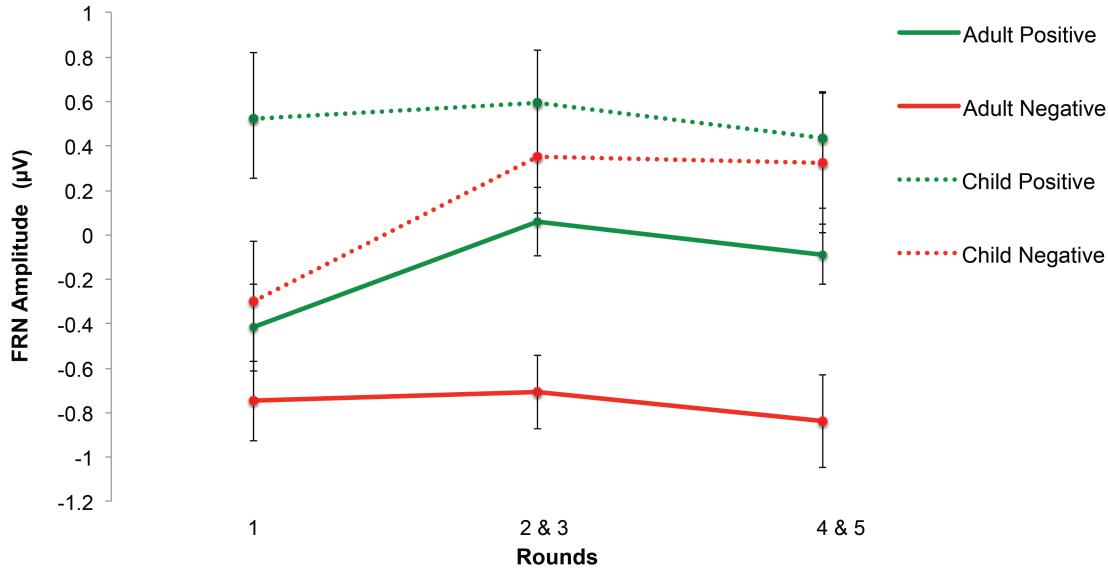


Figure 13. FRN amplitude across rounds in both age groups. Error bars represent SEM.

FRN Latency. A mixed ANOVA with within-subjects factors Round and Feedback, and a between-subject factor of Group indicated a significant main effect of Group, $F(1, 41) = 52.57, p < .0001, \eta^2 = .56$, suggesting that children demonstrated significantly longer latencies (mean difference = 61.39, $SE = 8.47$). Furthermore, a significant interaction between Feedback and Group was found, $F(1, 41) = 5.01, p = .03, \eta^2 = .11$ (see Figure 14). Separate repeated measure ANOVA for adults and children with the within-subject factors Round and Feedback revealed that a main effect of Feedback for adults drove the interaction, $F(1, 29) = 7.20, p = .01, \eta^2 = .19$, suggesting longer latencies on negative than positive feedback in adults, whereas no differences in the FRN latency were found between feedback type for children ($p = .38$).

Feedback processing during declarative learning

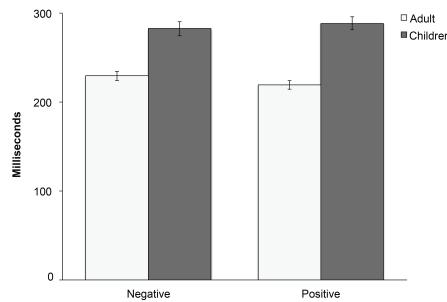


Figure 14. Group and Feedback interaction of latency (ms) in children and adults. Error bars represent SEM.

Fronto-Central Positivity Amplitude. To first determine whether a typical pattern of the FCP was found in adults, a within-subjects ANOVA was performed with the factors Round and Feedback. The FRN temporal factor scores from the adult PCA was entered as the dependent variable. Analyses revealed a significant Round and Feedback interaction effect, $F(2, 46) = 8.30$, $p = .001$, $\eta^2 = .26$ (see Figure 15). Follow-up paired t-tests with a Benjamini-Hochberg correction indicated significant differences between positive and negative feedback in round 1 ($p < .007$) and rounds 4 & 5 ($p < .02$), as well as significant differences between round 1 and rounds 2 & 3 following negative feedback ($p < .01$), suggesting that the amplitude of the FCP towards negative feedback increased with learning. No main effects of Round, $F(2, 46) = 1.87$, $p = .16$, or Feedback, $F(1, 23) = 1.18$, $p = .28$, were found.

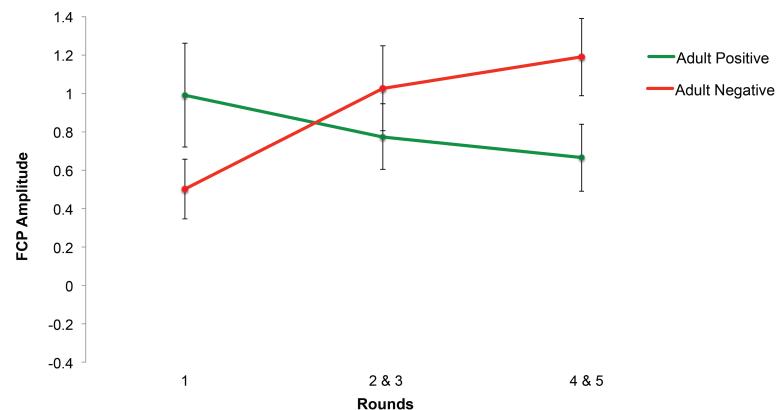


Figure 15. Round and Feedback interaction of the FCP in adults. Error bars represent SEM.

Feedback processing during declarative learning

To examine group differences, a mixed ANOVA with the factors Group, Feedback, and Round was employed. The FRN temporal factor scores from the combined PCA were entered as the dependent variable. Overall, a between-subjects effect of Group approached significance, $F(1, 30) = 3.02, p = .09, \eta^2 = .09$, which reflected larger amplitudes in adults overall (see Figure 16). No main effects of Round, $F(2, 60) = .33, p = .72$, or Feedback, $F(1, 30) = .31, p = .28$, was found. No interaction effects of Round and Group, $F(2, 60) = 2.06, p = .13$, Feedback and Group, $F(1, 30) = .23, p = .63$, Round and Feedback, $F(2, 60) = 2.18, p = .12$, or Round, Feedback, and Group, $F(2, 60) = 2.21, p = .11$, reached significance.

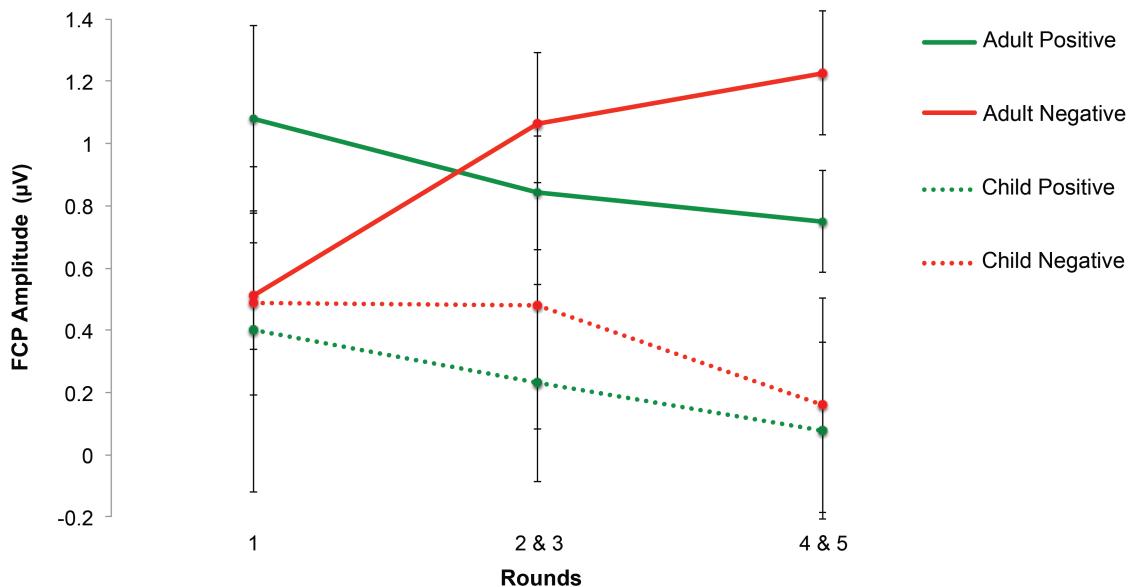


Figure 16. FCP amplitude across rounds in both age groups. Error bars represent SEM.

DISCUSSION

In the present study, we investigated developmental differences in feedback processing during declarative learning. We used a visual feedback-based paired associate task in 8 to 12 year old children and young adults. Participants learned stimulus pairs via trial and error over six rounds. Behavioral results showed that both adults and children reached similar learning outcomes. However, when stimulus exposure was controlled, the rate of learning was slightly decreased in children. We did not find any significant age differences in response time or self-reported ratings of confidence.

Though both age groups showed similar learning outcomes, electrophysiological results examining the FRN suggest different patterns of feedback processing between children and adults. Overall, adults showed larger FRNs following negative feedback compared to children. However, the FRN response to negative feedback in children and adults did not differ during the initial stage of learning. These results directly conflict with previous studies showing an age-related decrease in the FRN (Crowley et al., 2013; Eppinger et al., 2009; Mai et al., 2011; Zotoli & Grose-Fifer, 2012).

Adults demonstrated the typical pattern of decreases in FRN amplitude to positive feedback with learning. Children, however, did not demonstrate this learning-related decrease. Instead, they showed similar FRN amplitudes between positive and negative feedback. This electrophysiological pattern may suggest that children continuously engage with positive feedback despite successful learning. On the other hand, adults disengaged from positive feedback and utilized negative feedback, as evidenced by superior rates of learning. This pattern of similar FRN amplitudes to positive and negative feedback is supported by several studies (Crowley et al., 2013; Hammerer et al., 2010; Ferdinand et al., 2016), and is thought to reflect differences in the use of feedback in younger developmental populations. These results provide

Feedback processing during declarative learning

support for the use of the FRN to both positive and negative feedback as indicators of feedback processing and offer a direct comparison between feedback types.

The fronto-central positivity (FCP) that follows the FRN showed different patterns in adults and children. Overall, adults demonstrated larger FCP amplitudes than children, suggesting that adults employed greater attentional resources during learning. Furthermore, a learning-related increase in attentional resources towards negative feedback was found in adults, as the FCP amplitude to negative feedback increased over time. Children, on the other hand, showed similar FCP amplitudes to both positive and negative feedback throughout the learning process. When combined with the pattern of results seen in the FRN, these results lend support to the notion that children have difficulty extracting relevant information from feedback to alter future behavior, which may be due, in part, to difficulty recruiting sufficient attentional resources towards negative feedback during learning. Adults, however, demonstrated greater attentional resources to positive feedback when first exposed to stimuli but subsequently diverted these resources to negative feedback with learning. This differentiation in attention likely results from optimal learning strategies; as one learns, they must ignore information from stimulus pairs that they've mastered, and focus on learning incorrect stimulus pairs. Despite learning, these strategies are not evident in electrophysiological patterns of the FCP in children. Instead, they display difficulty allocating adequate attentional resources to relevant feedback in order to efficiently adjust learning strategies in real-time.

Although children and adults achieved comparable learning outcomes, the possibility remains that the current task, in which feedback was always valid, did not require one to distinguish positive and negative feedback or recruit adequate attentional resources to develop appropriate and useful learning strategies. Given a more challenging task, differences might arise

Feedback processing during declarative learning

not only in electrophysiological measures, but also behaviorally. In this sense, previous studies might have demonstrated a different pattern of results due to task demands.

Differences in FRN latency remain underreported in developmental ERP studies. We obtained age differences in latency, as the FRN in children occurred approximately sixty milliseconds after adults. This longer latency in children is consistent with previous developmental studies (Crowley et al., 2013; Mai et al., 2011; Zottoli & Grose-Fifer, 2011), though the FRN latency in young children has only been compared with similar age groups, not young adults. Additionally, adults demonstrated longer latencies following negative feedback compared to positive feedback, whereas children did not show this difference between feedback types. Thus, negative feedback required additional processing time in adults, whereas positive feedback did not. Children, on the other hand, processed positive and negative feedback similarly, which mirrors the lack of differentiation between FRN amplitudes of positive and negative feedback, reflecting difficulty in prioritizing relevant feedback to optimize learning. Finally, we found considerable variation in FRN latency across children. When left uncorrected, these latency differences diminished the FRN waveform.

The present study shows that children and adults achieved similar learning outcomes at comparable learning rates in a declarative learning task when feedback was valid. We provided further evidence of developmental differences in the processing of feedback during learning, as shown by different activity in the feedback-related negativity (FRN) and fronto-central positivity (FCP) in children and adults. Our results indicate that there are no age differences in FRN amplitude during the initial stage of learning and that, overall, adults demonstrated more negative FRN amplitudes to negative feedback compared to children. Additionally, children do not demonstrate the learning-related decrease in the FRN to positive feedback that we see in

Feedback processing during declarative learning

adults. This decrease is thought to reflect the reduction in prediction errors resulting from learning, which involves the formulation of internal representations and confirmation via external feedback (Eppinger et al., 2009; Holroyd, Pakzad-Vaezi, & Krigolson, 2008). Children have difficulty forming these internal representations due, in part, to a developing neural system that governs executive functions. This neural system, the ACC, allows for the efficient extraction of relevant information from feedback to ultimately guide learning strategies.

In summary, the present study has several important implications. First, although children and adults demonstrate similar learning outcomes, they show different patterns of electrophysiological activity that allow one to examine differences in feedback processing that cannot be assessed behaviorally. Secondly, these distinct patterns of electrophysiological processes associated with performance monitoring likely occur as a result of maturation of the anterior cingulate cortex. Though children demonstrate similar behavioral and FRN responses, differences may arise as task complexity increases. In the fronto-central positivity, a component thought to represent error awareness and allocation of attentional resources, children have difficulty disengaging from positive feedback as they learn. This might be due to differences in learning strategies, as children might utilize working memory resources to compensate for a developing neural system, whereas adults are able to allocate necessary attentional resources towards feedback and use it as an evaluative tool throughout the learning process. Finally, we provide evidence for age differences in processing efficiency in the FRN that is not seen behaviorally in motor reaction times. Taken together, the present findings suggest that children do not use feedback as effectively or efficiently as adults during declarative learning, which is in accordance with previous research demonstrating developmental differences in feedback processing.

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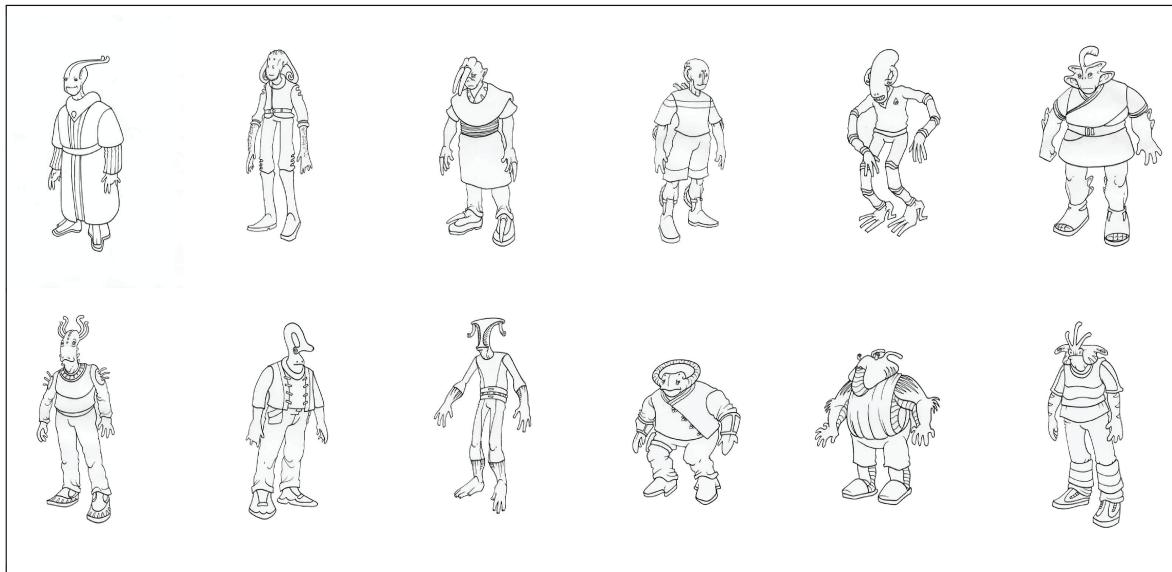
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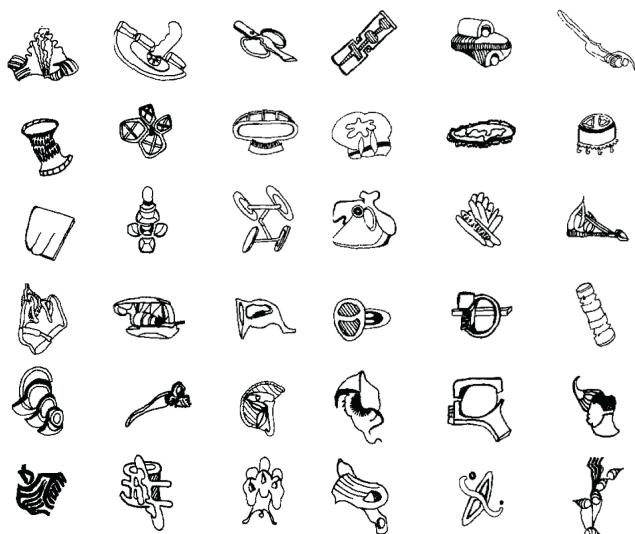
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APPENDIX A: Task Stimuli



Stimuli used in the child version of the nonlinguistic paired associate task.



Stimuli used in both the child and adult versions of the nonlinguistic paired associate tasks.