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DEVELOPMENTAL CHANGES IN THE FEEDBACK RELATED NEGATIVITY FROM 8 TO 14 YEARS

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Abstract

The study examined age related changes in the magnitude of the Feedback Related Negativity (FRN) in 8–14 year old children performing a variation of a Go/No-Go task. Participants were presented with four stimuli and tasked with mapping each of them either to a response or to a "no response" by trial and error guided by feedback. Feedback was valid for two stimuli (*Go* and *No-Go)* and invalid (.5 positive; .5 negative feedback) for the other two stimuli. The amplitude of the FRN was evaluated as a function of age separately for *Go* and *No-Go* trials. The results indicated that while performance on valid *Go* trials improved with age, accuracy on valid *No-Go* trials remained stable with age. FRN amplitude was found to be inversely related to age such that smaller FRN amplitudes were observed in older children even after controlling for variance in learning. Additionally, the FRN was found as a predictor of post-learning performance on *Go* trials but not on *No-Go* trials, regardless of age. These results do not provide support to the link between the FRN and inhibition control as measured by *No-Go* performance, but do suggest a link with other executive control abilities called for by the *Go* condition.

INTRODUCTION

Feedback processing is one of the executive functions, which are a class of high-level cognitive processes responsible for allocating resources, evaluating performance and its consequences, and changing strategies to improve future outcomes (e.g., Eslinger, 1996; Logan, 1985). Evidence indicates that executive functions develop during childhood and into early adulthood (e.g., Anderson, 2002; Davidson, Amso, Anderson, & Diamond, 2006; Huizinga, Dolan, & van der Molen, 2006; Romine, and Reynolds, 2005; Zelazo, Muller, Frye & Marcovitch, 2003). The Anterior Cingulate Cortex (ACC), Dorsolateral Prefrontal Cortex (DLPFC), and the cortico-striatal circuit play an important role in the development and function of the executive system (Adleman et al., 2002). Specifically, these brain regions

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have been implicated in feedback processing (Ferdinand, & Opitz, 2014; Hauser et al., 2014; Holroyd, & Coles, 2002; Woo et al., 2015) and undergo considerable maturational changes from childhood into early adulthood (Adleman, et al., 2002; Casey, et al., 1997; Cunningham, Bhattacharyya, & Benes, 2002; Rubia, Smith, Taylor, & Brammer, 2007; Velanova, Wheeler, & Luna, 2008; Vijayakumar, et al., 2014). Given that feedback processing relies on developing brain regions and circuits, it is pertinent to consider it as a developing skill.

The study of developmental changes in feedback processing has been enhanced by the discovery of the feedback related negativity (FRN) (Miltner, Braun, & Coles, 1997), an ERP component triggered by the presentation of feedback in various learning (e.g., Arbel, Goforth, & Donchin, 2013; Arbel, Murphy, & Donchin, 2014; Ernst and Steinhauser, 2012; Krigolson, Pierce, Holroyd, Tanaka, 2009; Luft, 2014; Pietschmann, Simon, Endrass, Kathmann, 2008; Sailer, Fischmeister, & Bauer, 2010; van der Helden, Boksem, & Blom, 2010) and gambling (e.g., Goyer, Woldorff, & Huettel, 2008; Hajcak, Moser, Holroyd, & Simons, 2007; Gehring & Willoughby, 2002) tasks. The goal of the present study is to examine age-related changes in feedback processing in children, as indexed by the FRN.

The FRN is a fronto-central negativity which peaks at about 250–300 ms following the presentation of the feedback stimulus. Converging evidence points to the Anterior Cingulate Cortex (ACC) as the source of the FRN (Carter, 1998; Critchley et al., 2005; Dehaene, Posner, & Tucker, 1994; Ladouceur, Dahl, & Carter, 2007; Mathalon, Whitfield, & Ford, 2003; Mars, et al., 2005; Menon, et al., 2001; van Veen, & Carter, 2002). There is evidence that in adults performing learning tasks, the amplitude of the FRN is sensitive to decision making (e.g., Chase, et al., 2011; Frank, Woroch, & Curran, 2005), and to learning outcomes (e.g., Arbel et al., 2013; Arbel, & Wu, 2016).

Developmental changes in FRN

In recent years, there is a growing effort to use the FRN to study developmental changes in children's feedback processing. This effort is supported by accumulated evidence that the FRN is reliably identified and measured in children (e.g., van Meel et al., 2012), and even in toddlers (Meyer et al., 2014; Roos et al., 2015). The typical FRN latency reported in children is in the 350–380 ms range (e.g., Roos et al., 2015; van Meel et al., 2012), approximately 100 ms later than the typical FRN latency in healthy young adults. In addition to latency differences, age related differences in FRN amplitude are reported when children are compared with adults and with adolescents. Eppinger et al. (2009), who employed a probabilistic learning task with valid and invalid feedback, found the FRN amplitude in 10–12 years old children to be larger than that of young adults. Zottoli and Grose-Fifer (2011) compared the FRN elicited by adolescents and adults, and reported larger amplitude in the adolescent group. Other examinations of FRN changes between adolescents and young adults did not find differences between the groups (Santesso et al., 2011; Yi et al., 2012). Other studies have examined developmental changes in feedback processing as measured by the FRN in children of different ages. Hämmerer et al. (2011) evaluated children of two age groups (9–11 years; and 13–14 years) with two groups of adults (20–30 years and 65–75 years), and Crowley et al. (2012) examined three age groups (10–12 yrs.; 13–14 yrs.; and

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15– 17 yrs.). Hämmerer et al. (2011) reported a gradual decrease in FRN amplitude with age when the two groups of children were compared with two groups of adults. Similarly, Crowley et al. (2012) found the FRN amplitude to be larger in children in the age groups of 10–12 and 13–14 years compared to children in the age-group of 15–17 years. Crowley et al. (2012), who employed a guessing-type task that did not require learning, suggested that the observed FRN differences were likely a function of age rather than of differences in rates or processes of learning. Contrary to these findings, Lukie, Montazer-Hojat, and Holroyd (2014) who studied the FRN in children 8–13, 14–17 years, and young adults, did not find amplitude differences between children in the different age groups. The discrepancy in the findings may be the result of differences in age groups. While studies reporting FRN differences among children used relatively narrow age ranges (e.g., 9–11, or 10–12), a broader age range was selected (8–13 years) in the study that did not find FRN differences. Given that changes are more evident in children in the pre-adolescence age-range (8–11 years), and less evident in adolescence (Hämmerer et al., 2011; Santesso et al., 2011; Yi et al., 2012), it is possible that the inclusion of early adolescents in a group affected results. Furthermore, the aforementioned studies considered age as categorical, possibly failing to capture meaningful variation across ages. We suggest that treating age as a continuous variable can shed light on developmental changes in FRN without the limitations presented by the selection of age groups.

FRN and the developing executive control system

The ability to use external feedback to monitor and adjust performance to achieve better outcomes is an important component of executive function. The study of the FRN as reflecting a developing executive function can be strengthened by evaluating the extent to which the FRN is associated with other components of executive function known to develop during childhood. One such component is inhibition control, commonly measured in a *Go*/*No-Go* task in which errors of commission (errors on *No-Go* trials) reflect disinhibition, and errors of omission (errors on *Go* trails) can serve as a measure of inattention (Barkley, 1997). Reports of improved inhibitory control during childhood and adolescence years are common (e.g., Brocki & Bohlin, 2004; Klimkeit et al. 2004; Jonkman, 2006; Levin et al., 1991; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), with some suggesting an age related increase in performance only in complex inhibition tasks (Cragg & Nation, 2008; Johnstone et al., 2007). Brocki and Bohlin (2004) reported improvement in inhibitory control from age 7 to 11 years. Similarly, Jonkman et al., (2003), and Casey et al. (1997) reported a decrease in commission errors in a *Go*/*No-Go* task from the age of 9 to early adulthood. Roos et al. (2015) studied the relationship between the FRN and inhibitory control in a sample of maltreated preschool-age children. The results indicated that larger FRN amplitude was associated with poorer inhibitory control. Interestingly, in children with poor inhibitory control, greater FRN amplitude was associated with better task performance, indicating that the larger FRN amplitude may reflect a greater effort associated with monitoring performance. While there is evidence that differences in FRN amplitude can be detected when groups of children with different levels of executive control are compared, it is yet unclear whether the FRN amplitude is modulated by finer, task specific individual differences in inhibitory control.

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The present study examined the FRN in 8–14 years old children performing a *Go/No-Go* task. The primary aim was to evaluate age-related changes in FRN amplitude, with age as a continuous variable. A secondary aim included determining the relationship between FRN and executive control. This aim was achieved by examining *No-Go* trials separately from *Go* trials and pre-learning trails from post-learning trials. The former separation permitted the evaluation of the FRN in relation to specific executive functions: inhibitory control in *No-Go* trials and the ability to maintain performance of the learned mapping in *Go* trails. The latter separation of pre-learning and post-learning trials allowed the examination of the FRN during the learning process (pre-learning trials), as it relates to a clean measure of executive control when the performance is no longer affected by the learning process (post-learning trials).

METHODS

Participants

One hundred and twelve children were recruited from a larger ongoing longitudinal study made up of same sex sibling pairs[1] and completed the ERP task. Data from 106 participants were included in the analyses. Six participants were excluded due to noisy data. Of the 112 who completed the ERP task, 86 were sibling pairs and the remaining 20 were those whose sibling did not complete the ERP portion of the study. The sample ranged in age from 8.8 to 14.2 (mean age = 11.0, SD = 1.3) and was roughly equally distributed across gender (45% female). Each participant's primary language was English and each had to exhibit reading proficiency within 1.5SD of the norm for his or her grade level to be admitted into the primary study. The sample consisted of 62% non-Hispanic White, 22% Hispanic, 6% Black, 1% Asian, and 9% other or multi-racial. Each had normal or corrected to normal vision. Ninety-two percent of the sample was right handed. Data collection began after assent was obtained from the participant and the parents signed a consent form. Participants were monetarily compensated for their time.

Data Acquisition & Signal Processing

The Electrical Geodesics Inc. (EGI; Eugene, OR) System 200 with 129-channel HydroCel Geodesic Sensor Nets from EGI was used to acquire and analyze dense-array electroencephalogram (EEG) data. The EEG was continuously recorded at a 250 Hz sampling rate with a vertex reference, and electrode impedances were kept below 50 kΩ, which is the manufacturer's recommended impedance threshold for this system. EEG data were filtered using an offline 40 Hz low-pass filter, and then segmented into epochs, each starting 200 ms before the feedback presentation and ending 800 ms after the feedback. Ocular artifacts were removed offline using an algorithm developed by Gratton, Coles, and Donchin (1983). Averages of the ocular-corrected and artifact-free epochs were calculated for each feedback type (positive and negative feedback), after baseline correcting each average over the 200 ms pre-feedback baseline. The averaged EEG epochs were re-referenced to linked mastoids.

[1]A total of 65 sibling pairs and one set of triplets were recruited from a large metropolitan area and were required to have one child between 8.5 and 9.5 years old and a same sex sibling 2–3 years older.

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Procedure

Each participant sat in a comfortable chair about 60 cm from a computer monitor and completed a variation of a *Go/No-Go* task. Participants were presented with four stimuli and were tasked with learning through trial and error guided by feedback whether a stimulus required a response (*Go*) or the withholding of a response (*No-Go*). Two of the stimuli were 100% mapped to the *Go/No-Go* conditions, and feedback associated with these stimuli was consistent with the participant's performance. For two other stimuli, there was no mapping rule to learn (negative feedback was provided on 50% of the trials and positive feedback on the other 50%, regardless of performance). Each participant was presented with 400 trials total. After 200 trials, the participant was allowed to take a 3-minute break. Each trial began with a fixation mark in the center of the screen for 1000 ms, followed by a visual stimulus for 450 ms. Each stimulus was followed by 550 ms blank screen prior to a visual presentation of the feedback. Participants had to respond or avoid responding within the time window of the stimulus presentation. The response window was increased by 50 ms after every 5 late responses up to a maximum length of 600 ms. Visual feedback appeared on the screen for 600 ms. Positive feedback was in the form of three check marks, while negative feedback was in the form of three Xs. Participants were considered to have learned a stimulus mapping when they responded correctly on 8 out of 10 consecutive trials of each stimulus type using a moving window.

Data Analysis

Data from the averages of each of the 129 electrodes for each feedback type, each condition (*Go, No-Go*), and each participant were entered into a spatio-temporal PCA procedure, using Varimax rotation. This analysis first reduces the spatial dimensionality of a large dataset and separates overlapping ERP components. Details of the PCA procedures are described by Spencer, Dien, and Donchin (2001) and were implemented using the Matlab toolbox provided by Dien (ERP PCA Toolkit, v.2.20; Dien, 2010). The analysis used the covariance between electrode sites and resulted with a set of 12 spatial factors accounting for 85% of the total variance. The original data were then filtered through these spatial factors (i.e., "virtual electrodes") and plotted across time as "virtual ERPs" (Spencer et al., 2001). The spatial factors were then entered into a temporal PCA to extract a set of temporal factors that can separate out components based on covariance. A total of 10 temporal factors were extracted, accounting for 95% of the variance. The spatio-temporal factors with morphology and scalp distribution corresponding to the FRN were then selected for additional analysis. Factor scores were taken as the index of the FRN in all analyses.

Age was treated as a continuous variable in all analyses. A series of multilevel models with an unstructured covariance matrix, where observations were nested within families to control for non-independence of sibling data, were estimated using restricted maximum likelihood to examine the hypotheses. First, for behavioral data, age and condition were used to predict learning speed (i.e., number of trials prior to learning). Secondly, age and learning rate were used to predict FRN amplitude. Lastly, similar multilevel models were conducted to examine whether the FRN from the pre-learning phase predicted performance (i.e., number of errors committed) after learning.

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RESULTS

Learning & Age

Differences in accuracy (see Figure 1) were examined across age. Overall, 75% of the sample learned the *Go* stimulus mapping, and 55% of the sample learned the *No-Go* stimulus mapping, while a total of 42% learned both mappings. Age was marginally related to learning speed on the task when compared in a single multilevel model (β=−1.6; t=−1.9, p=.06) with older participants learning more quickly and getting more trials correct; however, there was no age by condition (*Go* nor *No-Go*) interaction. As a follow-up evaluation, we examined only those participants who learned both stimulus mappings were included (n=45), and the same age effect was present (β=−1.4; t=−2.0, p=.05), but no age by condition interaction.

Age as a predictor of FRN amplitude

Spatial Factor 1 (SF1), yielded from the spatial PCA, was recognized as the fronto-central factor that captures the FRN and differentiates between positive and negative feedback stimuli. Examination of the virtual ERPs of this component (see figure 2) indicates that negative feedback elicited a negativity that peaked in the time window of 350–380 ms following the presentation of the feedback. Temporal Factor 2 (TF2) with maximal amplitude at 360 ms captures the time window of the observed FRN in the examined data. No other temporal factor exhibited a peak loading in this window surrounding the apparent FRN. Two factors captured peaks prior to the FRN (TF3: ~150ms peak; TF4 ~240ms peak), while the others captured variance subsequent to the FRN (e.g., TF1: ~700ms peak; TF6 ~ 440ms peak; & TF 7 ~560ms peak). Factor scores of TF2 in SF1, which represent the FRN amplitude for each participant, condition, and feedback valence, were entered into the statistical analyses.

Figure 3 depicts scatterplots of FRN amplitudes for pre-learning trials by stimulus and feedback type. The effect of age on FRN amplitude was assessed using multilevel models controlling for learning speed (i.e., the number of correct responses prior to meeting the learning criterion; higher values = slower learning). The results indicated that older age was significantly associated with smaller FRN (i.e., more positive) amplitude in the *Go* and *No-Go* conditions after controlling for learning (Table 1; cf. Figure 3). There were no differences by feedback type (i.e., positive or negative) and there were no significant interaction effects. A subsequent model was conducted using the portion of the sample (n=45) that learned both stimulus mappings; age remained the only significant predictor (β=.26; t=3.6, p<.01) with no interaction effects.

FRN as a predictor of post-learning performance

To evaluate the relationship between the FRN and executive control (the ability to maintain mapping and inhibit selected responses), a multilevel model was tested with the amplitude of the FRN as a predictor of subsequent errors after the learning criterion was achieved. Post-learning errors provided a cleaner measure (i.e., independent of the learning process) of the executive control abilities examined in this study. The results of the analysis revealed that in the *Go* condition, smaller (more positive) FRN predicted fewer errors after learning at a

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marginal level (p = .06; Table 2), after accounting for a significant effect of age in which higher age was associated with fewer errors after learning. There were no significant interactions between age, FRN, or feedback type. In the *No-Go* condition, FRN did not predict post-learning performance. As an exploratory follow-up, a model was evaluated on only those participants who learned both stimulus mappings (n=45) to examine whether the FRN in the *Go* and *No-Go* conditions were differentially related to post-learning errors. While a main effect of condition was found (β=8.2; t=5.1, p<.001), indicating that the *No-Go* condition was associated with more errors after learning when compared with the *Go* condition, there were no significant interaction effects in this model, likely due to insufficient power.

Summary of results

The analyses indicated that whereas learning the mapping of *Go* trials improved with age, performance on *No-Go* trials remained stable. Consistent with these findings, while both *Go* and *No-Go* conditions were associated with age related changed in the amplitude of the FRN, the relationship between the FRN and post-learning performance was only found in the *Go* condition. Our results suggest that the FRN is sensitive to age, such that increase in age is associated with decrease in FRN amplitude, even after controlling for variance in learning. Additionally, FRN amplitude in *Go* trials was found related to post-learning performance that may reflect executive control, even after controlling for age.

DISCUSSION

The present study evaluated performance on a *Go*/*No-Go* task involving the need to respond to some stimuli and withhold a response for other stimuli. The task also included a learning component, as participants were asked to determine through trial and error guided by feedback which stimulus was associated with a response, and which was associated with the need to withhold a response. This design allowed the examination of speed of learning (i.e., number of error trials before reaching a learning criterion), feedback processing as measured by the FRN, executive control (i.e., the ability to keep a representation of the mapping and inhibit responses when needed), and the possible interaction between them in children between the ages of 8 years and 14 years.

Learning & Age

Children within the examined age range showed comparable performance in *No-Go* trials that required inhibition of responses, but improved accuracy with age in *Go* trials that required a response. These results are surprising, as the ability to inhibit a response that is called for by the *No-Go* stimuli is known to show developmental changes (e.g., Bedard et al., 2002; Luna et al., 2004; Ridderinkhof, Band, & Logan, 1999; Van den Wildenberg & van der Molen, 2004; Williams et al., 1999). It is possible that young children in our sample exerted more effort to suppress responses in the *No-Go* condition, causing a tradeoff between performance on *Go* and *No-Go* trials. It is also possible that since fewer participants met the learning criterion in the *No-Go* condition (Table 1), power was limited to detect differences.

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FRN & Age

The results of the study suggested that increase in age is associated with reduced FRN amplitude even after controlling for variance in learning. This finding of a gradual reduction in FRN amplitude with age is in line with previous reports of larger FRN amplitude in children when compared with adults (Eppinger, 2009), and in young children when compared with older children (e.g., Crowley, 2012; Hämmerer et al., 2011). Such developmental changes are commonly interpreted as reflecting a greater reliance on external feedback at a younger age (e.g., Eppinger, 2009). It is important to note that Lukie et al. (2014) did not find amplitude differences between children in the two age groups. It is possible that including early adolescents in Lukie et al.'s younger age group (8–13) may have diminished any differences between the first and second age groups.

FRN & Executive Control

FRN amplitude was found to be related to post-learning performance on *Go* trials, suggesting a link between the FRN and an executive ability called for by *Go* trials (i.e., the need to keep the representation of the mapping active). More specifically, better performance on post-learning *Go* trials was associated with smaller FRN amplitudes (more positive) after controlling for age. An indication of the relationship between the FRN and executive control can be deduced from studies of the FRN in individuals with poor inhibitory control (e.g., Roos et al., 2005). In such reports high impulsivity has been found to be associated with larger FRN amplitude (more negative) to negative feedback, and interpreted to reflect greater reliance on external feedback by individuals in the highly impulsive group to maintain inhibitory control. Our results of a relationship between FRN amplitude and performance on post-learning *Go* trials are in line with these reports.

Results from this study can be explained within the framework of the utility account of the FRN offered by Arbel et al. (2013; 2014). The utility account asserts that the FRN reflects the amount of attentional or processing resources allocated to the extraction of information from the feedback, with faster, more efficient learners using less processing resources. Within this framework, the results of the present study suggest that individuals with better executive control abilities are also better at extracting information from feedback, thus their smaller FRN amplitude. These results are in line with our previous finding of an association between small FRN amplitude and fast learning (Arbel & Wu, 2016). In Roos et al. (2005) the FRN amplitude in the highly impulsive group was positively correlated with learning, such that larger FRN amplitude was related to better performance among children in this group. Although Roos et al.'s results appear to be in contrast with our previous reports (Arbel et al., 2014; Arbel & Wu, 2016) and current findings, the discrepancy can be resolved by the utility account of the FRN. If smaller FRN amplitude reflects a reduced need to rely on feedback, smaller FRN amplitude should be found in individuals with a mature cognitive system and advanced executive control abilities. It is therefore expected to find smaller FRN amplitude in older children when compared with younger children, in stronger learners, and in those with better executive control abilities. In those individuals whose executive control system is immature or impaired, there is a need and a benefit to exerting more resources to the processing of feedback, such that greater effort to process feedback as reflected in larger FRN amplitude results in better performance. While our finding of a relationship between

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FRN amplitude and post-learning performance on *Go* trials is in line with the utility account of the FRN, the absence of such relationship for *No-Go* trials should be further explored.

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Highlights

- FRN amplitude was found to be inversely related to age
- Smaller FRN amplitudes were observed in older children even after controlling for variance in learning.
- FRN was found as a predictor of post-learning performance on *Go* trials but not on *No-Go* trials, regardless of age.

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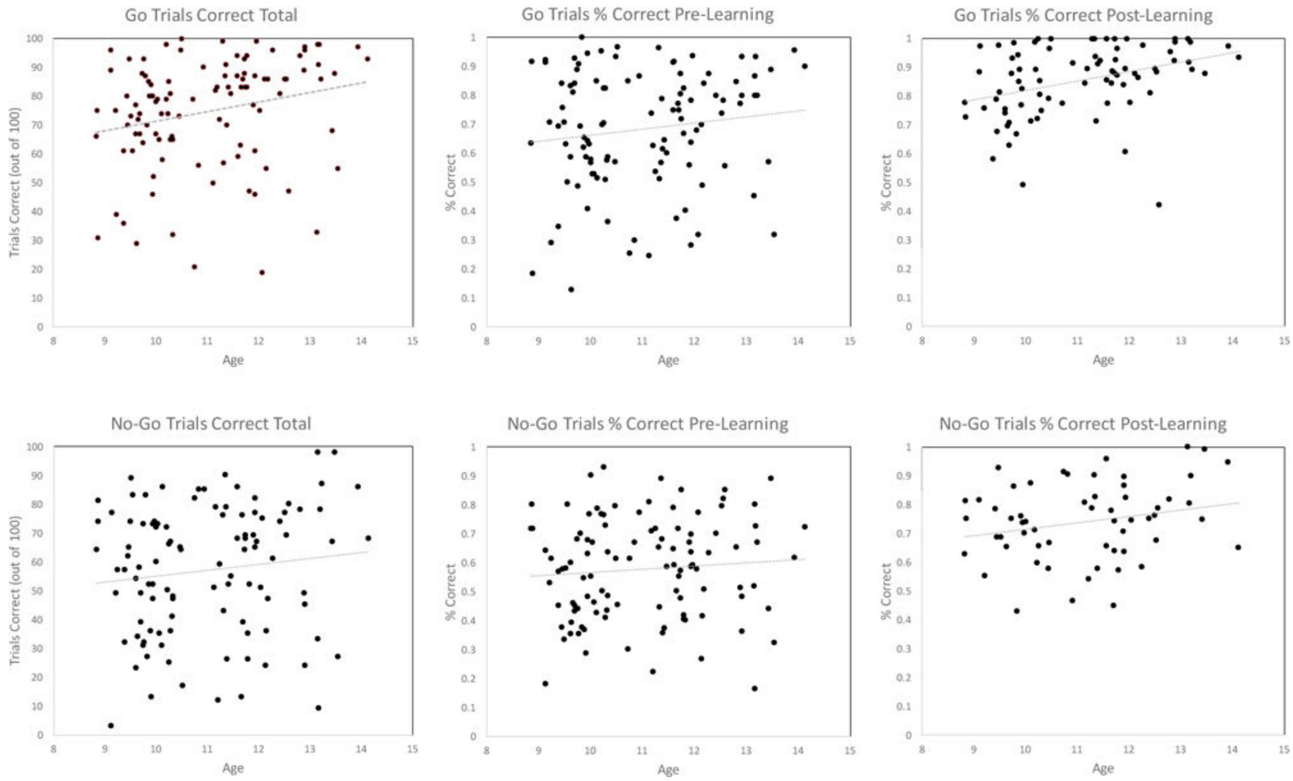

Figure 1.

Scatterplots of performance by condition. Number of correct *Go* trials (top row) and *No-Go* trials (bottom row) out of 100 trials per condition (left column) and percent of trials correct prior to learning the stimulus mapping (i.e., "pre-learning"; column 2) for all participants. Performance on post-learning trials (column 3) represent only the proportion of the sample that learned the stimulus mapping for each condition.

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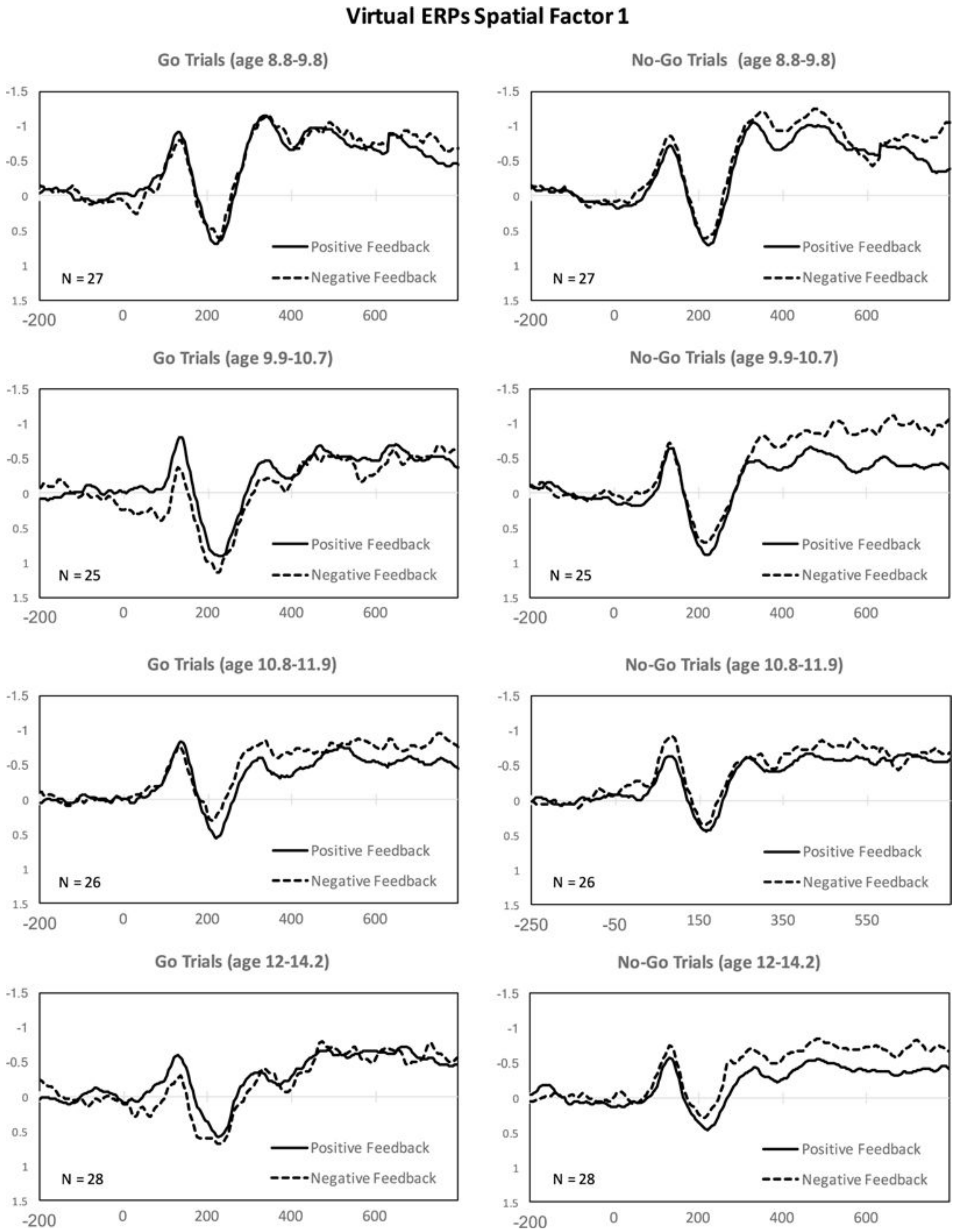

Figure 2.

Virtual ERPs of Spatial Factor 1 for positive feedback (solid line) and negative feedback (dashed line) in Go trials (left) and NoGo trials (right). The separation of plots based on age is for visualization only and does not reflect our analysis.

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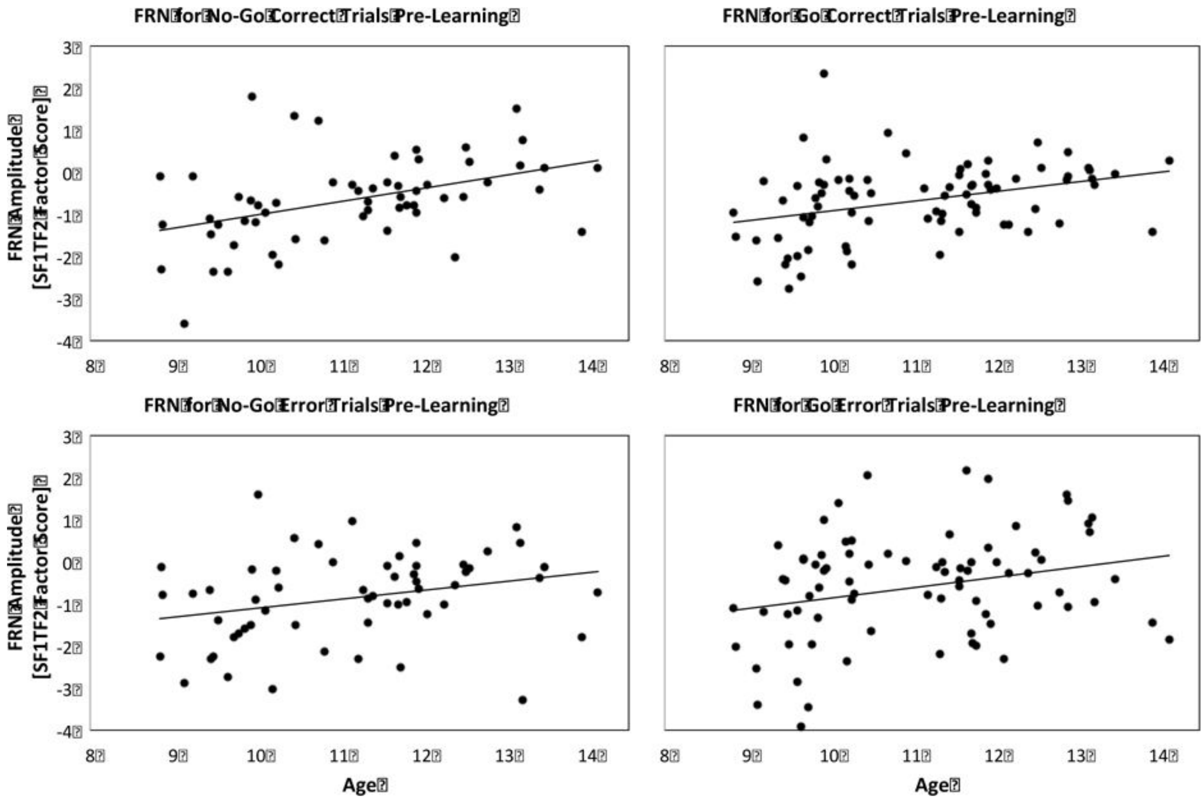

Figure 3.

Amplitude of FRN (measured as factor scores of SF1-TF2) elicited by positive (top row) and negative (bottom row) feedback in No-Go (left column) and Go (right column) trials before achieving a learning criterion.

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Table 1

Multilevel linear model results predicting Feedback Related Negativity with age, feedback type (positive or negative) and learning speed for *Go* and *No-Go* trials.

	Estimate	Std. Error	t-value	p-value	Model AIC
No-Go Trials					
DV: FRN					332.4
Age	.24	.07	3.47	<.001	
Learning Speed	−.01	.01	−.71	.48	
Feedback Type	−.27	.17	−1.62	.11	
Go Trials					
DV: FRN					488.0
Age	.22	.07	3.32	<.01	
Learning Speed	−.001	.01	−.35	.72	
Feedback Type	.02	.20	.12	.90	

Note: observations were nested in families to account for potential non-independence of sibling data

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Table 2

Multilevel linear model results predicting post-learning errors on Go and No-Go trials with age Feedback Related Negativity (FRN), age, and feedback type.

		Estimate	Std. Error	t-value	p-value	Model AIC
No-Go Trials						
DV.Post-learning Errors						845.7
	Age	.02	.75	.02	.98	
	FRN	1.20	.87	1.38	.17	
	Feedback Type	.25	1.13	.22	.82	
Go Trials						
DV.Post-learning Errors						1049.1
	Age	−2.20	.40	−5.54	<.001	
	FRN	.86	.45	1.89	.06	
	Feedback Type	−.06	.72	−.09	.93	

Note: observations were nested in families to account for potential non-independence of sibling data