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# A heart rate analysis of developmental change in feedback processing and rule shifting from childhood to early adulthood

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## Abstract

Over the course of development, the ability to switch between different tasks on the basis of feedback cues increases profoundly, but the role of performance monitoring remains unclear. Heart rate indexes can provide critical information about how individuals monitor feedback cues indicating that performance should be adjusted. In this study, children of three age groups (8–10, 12–14, and 16–18 years) performed a rule change task in which sorting rules needed to be detected following positive or negative feedback. The number of perseverative errors was lower for 16- to 18-year-olds than for 8- to 10-year-olds, and 12- to 14-year-olds performed at an intermediate level. Consistent with previous findings, heart rate slowed following feedback indicating a rule change, and the magnitude of slowing was similar for all age groups. Thus, 8- to 10-year-olds are already able to analyze feedback cues. In contrast, 12- to 14-year-olds and 16- to 18-year-olds, but not 8- to 10-year-olds, showed heart rate slowing following performance errors, suggesting that with age children are increasingly able to monitor their performance online. Performance monitoring may therefore be an important contributor to set-shifting ability.

*Keywords:* Perseveration; Inhibition; Children; Heart rate; Errors; Feedback; Performance monitoring

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# Introduction

A rapidly growing body of evidence indicates that between childhood and early adulthood, there are pronounced changes in executive control that involve changes in deliberate thought and action for the purpose of attaining future goals (for reviews, see Diamond, 2002; Huizinga, Dolan, & Van der Molen, 2006). Executive control is especially important in novel or demanding situations where rapid and flexible adjustment of behavior to changing task demands is required (Stuss & Levine, 2002). Executive control is commonly attributed to the prefrontal cortex (PFC) (for a review, see Miller & Cohen, 2001), and developmental changes in executive control have been associated with the late functional maturation of the PFC (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey, 2002).

Set shifting frequently is used to assess executive functioning. During set shifting, participants are required to rapidly switch among several task rules, either on the basis of preset task cues (Meiran, 1996; Monsell, 2003) or on the basis of feedback indicating that prior performance no longer is correct (Barcelo & Knight, 2002; Demakis, 2003). Both procedures revealed interesting developmental trends in the ability to shift task sets. For example, Cepeda, Kramer, and Gonzalez de Sather (2001) showed that between 8 and 14 years of age, there is a large decrease in the time required to switch flexibly between two task rules on the basis of shift cues. Using tasks with performance-based shift cues (i.e., performance feedback), children become more successful in performing intra- and extradimensional switches (Luciana & Nelson, 1998), and they detect more sorting categories and make fewer errors on rule change tasks, with the most pronounced changes occurring before 12 years of age (Chelune & Baer, 1986; Crone, Ridderinkhof, Worm, Somsen, & Van der Molen, 2004; Welsh, Pennington, & Groisser, 1991; Zelazo, Craik, & Booth, 2004).

An essential component of executive control, as required in many shifting paradigms, is the ability to use performance feedback for subsequent performance adjustment, also referred to as performance monitoring (Holroyd & Coles, 2002). Research on performance monitoring has distinguished between (a) monitoring of behavior without explicit cues (i.e., response monitoring) and (b) monitoring of behavior on the basis of external cues such as positive or negative feedback (i.e., feedback monitoring) (Holroyd & Coles, 2002). Performance monitoring is therefore an important aspect of set shifting because it is involved when performance adjustment is necessary following changes in task demands as well as following committing an error. Previous developmental studies that have examined the development of executive function focused mostly on response selection processes such as those involved during selective attention (Ridderinkhof & van der Molen, 1995) and response selection (Cepeda et al., 2001) as well as the ability to withhold a certain response (Williams, Ponesse, Schachar, Logan, & Tannock, 1999). However, it remains unclear to what extent changes in executive control are associated with the development of the ability to monitor behavior following changing task demands. In this study, we examined the development of both aspects of performance monitoring between late childhood and early adulthood using a task in which participants needed to switch between task rules following performance feedback.

## *Performance monitoring*

Performance monitoring has been studied in the neuropsychological literature using the classic Wisconsin Card Sorting Task (WCST). This task requires participants to match target cards to standard cards following sorting rules that can change unexpectedly. In this task, each sort is followed by positive or negative feedback depending on the correctness of the sort (Demakis, 2003). Neuropsychological studies indicate that patients with damage to the lateral PFC perseverate on previously relevant rules in the WCST (Barcelo & Knight, 2002; Stuss & Levine, 2002). Children also perform less successfully than adults because children perseverate in the previous sorting rule. Perseveration refers to behavior that occurs when participants keep sorting to the dimension that was correct previously (e.g., Chelune & Baer, 1986; Welsh et al., 1991). Although these findings are indicative of developmental change in performance monitoring, the interpretation of developmental changes in the classic WCST is difficult because of the complexity of this task.

Using simpler, more straightforward set-shifting tasks, several investigators have shown a pronounced developmental change in perseveration between 3 and 6 years of age (Kirkham, Cruess, & Diamond, 2003; Muller, Zelazo, Hood, Leone, & Rohrer, 2005; Zelazo, Frye, & Rapus, 1996; Zelazo, Muller, Frye, & Marcovitch, 2003). These studies have shown consistently that young children perseverate while knowing the correct sorting dimension, suggesting that errors occur at the response selection phase (Zelazo et al., 1996). Several explanations have been offered for this finding. For example, Kirkham and colleagues (2003) suggested that young children perseverate because they suffer from attentional inertia, resulting in a failure to inhibit focusing attention on the previously attended dimension. Zelazo and colleagues (2003; see also Jacques, Zelazo, Kirkham, & Semcesen, 1999; Muller et al., 2005; but see Munakata & Yerys, 2001) offered a different interpretation of children's perseveration. They argued that young children fail to reflect on rules when there are multiple bivalent rules that come into play. Thus, they may understand the meaning of one rule but fail to follow this rule in their actions because their actions are still biased in favor of the previously relevant rule. In addition, Deak and colleagues (Deak & Narasimham, 2003; Deak, Ray, & Pick, 2004) suggested that perseveration in young children might not be due only to failure to inhibit or reflect on rules; instead, it may also be associated with a failure to understand that task rules have changed. Taken together, several accounts have been offered to explain changes in set shifting by theories of early cognitive development, but these theories fall short in offering an explanation with respect to the development of performance monitoring. The theories implicate that children analyze feedback indicating that performance needs to be adjusted, and they offer different explanations with respect to putting this knowledge into actions. However, it remains to be investigated whether children are indeed capable of analyzing the feedback that indicates performance adjustment.

In our previous research (Crone, Ridderinkhof, et al., 2004), we found that age differences in set shifting can be attenuated by modulating the extent to which feedback needs to be processed. We examined the performance of school-age children (8–9, 11–12, and 13–15 years) and young adults on two versions of a WCST analogue task. Participants were asked to sort a stimulus according to three possible location rules, and they received positive or negative feedback following each sort. After a certain number of correct sorts, the rule changed unexpectedly and participants needed to apply another location rule. In the first version of the task, rule changes were indexed by positive or negative feedback, whereas in the second version, rule changes were explicitly cued. When rule changes were explicitly cued (and therefore did not require the ability to use feedback), children's perseverative errors decreased more than those of adults, suggesting that failure to process performance feedback is a critical component contributing to set-shifting development. Thus, these findings argue against the hypothesis that children analyze feedback in the same way as do adults. Despite the performance improvement, however, 8- and 9-year-olds still made more perseverative errors than did adults on the cued task. It is unclear what causes these developmental differences, but possibly these are related to a failure to monitor performance in a similar way as do adults. These changes are difficult to observe based on behavior alone, but they can be examined by the use of psychophysiological measures.

## *Psychophysiological measures*

A more direct approach to studying children's ability to use performance feedback makes use of psychophysiological indexes. This can be achieved by the use of electroencephalogram (EEG) measures or by the use of autonomic signals. Recently, brain activity associated with response monitoring and the valence of performance feedback (i.e., positive or negative) has been studied using electrophysiological correlates of the medial frontal cortex. These studies have shown that following committing an error, a negative polarity, frontocentrally distributed scalp potential is observed approximately 100 to 200 ms following the erroneous response and is referred to as the error-related negativity (ERN) (Gehring, Goss, Coles, Meyer, & Donchin, 1993). Source localization studies have shown that this response originates from the anterior cingulate cortex (Van Veen & Carter, 2002). Consistent with the hypothesis of late development of performance monitoring, developmental studies have reported that this error-related potential increases during late childhood, suggesting that response monitoring still develops between late childhood and early adulthood (Davies, Segalowitz, & Gavin, 2004; Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005). Following externally presented feedback, a similar frontocentrally located scalp potential is observed, peaking approximately 250 ms following feedback with a negative valence (Holroyd & Coles, 2002). It has been suggested that this potential originates from the same source as does the ERN (Miltner, Braun, & Coles, 1997). However, there are currently no psychophysiological studies that have examined the development of feedback monitoring.

Several recent studies have shown that feedback processing can be reliably indexed by phasic heart rate changes measured during the performance of complex tasks (Crone et al., 2003; Somsen, Van der Molen, Jennings, & Van Beek, 2000; Van der Veen, Van der Molen, Crone, & Jennings, 2004), consistent with the literature suggesting that regulating the autonomic substrate supports appropriate attentive and social behaviors (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996). It is well known from the phasic heart rate literature that heart rate slows in preparation for a response and is then followed by an acceleratory recovery to baseline (for a review, see Jennings & Van der Molen, 2002). When participants receive negative performance feedback, heart rate slows profoundly before recovering to baseline (Crone et al., 2003; Van der Veen et al., 2004). Somsen and colleagues (2000) examined heart rate changes occurring around the presentation of positive or negative feedback in the WCST and showed that heart rate slowing was largest when negative feedback indicated that the previous sorting rule no longer was correct. This finding was interpreted to suggest that heart rate slows most when performance expectations are violated (see also Crone et al., 2003). In addition, heart rate slowing is indicative of error processing because heart rate slows following committing an error when no feedback is presented (Hajcak, McDonald, & Simons, 2003). Thus, heart rate slowing is associated with the processing of both an internal signal (i.e., response monitoring) and an external signal (i.e., feedback monitoring) indicating that an error has been committed.

The developmental literature has shown that heart rate changes correspond to individual differences in self-regulation, anger management, and fear (e.g., Fox & Calkins, 2003; Porges et al., 1996), but little is known about the developmental changes in autonomic response processes associated with cognitive control. We recently examined how heart rate changes of adults, as well as those of 8- and 12-year-olds, were sensitive to informative and uninformative performance feedback (Crone, Jennings, Van Beek, & Van der Molen, 2004). We found that 8-year-olds differed from 12-year-olds and adults in that the younger children showed heart rate slowing following both informative and uninformative negative feedback, whereas heart rates of 12-year-olds and adults slowed only following performance-related negative feedback. These results were interpreted to suggest that 8-year-olds were less successful in selecting which feedback is necessary for future performance adjustment. Therefore, heart rate changes associated with positive or negative feedback during rule switching may be especially informative as a more direct index of what aspects of performance monitoring contribute to set-shifting performance in young children.

## *The current study*

In the current study, we examined performance and heart rate changes in school-age children (8–10, 12–14, and 16–18 years) while they performed a set-shifting task resembling the WCST (Crone, Ridderinkhof, et al., 2004). This task required them to switch among three different stimulus–response association rules on the basis of positive or negative feedback. The age range was chosen so that we could compare the findings with those from other studies on performance monitoring during adolescence (e.g., Davies et al., 2004). We expected the largest changes to occur between 8- to 10-year-olds and 12- to 14-year-olds (see also Crone, Jennings, et al., 2004). Our scoring system benefited from a recently introduced method by Barcelo and Knight (2002) for examining performance errors of patients with dorsolateral prefrontal cortex (DLPFC) damage on the WCST. This method distinguishes among four types of negative feedback: first-warning negative feedback, indicating that the sorting rule has changed, and negative feedback following three types of errors: an efficient error (i.e., an error that is made to find the currently correct sorting rule), a perseverative error (i.e., an error associated with continued performance according to the previously correct sorting rule), and a distraction error (i.e., performance error associated with failure to keep performing according to the currently correct sorting rule). It was expected that perseverative errors would be higher for 8- to 10-year-olds than for 12- to 14-year-olds and 16- to 18-year-olds (Chelune & Baer, 1986; Crone, Ridderinkhof, et al., 2004; Welsh et al., 1991). We expected that distraction errors would be larger for 8- to 10-year-olds and 12- to 14-year-olds than for 16- to 18-year-olds (Crone, Ridderinkhof, et al., 2004).

To examine the extent to which performance changes are associated with processing first-warning feedback, heartbeats were selected around the feedback (see also Fig. 1A). First-warning feedback was expected to result in the slowing of sequential heartbeats immediately following the feedback because this feedback is unexpected (Somsen et al., 2000). The second heart rate analysis focused on changes occurring after performance errors (perseverative and distraction errors) (see also Fig. 1A). Heart rate slowing associated with performance errors (rather than unexpected negative feedback) has been associated with the ability to monitor ongoing performance (Crone et al., 2003; see also Holroyd & Coles, 2002).

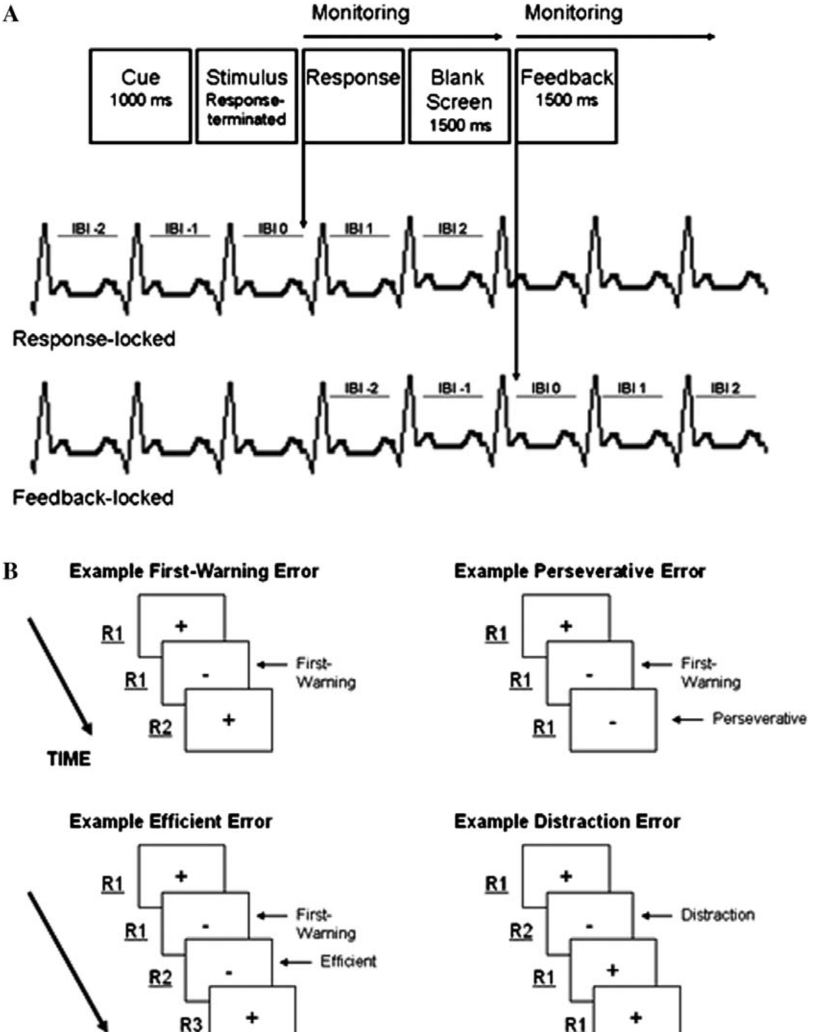

Fig. 1. Example of task design. (A) Different phases of the task. (B) Examples of different feedback conditions. Rules 1 to 3 refer to rules applied by the participant. IBI, interbeat interval. See text for further details.

We examined three hypotheses. First, if young children detect incorrect responses (i.e., show response and feedback monitoring at an adult level), then the heart rate pattern following first-warning feedback and following performance errors should be similar for all age groups. Second, if 8- to 10-year-olds fail to monitor erroneous responses, then heart rate slowing should be larger following perseverative errors for 12- to 14-year-olds and 16- to 18-year-olds than for 8- to 10-year-olds. Finally, if 8- to 10-year-olds fail to analyze feedback indicating that expectations are violated, then heart rate slowing should be larger for 12- to 14-year-olds and 16- to 18-year-olds than for 8- to 10-year-olds following first-warning feedback. In addition, we expected that those individuals who perform best on the task would show more pronounced heart rate slowing following errors and feedback (Somsen et al., 2000).

# Method

## Participants

Three age groups participated in the study: 23 8- to 10-year-olds, 23 12- to 14-year-olds, and 25 16- to 18-year-olds. Children and adolescents were recruited by contacting schools. These participants were selected with the help of their teachers, and their primary caregivers signed consent letters for participation. The teacher confirmed that all participants were average or above average students, and all children took a computerized version of the Raven Standard Progressive Matrices task (Raven task) to obtain estimates of their cognitive functioning. Descriptive characteristics for each group are presented in Table 1. Norm-referenced scores (Vodegel Matzen, 1994) showed that IQ did not differ among the three age groups.

Chi-square analyses indicated that gender did not differ significantly among the three age groups for either of the tasks. A one-way analysis of variance (ANOVA) performed on the estimated IQ scores revealed no significant difference among age groups, $F(2, 70) = 1.85$, $p = .17$. We analyzed how the raw Raven scores were related to performance on the task by correlating Raven performance with (a) number of errors and (b) magnitude of heart rate slowing. Performance on the Raven task correlated significantly with the number of errors (including perseverative errors and distraction errors) that were made on the task, also when the effect of age was factored out, $r = -.33$, $p < .05$. This correlation indicates that there is a relation between set-shifting performance and inductive reasoning (see also Carpenter, Just, & Shell, 1990). However, when performance on the Raven task was correlated with the number of distraction errors or the number of perseverative errors separately, and with the number of categories completed, these correlations were not significant. There was also not a significant correlation with heart rate slowing.

## Rule shift task

The rule shift task was based on Crone, Ridderinkhof, and colleagues (2004). Participants were seated in front of a 15-inch computer monitor at a viewing distance of approximately 75 cm. Two displays were presented on each trial: a stimulus display and an outcome display. The stimulus display consisted of four doors (A, B, C, and D) (3 × 5 cm) presented in two separate "houses" in a horizontal row, followed by a 1000-ms delay, followed by a donkey (2 × 4.5 cm) that was presented in front of the doors. Participants were told to assist the donkey in finding its way home by pressing one of four keys correspond-

Table 1
Descriptive characteristics of the participants: Number of participants, mean ages, and mean Raven scores

| Age group (years) | *n* | Mean age (years) | Mean Raven score |
|---|---|---|---|
| 8 to 10 | 23 (10 boys and 13 girls) | 9.4 (0.9) | 114.2 (11.8) |
| 12 to 14 | 23 (10 boys and 13 girls) | 13.3 (1.1) | 107.3 (12.6) |
| 16 to 18 | 25 (4 boys and 21 girls) | 17.2 (1.1) | 111.1 (12.4) |

*Note.* In last two columns, standard deviations are in parentheses.

ing to the doors. The left middle, left index, right index, and right middle fingers were assigned to the Z, X, <, and > keys of the computer keyboard, respectively. These keys were mapped onto the doors from left to right. When participants pressed one of the keys, the stimulus display was replaced by a 1500-ms blank screen, followed by the outcome display, showing a plus (+) sign indicating positive feedback or a minus (−) sign indicating negative feedback at the location of the selected door. The stimulus associated with the next trial was presented 1500 ms after feedback onset (see also Fig. 1A).

During the task, participants sorted stimuli according to one of the three location rules. Following Rule 1, stimuli that appeared on one of four locations designated a response with the finger compatible to the location. Thus, spatially compatible button presses were required in response to the location of the stimulus. Following Rule 2, stimuli that appeared at any of the four possible stimulus positions designated a response with the opposite finger of the same hand. Following Rule 3, stimuli that appeared at any of the four possible stimulus positions designated a response with the finger that was assigned to the location two positions from the stimulus location (see also Stoffels, 1996). The critical sorting rule initially was unknown to participants and needed to be inferred using trial-by-trial feedback. Participants were told that the relevant sorting rule could change from time to time and that they needed to use trial-by-trial feedback to infer a new sorting rule (see also Barcelo & Knight, 2002). When participants had correctly applied the relevant sorting rule for eight consecutive trials, the sorting rule was shifted to another dimension without notice. The task consisted of 150 trials. To familiarize participants with the stimuli and procedure, they received three blocks of 15 practice trials of each sorting rule. Participants practiced the three rules separately before they started the experimental task. The order of practice rules was counterbalanced between participants. Our program required a baseline of success on 80% of the trials for participants to start with the new practice trials with a minimum practice set of 15 trials. The symbolic meanings of positive and negative feedback were explained, and all participants understood their meanings.

### *Procedure*

All participants were tested individually in a quiet laboratory or classroom. The rule shift task took approximately 15 to 25 min to complete. Care was taken that all children understood the instructions and understood the symbolic meanings of positive and negative feedback. The Raven task was administered following the completion of the rule shift task and took approximately 20 min to complete. Including instructions and breaks, participants spent approximately 50 min in the laboratory or classroom.

### *Data recording and reduction*

During the task, the electrocardiogram (ECG) and respiration were recorded continuously. The ECG was recorded from three AgAg/Cl electrodes attached via the modified lead-2 placement. Respiration was recorded through a temperature sensor placed under the nose. The signals were amplified by a Nihon Kohden polygraph and sampled by a Keithley AD converter at a rate of 400 Hz. The recorded interbeat intervals (IBIs) were screened for physiologically impossible readings and artifacts. These were corrected by adjusting specific parameters in the program that extracted the IBIs from the digitized ECGs. Respiration was recorded continuously throughout the task, and heart beats were excluded only when there were gross respiratory movements, usually associated with movement (Jennings et al., 1981). This occurred on only a small proportion of the trials (<5% for each age group), and there were no differences in number of exclusion trials among age groups, $F < 1$. Each time participants pressed a response key, this action was recorded as a pulse on the sampling computer that was accurate to the nearest millisecond.

## Results

### *Performance analysis*

*First-warning feedback* was defined as the first negative feedback indicating that the sorting rule had changed. Errors were scored as a function of past contextual information (Barcelo & Knight, 2002). An *efficient error* was defined as a shift to the wrong sorting dimension on the second trial of an otherwise clear series (i.e., a series with no further errors other than the first-warning error). Efficient errors were scored only on the second trial of the series and were incompatible with any other type of error. A *perseverative error* was defined as a failure to shift category after receiving negative feedback from the previous trial. A *distraction error* was defined as a shift to a wrong category different from the one chosen in the previous trial. Distraction errors indicated that participants had not kept track of all previously discarded categories. Examples of these errors are presented in Fig. 1B.

There were on average 112, 113, and 119 correct feedback trials for 8- to 10-year-olds, 12- to 14-year-olds, and 16- to 18-year-olds, respectively. For errors, there were on average 10.0, 10.5, and 11.8 first-warning errors; 2.4, 2.2, and 2.8 efficient errors; 6.6, 5.5, and 4.0 perseverative errors; and 14.7, 14.6, and 9.2 distraction errors for 8- to 10-year-olds, 12- to 14-year-olds, and 16- to 18-year-olds, respectively. Efficient errors, perseverative errors, and distraction errors were computed as the total number of each error type divided by the number of sorting rule shifts (i.e., similar to the categories achieved in the standard WCST). These scores were submitted to ANOVA with the between-subjects effect of Age Group (8–10, 12–14, or 16–18 years) and the within-subjects effect of Error Type (efficient, perseverative, or distraction).

Fig. 2 displays the number of errors per shift for each age group. A main effect of error type showed that all participants made more perseverative errors ($M = 0.56$, $SD = 0.07$) than efficient errors ($M = 0.23$, $SD = 0.02$) and made more distraction errors ($M = 1.48$,

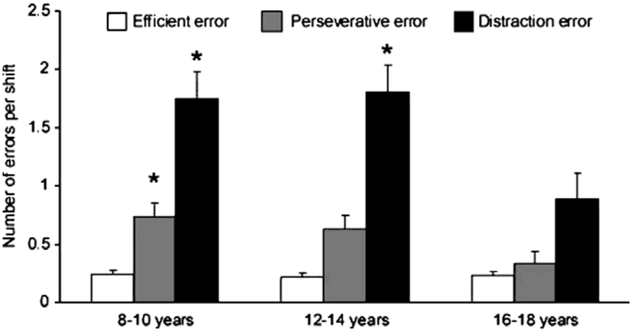

Fig. 2. Mean numbers of efficient, perseverative, and distraction errors per response shift for each age group separately. *Significantly different from adults at $p < .05$.

$SD = 0.13$) than perseverative errors, $F(2,136) = 77.62, p < .001$. An interaction between age group and error type, $F(4,136) = 4.36$, $p < .001$, showed that younger participants were more prone to making perseverative errors, $F(2,68) = 3.46$, $p < .05$, and distraction errors, $F(2,68) = 5.34, p < .01$, whereas there was no significant difference in the number of efficient errors among age groups, $F(2,68) = 0.16, p = .84$. Results of planned between-age contrasts of these effects with a $p < .05$ indicated that distraction errors of both 8- to 10-year-olds and 12- to 14-year-olds exceeded those of 16- to 18-years-olds and that 12- to 14-year-olds and 8- to 10-year-olds did not differ from each other. In contrast, perseverative errors of 8- to 10-year-olds exceeded those of 16- to 18-year-olds but did not discriminate between 12- to 14-year-olds and 16- to 18-year-olds.

### *Rule shift task: Heart rate analyses*

Four IBIs were selected for the time window that included the response and feedback. For feedback-locked analyses, these were the concurrent IBI (IBI 0), the IBI preceding the feedback stimulus (IBI −1), and two IBIs following the feedback stimulus (IBI 1 and IBI 2). IBIs were compared with the second IBI preceding the feedback (IBI −2). For response-locked analyses, IBIs were selected concurrent with the response (IBI 0), preceding the response (IBI −1), and following the response (IBI 1 and IBI 2). IBIs were compared with the second IBI preceding the response (IBI −2) (see also Fig. 1A; Crone, Jennings, et al., 2004; Somsen et al., 2000). Heart rate analyses with IBI as a repeated-measures factor were adjusted using Huynh–Feldt corrections to adjust for inhomogeneity of the variance–covariance matrix.

IBI length is sensitive to a number of factors, including age. In the current study, we examined Age × Condition interactions across IBIs. We expected no age differences in IBI length prior to the event, and we expected age differences to occur following the event (Condition × IBI Sequence interaction). Although the number of observations was relatively small for some conditions (e.g., for number of perseverative errors), previous research has indicated that these events result in reliable heart rate changes (Somsen et al., 2000).

### *Positive feedback*

First, we examined whether there were age-related differences in responsiveness to positive feedback. This analysis was performed to examine whether there were global differences between age groups in responsiveness to positive feedback. Four IBIs were selected before and after the positive feedback and were submitted to a 3 (Age Group) × 4 (IBI) mixed-measures ANOVA. The analysis revealed a main effect of IBI, $F(3,192) = 70.14$, $p < .001$, but there was no interaction between IBI and age group, $F < 1$. A similar 3 (Age Group) × 4 (IBI) ANOVA for IBIs selected around the response again revealed a main effect of IBI, $F(3,198) = 45.14$, $p < .001$, but no significant interaction between age group and IBI, $F < 1$. Thus, age groups did not differ in responsiveness to positive feedback. For the next set of analyses, responsiveness to positive feedback was used as a reference for responsiveness to negative feedback and errors.

### *First-warning feedback*

The first question focused on cardiac changes evoked by first-warning errors. For this analysis, four IBIs around the *feedback* were selected and submitted to a 3 (Age Group) × 2

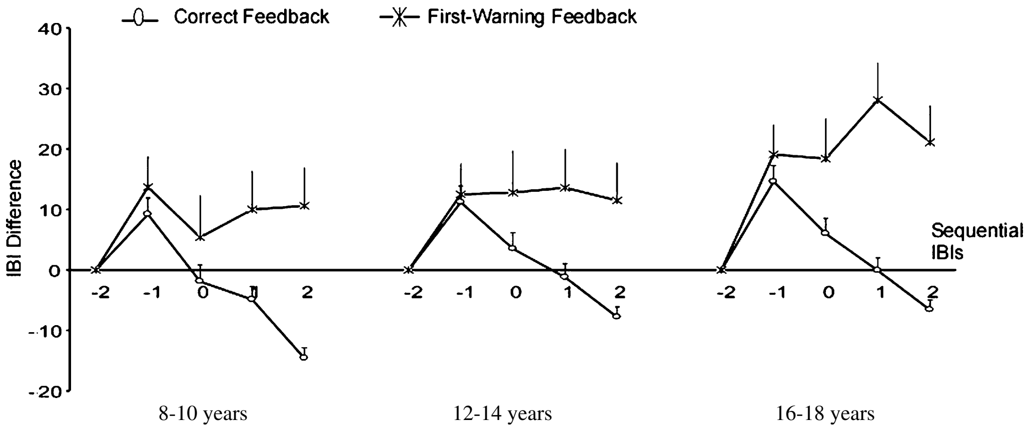

Fig. 3. Heart rate changes evoked by first-warning feedback, relative to positive feedback, for each age group. IBI 0 refers to the IBI concurrent with feedback presentation. An increase in IBI length indicates heart rate slowing, and a decrease in IBI length indicates heart rate speeding. Heart rate slowed following first-warning feedback relative to positive feedback for all age groups.

(Feedback: positive or first warning) × 4 (IBI) ANOVA. This analysis resulted in main effects of feedback, $F(1,66) = 28.16$, $p < .001$, and IBI, $F(3,198) = 10.90$, $p < .001$, and an interaction between feedback and IBI, $F(3,198) = 18.27$, $p < .001$. As Fig. 3 indicates, heart rate showed an acceleratory recovery initiated by the response, but this acceleratory recovery was significantly delayed when first-warning errors were presented. This visual impression was verified by post hoc ANOVAs revealing significant differences between heart rate responses to correct and first-warning feedback at IBI 0, $F(1,66) = 7.89$, $p < .005$, IBI 1, $F(1,66) = 32.14$, $p < .001$, and IBI 2, $F(1,66) = 42.89$, $p < .001$. Importantly, heart rate responses to first-warning errors did not differentiate among age groups, $F(6,198) = 0.82$, $p = .55$.

### *Perseverative and distraction errors*

The analyses of performance errors focused on heart rate responses around the *response*. Four IBIs were selected around the response and submitted to a 3 (Age Group) × 2 (Error/Correct) × 4 (IBI) ANOVA. The analysis on perseverative errors revealed a main effect of IBI, $F(3,189) = 10.03$, $p < .001$, and interactions between error/correct and IBI, $F(3,189) = 6.60$, $p < .001$, and among age group, error/correct, and IBI, $F(6,189) = 3.02$, $p < .05$. This last interaction is plotted in Fig. 4. Separate post hoc ANOVAs for each age group showed that for 16- to 18-year-olds, heart rate slowed following perseverative errors compared with correct responses, as indicated by a significant IBI × Error/Correct interaction, $F(3,63) = 5.51$, $p < .05$. Similarly, a significant IBI × Error/Correct interaction was observed for 12- to 14-year-olds, $F(3,63) = 4.40$, $p < .05$. In contrast, no IBI × Error/Correct interaction was observed for 8- to 10-year-olds, $F(3,63) = 0.30$, $p = .82$. The difference between heart rate responses to correct and perseverative responses was significant by IBI 2 for both older groups, $F(1,42) = 8.77$, $p < .001$.

The analysis of distraction errors revealed a main effect of IBI, $F(3,198) = 12.68$, $p < .001$, and interactions between age group and IBI, $F(6,198) = 2.36$, $p < .05$, between error/correct and IBI, $F(3,198) = 11.21$, $p < .001$, and among age group, error/correct,

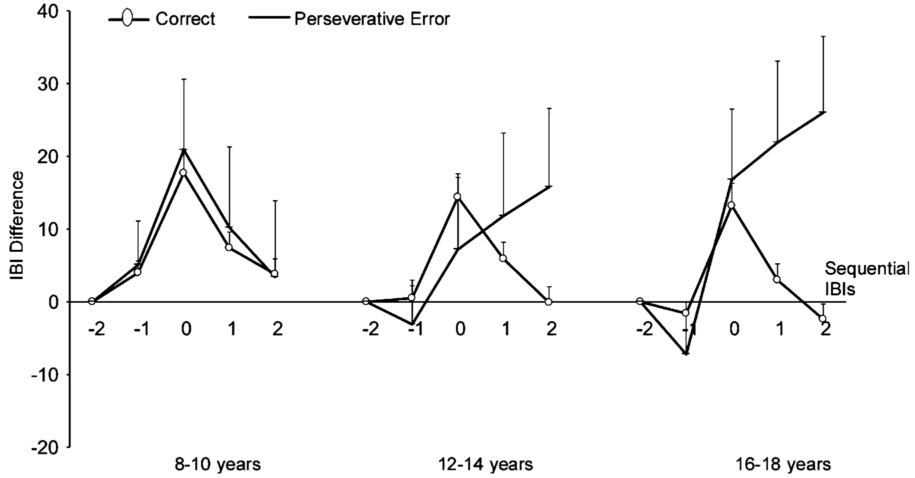

Fig. 4. Heart rate changes evoked by perseverative errors, relative to correct responses, for each age group. IBI 0 refers to the IBI concurrent with the response. An increase in IBI length indicates heart rate slowing, and a decrease in IBI length indicates heart rate speeding. Heart rate slowed following perseverative errors relative to correct responses for the two oldest age groups but not for 8- to 10-year-olds.

and IBI, $F(6,198) = 2.26$, $p < .05$. This last interaction is plotted in Fig. 5. Separate post hoc ANOVAs for each age group again revealed significant IBI × Error/Correct interactions for 16- to 18-year-olds, $F(3,69) = 6.10$, $p < .01$, and 12- to 14-year-olds, $F(3,66) = 9.11$, $p < .01$, revealing that heart rate slowed following distraction errors for these groups. The difference between correct responses and distraction errors was significant by IBI 2 for both older age groups, $F(1,45) = 15.76$, $p < .001$. Again, for 8- to 10-year-olds, there was no significant difference between heart rate responses to distraction

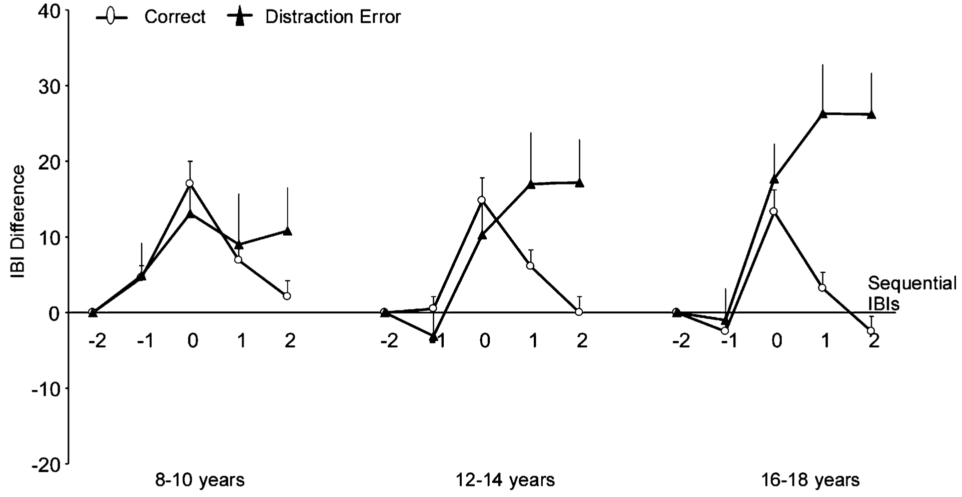

Fig. 5. Heart rate changes evoked by distraction errors for each age group. IBI 0 refers to the IBI concurrent with the response. An increase in IBI length indicates heart rate slowing, and a decrease in IBI length indicates heart rate speeding. Heart rate slowed following perseverative errors relative to correct responses for the two oldest age groups but not for 8- to 10-year-olds.

errors and correct responses, as indicated by a nonsignificant IBI × Error/Correct interaction, $F(3,63) = 0.94, p = .40$.

To examine whether 8- to 10-year-olds showed a heart rate response during later IBIs (because children have a faster heart rate, differences may occur later in the IBI window), we also analyzed heart rate changes for IBIs 3 to 5 so that we were now using approximately the same real-time window for each age group. None of these IBIs showed a significant difference for either perseverative errors or distraction errors ($p$s > .10). To examine whether 8- to 10-year-olds showed heart rate slowing following negative feedback that followed perseverative and distraction errors, we also submitted the IBI × Error/Correct data to an ANOVA with IBIs averaged around the *feedback*. This analysis did not result in significant effects for either perseverative errors or distraction errors (all $p$s > .10).

### Relation to performance

The relation between performance errors and heart rate slowing was examined for perseverative errors and distraction errors by correlating these measures with heart rate slowing across all age groups. For this purpose, we computed the response-locked difference in heart rate response to perseverative errors at IBI 2 and heart rate response to correct responses at IBI 2, referred to as the perseveration difference score. Second, we computed the response-locked difference in heart rate response to distraction errors at IBI 2 and the heart rate response to correct responses at IBI 2, referred to as the distraction difference score. IBI 2 was chosen because the largest age differences were observed at this interval. The analyses resulted in a nonsignificant correlation between perseverative errors and the perseveration difference score ($r = -.10, p = .36$) and a significant correlation between distraction errors and the distraction difference score ($r = -.44, p < .001$). A higher number of distraction errors was associated with less cardiac slowing. No such relation was seen for perseverative errors, but this could be due to the smaller range.

## Discussion

The behavioral results show that set-shifting performance becomes better between 8 to 10 years of age and 12 to 14 years of age, consistent with previous behavioral studies (Chelune & Baer, 1986; Crone, Jennings, et al., 2004; Crone, Ridderinkhof, et al., 2004; Diamond, Kirkham, & Amso, 2002; Muller et al., 2005; Welsh et al., 1991). Performance was indexed by the number of distraction and perseverative errors on the task. For both types of errors, there was a steep decrease between 8 to 10 years of age and 12 to 14 years of age, with a smaller difference between 12 to 14 years of age and 16 to 18 years of age (see also Crone, Ridderinkhof, et al., 2004). Thus, it is likely that the largest decrease in set shifting in this age range occurs during late childhood relative to adolescence and young adulthood. These results are consistent with those of developmental studies that argue that there is a slow development of executive functions (e.g., Cepeda et al., 2001; Huizinga et al., 2006). In the current study, we examined the extent to which these changes are associated with developmental differences in performance and feedback monitoring.

As expected, heart rate changes following feedback provided a sensitive index of how performance feedback was evaluated. Heart rate slowed following negative feedback, and this slowing was largest when the feedback was unexpected (see also Somsen et al., 2000).

The results were convincing in showing that there were no statistically significant age differences in heart rate responsiveness to first-warning feedback. In addition, a significant Age × Condition interaction was observed for the comparison first-warning feedback versus positive feedback, even in the youngest age group. First-warning feedback refers to the negative feedback that unexpectedly indicates that prior performance no longer is correct. Thus, the results suggest that even young children show heart rate slowing when feedback indicates unexpected or changing task demands. The results therefore do not support the hypothesis that young children perseverate because they fail to analyze the first-warning feedback in general.

In a previous behavioral developmental study (Crone, Ridderinkhof, et al., 2004), we found that when the new sorting rule is explicitly prompted (and therefore the need to process performance feedback decreases), perseveration decreases in all age groups but does so more in 8- to 10-year-olds than in the older age groups. We interpreted these results as suggesting that young children fail to analyze first-warning feedback. The current results do not support the strict version of this hypothesis because the heart rate results indicate that children do analyze the first-warning feedback, just like older children. However, it is possible that the first-warning feedback is evaluated similarly by 8- to 10-year-olds as by adolescents and adults but that 8- to 10-year-olds fail to apply this knowledge in a new situation. This interpretation was also offered for infants, who sometimes show a dissociation between knowledge of the task rules and application of the new task rule (Zelazo et al., 1996).

When examining the heart rate changes associated with making performance errors, 8- to 10-year-olds did not show heart rate slowing following performance errors (perseverative and distraction errors), whereas 12- to 14-year-olds and 16- to 18-year-olds showed a pronounced heart rate slowing following performance errors. In addition, the number of distraction errors was negatively correlated with the amount of heart rate slowing. This developmental pattern was the same for perseverative errors and distraction errors. This is surprising because these errors are presumed to reflect different processes; distraction errors are associated with rule maintenance, and perseverative errors are associated with rule switching (Barcelo & Knight, 2002). In a previous study, we found that perseverative errors were at an adult level earlier than were distraction errors. The common cardiac pattern seen for both types of errors suggests that this pattern is indicative of error monitoring in general rather than the specific processes tapped by these errors. The current findings suggest that the ability to detect an error develops between 8 to 10 years of age and 12 to 14 years of age (see also Davies et al., 2004; but see Hogan et al., 2005). The lapses in performance monitoring in the youngest age group may lead to failure to shift successfully (see also Deak et al., 2004; Kirkham et al., 2003).

Effortful processes associated with performance monitoring and subsequent performance adjustment are presumed to be dependent on the integrity of the PFC (e.g., Holroyd & Coles, 2002; Miller & Cohen, 2001). There are several important PFC structures that are involved in performance monitoring, including the anterior cingulate cortex (ACC) and the lateral PFC (Kerns et al., 2004). Source localization studies have suggested that error monitoring takes place in the ACC (Van Veen & Carter, 2002), and functional magnetic resonance imaging (fMRI) studies have suggested that the subsequent performance adjustment takes place in the lateral PFC (Kerns et al., 2004; see also Holroyd & Coles, 2002). Thus, it is likely that the development of these two brain regions contributes to the development of performance monitoring.

The current data suggest an age-related change in 8- to 10-year-olds in error monitoring, but not in the monitoring of feedback indicating that prior performance no longer is correct. Previous developmental studies have reported ERP results that are consistent with this interpretation. Davies and colleagues (2004) showed that in the same age range, the brain potential that is associated with making errors, the ERN, increases with age, especially between 7 to 10 years of age and 12 to 14 years of age. These researchers interpreted this effect as indicating that the ACC develops slowly. In the study reported by Davies and colleagues, further evidence was provided that 7- to 10-year-olds notice that an error is made, so they are not oblivious to their errors; for example, they slow down on the trial following an error, similar to adults.

Thus, the absence of the ERN and the heart rate slowing in the current study may indicate that the monitoring of the error, not the awareness of the error, develops slowly (see also Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). Other studies have suggested that error monitoring may still develop into adolescence (Hogan et al., 2005; LaDouceur, Dahl, & Carter, 2004), but we did not find evidence for this late development in the current study. Larger sample sizes are necessary to examine more specific interactions with age, gender, and pubertal stage (see also Davies et al., 2004).

Patients with damage to the PFC, especially the lateral PFC, seem to make perseverative and distraction errors similar to those observed in young children (Barcelo & Knight, 2002; Demakis, 2003). Moreover, as in young children, the performance of lateral PFC patients is also not attenuated by explicit rule change cues (Nelson, 1976; see also Stuss & Levine, 2002). This similarity between children and lateral PFC patients is consistent with the assumption that developmental changes in the ability to attain appropriate levels of task representation and associated changing task demands are associated with the maturation or fine-tuning of the PFC (Casey, 2002; Diamond, 2002). The increasing involvement of the lateral PFC when switching sets is supported by event-related neuroimaging studies, which show that frontal regions come into play as children mature (e.g., Bunge et al., 2002; Crone, Bunge, De Klerk, & Van der Molen, 2005; Klingberg, Forssberg, & Westerberg, 2002; Kwon, Reiss, & Menon, 2002; Schlaggar et al., 2002).

The contribution of the PFC to developmental change in set shifting could be tested directly using neuroimaging techniques, which can give more insight into the brain structures that young children use when performing a set-shifting task. Given the complexity of set-shifting tasks, different regions within the PFC may be associated with the development of different functions (for reviews, see Bush, Luu, & Posner, 2000; Casey, Giedd, & Thomas, 2000). For example, researchers have also emphasized the role of the ACC in autonomic control (Critchley et al., 2003) and in performance monitoring (Carter et al., 1998). Also, different brain structures may be important for perseverative errors and distraction errors (Barcelo & Knight, 2002). The current findings illustrate that psychophysiological methods can give us more insight into the covert components of developmental change in rule use and perseveration that cannot always be examined using behavioral indexes.

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