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Developmental Change in Feedback Processing as Reflected by Phasic Heart Rate Changes

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Heart rate was recorded from 3 age groups (8–10, 12, and 20–26 years) while they performed a probabilistic learning task. Stimuli had to be sorted by pressing a left versus right key, followed by positive or negative feedback. Adult heart rate slowed following negative feedback when stimuli were consistently mapped onto the left or right key (response-dependent condition) but not when responses to stimuli were always followed by negative feedback (uninformative condition). Young children's heart rate showed slowing following both response-dependent and uninformative negative feedback. These findings suggest that the ability to assess the relevance of performance feedback improves with age, resulting in improved adjustment to dynamical changes in the task environment.

Much of children's learning involves interpreting a wide range of input from the world that should be used to monitor and adjust performance for following actions. A variety of paradigms in the behavioral developmental literature have indicated that the ability to make successful use of performance feedback increases with age. For example, on tasks in which children and adults are asked to infer and change rules on the basis of feedback, children typically need more trials to learn the concept, and they use feedback less efficiently when sorting rules are changed (e.g., Dempster, 1993; Esposito, 1975; Kendler, 1995; Spiker & Cantor, 1979; Zelazo, Frye, & Rapus, 1996). Likewise, when children need to infer an optimal strategy for attaining future goals on the basis of reward and punishment, the efficiency of adopting an advantageous strategy also increases with age (Crone & Van der Molen, 2004).

Age differences in performance on rule-change tasks suggest that children might fail to use feedback outcomes for the purpose of adjusting future behavior (Chelune & Thompson, 1987; Luciana & Nelson, 1998; Zelazo et al., 1996). This is well illustrated by children's performance on, for example, the Wisconsin Card Sorting Task (WCST; Chelune & Baer, 1986). This task requires participants to match figures following a response rule that has to be determined on the basis of positive and negative feedback. The response rule sometimes changes without warning, and participants then have to use negative and positive feedback to find the new sorting rule. Thus, a critical aspect of this task involves the ability to monitor performance outcomes to reduce the likelihood of future negative outcome. Adults typically adopt this strategy fairly quickly. Young children, in contrast, perseverate, using the sorting rule that is no longer appropriate (Chelune & Thompson, 1987; Riccio et al., 1994; Welsh, Pennington, & Groisser, 1991).

A major obstacle hindering the interpretation of these developmental patterns is that tasks such as the WCST (and its variants) may involve many processes besides feedback processing. For example, some researchers have argued that changes on the WCST reflect increased ability to overcome interference from an incorrect but prepotent response tendency (Welsh, 2002; Welsh et al., 1991; Zelazo et al., 1996). The prominent interpretation of these research studies is that children process the feedback correctly but fail to inhibit inappropriate responses. Another reason for poor performance on the WCST is children's difficulty keeping the relevant sorting rule on-line, as indexed by large numbers of distraction errors (Crone, Ridderinkhof, Worm, Somsen, & Van der Molen, 2004; see also Luciana & Nelson, 1998). The latter interpretation suggests that children may fail to constantly monitor the outcome of their performance on the basis of previous trials. Thus, these behavioral studies have shown that developmental changes in successful feedback processing may be related to increased capacity to adjust performance for future actions, but given the complexity of the previously used tasks, there is no direct indication of how children process feedback.

Component processes of performance monitoring can be indexed more directly by psychophysiological measures obtained during the performance of complex tasks (Jennings & Van der

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Molen, 2002; Stuss, 1992). An important advantage of this approach is that psychophysiological measures can provide insight into processes that are not easily detected on the basis of overt behavior (Van der Molen & Molenaar, 1994). This approach has previously been successfully applied by Somsen, Van der Molen, Jennings, and Van Beek (2000) in both adolescents and adults by studying feedback processing using heart rate indices. It is well known that in preparation for a response, heart rate slows, which is followed by an acceleratory recovery when the response is initiated (Somsen, Van der Molen, Jennings, & Orlebeke, 1985). Somsen et al. (2000) demonstrated that this recovery is not influenced by positive feedback but is delayed by negative feedback. Moreover, heart rate slowing following negative feedback is typically larger for good performers than for poor performers. These findings led to the conclusion that heart rate slowing following negative feedback is associated with the extent to which the feedback is used to adjust subsequent performance. Interestingly, in a recent study we found that heart rate slowing is not related to negative feedback per se but is typically associated with the extent to which feedback needs to be evaluated to adjust subsequent performance (Crone et al., 2003; but see Van der Veen, Van der Molen, Crone, & Jennings, 2004). Accordingly, heart rate may be especially sensitive to monitoring feedback outcome for the purpose of adjusting future performance (Jennings & Van der Molen, 2002; Van der Molen, 2000).

In the present study, we made use of heart rate indices to study developmental changes in feedback processing by adopting a probabilistic learning task from the event related potential literature (Holroyd & Coles, 2002). Three primary hypotheses were tested. We expected that (a) negative feedback is more crucial in behavioral monitoring and performance adjustment than positive feedback, (b) heart rate slowing following negative feedback is associated with the extent to which feedback is used to adjust performance, and (c) children and adults differ in the ability to distinguish between informative and uninformative feedback. Therefore, children should show heart rate slowing to all types of negative feedback, informative or uninformative, whereas for adults heart rate continues to slow only following feedback that can be used to adjust performance.

Using a variant of Holroyd and Coles's (2002) probabilistic learning task, we asked participants from three age groups (8-year-olds, 12-year-olds, and 20–26-year-olds) to sort stimuli and evaluate feedback while their heart rate was continuously recorded. The participant's task was to sort stimuli using a left or right response button. The experimental conditions differed in the degree to which feedback provided information for subsequent performance.

In the first condition (referred to as the *response-dependent* condition), positive and negative feedback were dependent on the correctness of the response, thus requiring participants to evaluate the feedback and use it to improve subsequent performance. This condition matches traditional feedback-learning tasks (discrimination learning, WCST) most closely because participants need to infer the appropriate sorting rule on the basis of positive and negative feedback. Adults were expected to learn the stimulus–response (S-R) rule quickly and to show sustained heart rate slowing following feedback indicating that an error was committed (Crone et al., 2003). Children were expected to be less successful in using feedback to adjust subsequent performance (Dowsett & Livesey, 2000; Kendler, 1995; Luciana & Nelson, 1998; Zelazo et al., 1996), as indexed by slower acquisition of the S-R rule in the response-dependent condition. Consistent with this behavioral pattern, sustained heart rate slowing associated with incorrect responses in the response-dependent condition should be less pronounced for children compared with adults (see also Somsen et al., 2000).

In the second condition (referred to as the *uninformative-same* condition), responses to two stimuli were always followed by negative feedback for the first stimulus and positive feedback for the second stimulus, independent of the response that was executed. Given that the feedback was always uninformative, this condition did not require feedback evaluation. For adults, heart rate was expected to accelerate immediately following the response for both stimuli that resulted in always positive and stimuli that resulted in always negative feedback (Crone et al., 2003). If children are less successful in monitoring feedback outcomes for performance adjustment, they should differentiate less between informative and uninformative feedback and therefore show a similar heart rate response to feedback that is always negative (uninformative-same condition) and negative feedback that is response-dependent (response-dependent condition).

Finally, in the last condition (referred to as the *uninformative-random* condition), feedback was presented that changed randomly (50% positive and 50% negative). Previous performance results indicated that individuals change their performance strategy following negative feedback, suggesting that (although pointless) they use the feedback in an attempt to improve performance. In this condition heart rate was expected to show a deceleration associated with both positive and negative feedback, and the slowing should be larger when feedback was different from the feedback that was received on the previous encounter of that stimulus (Crone et al., 2003). Under the hypothesis that performance monitoring develops with advancing age, the age groups were expected to differ in their ability to adjust performance to changing feedback. At a behavioral level, children should make fewer performance adjustments in the uninformative-random condition than adults because they fail to adjust performance on the basis of feedback. Consequently, their heart rate responses were expected to show less sensitivity to feedback than adults' heart rate responses to feedback that had changed in comparison to the previous encounter of the same stimulus.

Method

Participants

Two groups of children and one group of young adults participated in the study. Participants were thirty 8–10-year-olds (M = 8.4, SD = 0.79; 15 boys, 15 girls), thirty 12-year-olds (M = 12.1, SD = 0.62; 19 boys, 11 girls), and twenty-two 20–26-year-olds (M = 23.3, SD = 3.80; 2 men, 20 women). The young adults were first-year psychology students and took part in the experiment for course credits. The children were recruited from local schools in the greater Amsterdam area. The children were selected with the help of their teacher and with consent of their parents. IQ measures were not obtained, but according to teacher report, all children performed in the average-to-above-average range. All participants were reported to be in good health. Despite the overall difference in gender distribution between age groups, the effect of gender failed to interact significantly with the effect of age in all analyses reported below. Therefore, effects of gender were not further investigated.

Participants of each age group were randomly assigned to one of two groups. The two groups performed either the response-dependent condition combined with the uninformative-same condition or the response-dependent condition combined with the uninformative-random condition. Sixteen young children, 14 older children, and 11 adults were assigned to the response-dependent and uninformative-same group. Fourteen young children, 16 older children, and 11 adults were assigned to the response-dependent and uninformative-random group. The random assignment of participants to the two different groups did not result in significant differences in gender distribution or age.

Stimuli

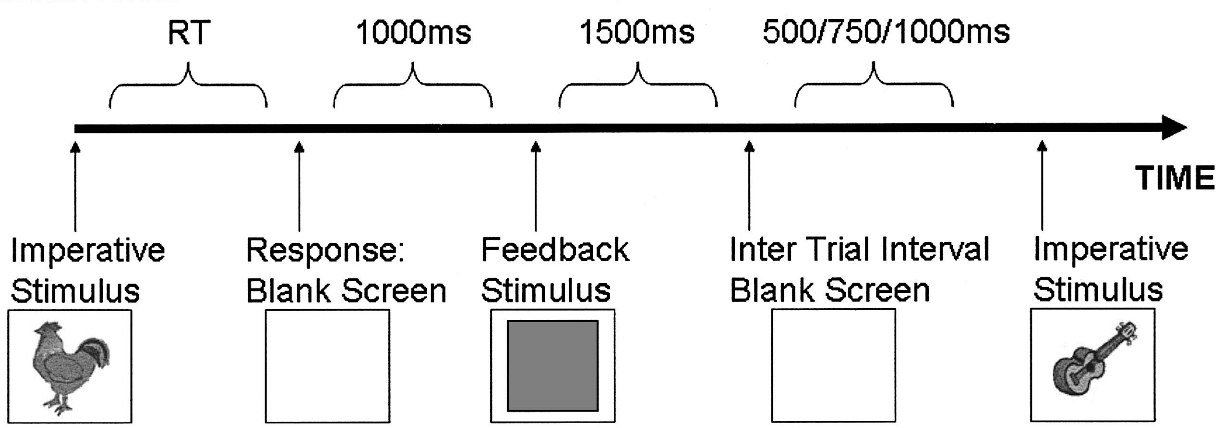
Stimuli were presented in color against a white background on a 17-in. (43.18 cm) computer screen placed at a distance of 75 cm from the participant. Each experimental block involved a new set of four imperative stimuli. Imperative stimuli included neutral pictures of animals, buildings, and similar objects and were scaled to a uniform size (see Figure 1 for examples). A pink or a blue square served as a positive or negative feedback signal, indicating that the participant was rewarded or penalized on that trial. The S-R mappings and feedback assignments were counterbalanced across participants and were fixed across the experiment. A black cross was presented whenever a response deadline was missed. Response deadlines were computed for each individual participant and were based on the mean response time observed in a 100-trial practice block plus 10%.

Experimental Task

A schematic of the trial structure is presented in Figure 1. On each trial, the imperative stimulus was response terminated. The response initiated a blank screen for 1,000 ms that was terminated by the feedback stimulus, which had a duration of 1,500 ms. The intertrial interval was 500, 750, or 1,000 ms (equiprobable). The interval between consecutive imperative stimuli was approximately 4 s. Participants were required to make a two-choice decision by pressing the "Z" or "/" button on a computer keyboard. To ensure that participants would make a sufficient number of mistakes in the response-dependent condition when they understood the S-R mapping, the participants were required to respond before an individually determined deadline. If they did not respond before the deadline, they received a penalty signal indicating that they had lost two points. Otherwise, the feedback stimulus indicated that the participant had gained (in the case of a correct response) or had lost (in the case of an incorrect response) one point on that trial. Trials on which the penalty signal was presented were not analyzed (5%–10% of the trials).

The task was divided into six blocks of 140 trials. For each block, four different new imperative stimuli were presented, each of which was presented 35 times in a pseudo-random order. The participant had to learn the S-R mappings anew for each block of trials. Participants were not informed about the S-R mappings but were told to infer the mappings by trial and error. They were instructed to respond as quickly and accurately as possible so as to maximize their number of points.

TRIAL STRUCTURE:



TASK CONDITIONS:

RD-US		RD-UR	
Stimuli	**Response dependent**	Stimuli	**Response dependent**
Picture A	Left=Negative FB Right=Positive FB	Picture A	Left=Negative FB Right=Positive FB
Picture B	Left = Positive FB Right = Negative FB	Picture B	Left = Positive FB Right = Negative FB
	Uninformative-same		**Uninformative-random**
Picture C	Left=Negative FB Right= Negative FB	Picture C	Left=50% Negative FB, 50% Positive FB Right=50% Negative FB, 50% positive FB
Picture D	Left= Positive FB Right=Positive FB	Picture D	Left=50% Negative FB, 50% Positive FB Right=50% Negative FB, 50% positive FB

Figure 1. Schematic diagram of the experimental trial structure and conditions. Half of the participants of each age group were assigned to the response-dependent and uninformative-same group (RD-US), and the other half were assigned to the response-dependent and uninformative-random group (RD-UR). Participants performed six task blocks in total, each presenting different pictures. The picture presentation was counterbalanced between participants and kept fixed during the experiment. Left = left response key; Right = right response key; FB = feedback.

A schematic of the different conditions is also presented in Figure 1. Within each block, each participant received two stimuli from the response-dependent condition. One of these stimuli was mapped to the left button so that the participant received positive feedback if the left key was pressed and negative feedback if the right key was pressed. The second stimulus was mapped to the right button so that the participant received positive feedback if the right key was pressed and negative feedback if the left key was pressed. For participants in the response-dependent and uninformative-random group, the two response-dependent stimuli were presented with two stimuli from the uninformative-random condition. For participants in the response-dependent and uninformative-same group, the two response-dependent stimuli were presented with two stimuli from the uninformative-same condition. In the uninformative-random condition, feedback was delivered at random to the participants, independently of whether the participant pressed the left or the right key. As a result, the participant received positive feedback on 50% of the trials and negative feedback on the other 50% of the trials (see Figure 1). In the uninformative-same condition, one of the stimuli was always followed by positive feedback (same positive feedback), and the second stimulus was always followed by negative feedback (same negative feedback; see Figure 1).

Before the experimental phase, participants received instructions and performed a practice block of 100 trials containing four stimuli according to the mappings of the group to which the participant was assigned. These stimuli were not used again in the experimental blocks. Participants began the task with a bonus of 25 points. At the end of each block, participants were provided with information indicating the total amount of points they earned throughout the task. There was no bonus money associated with the number of points earned.

Recordings and Data Reduction

During the task, the electrocardiogram (ECG) and respiration were continuously recorded. 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 (Amsterdam, the Netherlands) polygraph and sampled by a Keithley (Amsterdam, the Netherlands) 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. The respiration signal was used only to eliminate heart rate changes associated with large respiratory changes.

Results

Performance

Performance could improve only in the response-dependent condition, because in this condition feedback was dependent on the correctness of the response. Therefore, we asked whether accuracy discriminated between age groups as a function of trial block quintile (28 trials for each quintile, averaged across the six experimental blocks with four new stimuli each) for response-dependent trials. The 3 (age group) × 5 (quintile) repeated measures analysis of variance (ANOVA) yielded a main effect of age group, $F(2, 79) = 26.80$, $p < .01$, showing that younger children performed less accurately (64% correct) than older children (81% correct) and young adults (88% correct). There was also a main effect of quintile, showing that participants were more successful in applying the S-R mapping rule as the task progressed, $F(4, 304) = 21.15$, $p < .01$. Importantly, there was a significant Age Group × Quintile interaction, $F(8, 304) = 2.02$, $p < .05$, depicted in Figure 2—the effect just failed to reach significance when we performed repeated measures analysis using Huyn–Feldt correction, $F(8, 304) = 1.86$, $p = .08$. ANOVAs for each age group separately revealed that the quintile effect was significant for all age groups: young children, $F(4, 112) = 2.97$, $p < .05$; older children, $F(4, 112) = 8.19$, $p < .01$; young adults, $F(4, 80) = 20.98$, $p < .01$. Subsequent between-age-groups comparisons indicated that the Age Group × Quintile interaction was significant when young adults were compared with younger children ($p < .01$), but it was not significant when younger children were compared with older children ($p = .28$) or when older children were compared with young adults ($p = .42$).

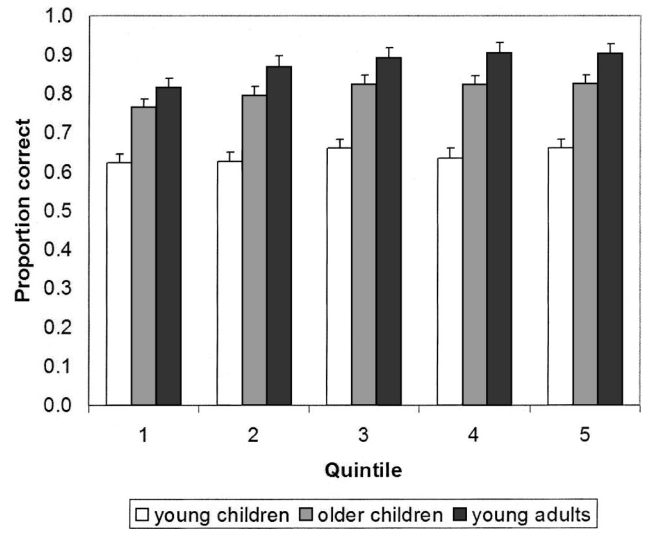


Figure 2. Proportion correct for the response-dependent condition as a function of task duration (in quintiles of 28 trials) for each age group. Vertical rules depict standard errors.

To further examine whether all age groups increased performance over the course of the task, we compared percentage correct for the first and the last quintile for each age group. These analyses showed a significant increase in task performance for the youngest age group (62% to 66%), $F(1, 29) = 4.82$, $p < .05$; for the older age groups (76% to 83%), $F(1, 29) = 17.55$, $p < .01$; and for the young adults (81% to 90%), $F(1, 21) = 38.09$, $p < .01$. Post hoc one-sample t tests for each group separately showed that all age groups performed above chance level in the first trial block quintile: younger children, $t(29) = 4.98$, $p < .01$; older children, $t(29) = 11.27$, $p < .01$; and young adults, $t(21) = 16.80$, $p < .01$. Together these results indicate that all age groups used feedback to improve their performance but that adults learned the S-R mapping faster than did younger children.[1]

Feedback was not systematically linked to responses for uninformative-random stimuli, but Crone et al. (2003) had found previously that participants still made use of the fake feedback in

[1] In this analysis and the following analyses there was no effect of group, indicating that there were no differences in performance or heart rate responses for participants who performed in the response-dependent and uninformative-same condition or the response-dependent and uninformative-random condition. Therefore, effects of group were not further investigated.

an attempt to improve performance. To examine age differences in the extent to which participants used the fake feedback, we examined whether participants changed their response to the stimulus on the next encounter with that stimulus more frequently after receiving negative relative to positive feedback. Our intention was to see whether the "stay" versus "switch" proportion would provide an index as to what extent participants continued to use the feedback. This was evaluated by examining responses on consecutive encounters with the same stimulus. For each participant, the stay–switch proportion was computed for positive and negative feedback separately (i.e., number of same responses / [number of same responses + number of switch responses]).

The analysis resulted in a main effect of feedback, $F(1, 37) = 56.09$, $p < .01$. As can be seen in Figure 3, negative feedback led participants to switch responses on the consecutive encounter with the same stimulus more often than did positive feedback. There was no main effect of age group, $F(1, 37) = 0.42$, $p = .66$, but there was an Age Group × Feedback interaction, $F(2, 37) = 5.62$, $p < .01$. Post hoc ANOVAs for each age group separately revealed that the difference between the proportion of response switches following positive and negative feedback was significant for all groups: $F(1, 12) = 6.18$, $p < .03$, for young children; $F(1, 15) = 35.35$, $p < .01$, for older children; and, $F(1, 10) = 18.92$, $p < .01$, for young adults. Separate comparisons for switches following positive and negative feedback revealed no differences between age groups in switch proportion following positive feedback, $F(2, 37) = 0.54$, $p = .59$, but there was an age-related increase in switch proportion following negative feedback, $F(2, 37) = 4.26$, $p < .05$. Post hoc Tukey comparisons revealed that young adults switched more following negative feedback than did young children ($p < .05$), whereas older children did not significantly differ from either younger children or young adults ($ps > .10$).

Heart Rate Associated With Positive and Negative Feedback

IBI values are highly serially dependent, and it is therefore important to be aware of immediately preceding and following heartbeats and events. The IBI concurrent to the start of feedback presentation (see Figure 1) is referred to as IBI 0. IBI −2 was used as a baseline, and therefore the value of IBI −2 was subtracted from the IBIs of interest. To indicate the temporal characteristics of IBI responses, five IBIs are presented in Figure 4 around the onset of the feedback (−2, −1, 0, 1, and 2) for each of the three conditions. Given that there was a 1,000-ms delay between the response and the feedback, IBI −1 value likely reflects continuing anticipatory deceleration preceding the feedback stimulus. Therefore, the (IBI −1) − (IBI −2) subtraction results in a value above zero.

This study was directed toward the detection of the feedback stimulus and the relation of its processing to task performance, and therefore we only focus on data points that commence at the beginning of feedback presentation. The IBIs of interest were the IBI concurrent to the onset of feedback presentation (IBI 0) and the first IBI following IBI 0 (IBI 1), because these IBIs have been found most sensitive to the direct effects of feedback presentation (Crone et al., 2003). IBIs were submitted to the ANOVAs as change scores relative to IBI −2.

A preliminary analysis of the raw scores at IBI −2 showed, not surprisingly, that IBIs were shorter for young children ($M = 654$ ms, $SD = 69.9$) and older children ($M = 678$ ms, $SD = 84.6$) than for young adults ($M = 776$ ms, $SD = 80.6$), $F(2, 75) = 16.25$, $p < .01$, but most important, there was no interaction with condition ($p = .42$) or feedback ($p = .25$). Moreover, additional analyses in which groups were separated by high and low mean IBI values using a median-split method did not modulate effects reported below.

The first set of analyses focused on differences between positive and negative feedback in the response-dependent condition, the uninformative-random condition, and the uninformative-same condition. A comparison between these conditions should reveal to what extent age groups processed the informative value of the feedback differently.

Response-dependent condition. The first analysis focused on IBIs in the response-dependent condition and examined whether cardiac slowing following the detection of negative feedback was larger for older individuals. Participants of the response-dependent and uninformative-random and response-dependent and uninformative-same groups were pooled because no differences between groups occurred in the following analyses. Therefore, 30 younger children, 30 older children, and 22 adults were included in the analysis. In Figure 5, it can be seen that in the response-dependent condition (top), heart rate decelerated prior to stimulus presentation and returned to baseline upon the execution of the response (1,000 ms before feedback). Importantly, acceleratory recovery was delayed when a negative feedback signal was detected. Two separate analyses were conducted for the response-dependent condition, one for IBI 0 and one for IBI 1. These analyses were based on prior findings indicating that cardiac slowing was largest for these IBIs (Crone et al., 2003; see also Somsen et al., 2000).

The 3 (age group) × 2 (feedback) repeated measures ANOVA for IBI 0 resulted in a main effect of feedback, $F(1, 76) = 39.24$, $p < .01$, and a significant Age Group × Feedback interaction, $F(2, 76) = 4.16$, $p < .02$. A Tukey post hoc comparison for difference scores between positive and negative feedback at IBI 0 showed that differences were larger for adults than for both older and younger children, whereas the younger and older children did not

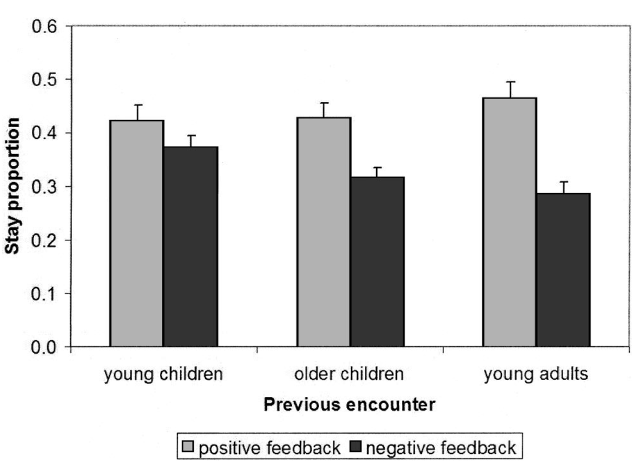


Figure 3. Proportion of response repetitions ("Stay proportion") following positive and negative feedback in the uninformative-random condition for each age group. Vertical rules depict standard errors.

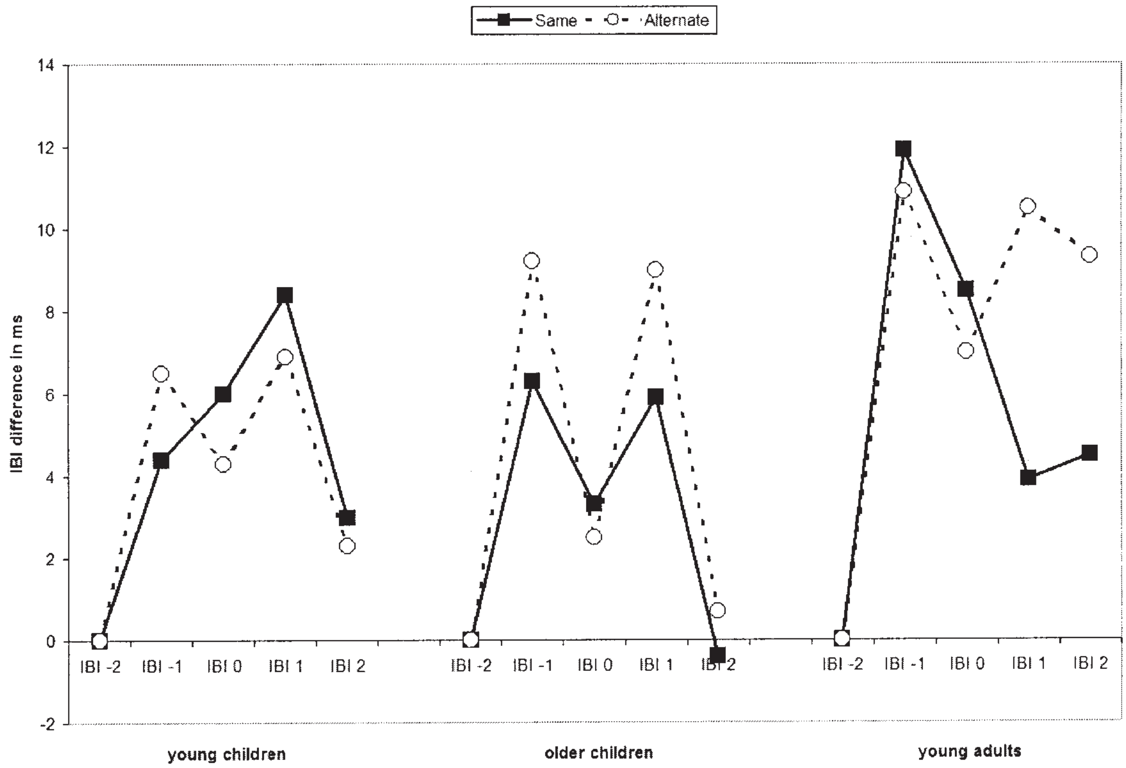


Figure 4. Sequential effects for cardiac responses in the uninformative-random condition. IBI = interbeat interval.

differ from each other. The difference scores were statistically significant from zero, even for the youngest age group. Separate analyses for negative and positive feedback responses at IBI 0 showed that the age group effect was significant for negative feedback, $F(2, 76) = 3.23$, $p < .05$, but not for positive feedback, $F(2, 76) = 1.45$, $p = .25$.

A similar 3 (age group) × 2 (feedback) repeated measures ANOVA for IBI 1 resulted in a main effect of feedback, $F(1, 76) = 30.08$, $p < .01$, showing that heart rate was slower following negative feedback than following positive feedback, but the interaction between feedback and age group was not significant, $F(2, 76) = 2.04$, $p = .14$.

Uninformative-random condition. In the uninformative-random condition, we analyzed IBI 0 and IBI 1 for participants who performed the task with response-dependent stimuli and uninformative-random stimuli. Thus, 14 younger children, 16 older children, and 11 adults were included in this analysis. The 3 (age group) × 2 (feedback) ANOVA for IBI 0 did not result in significant effects. The same analysis for IBI 1 yielded a main effect of feedback, showing that heart rate deceleration was larger for negative relative to positive feedback, $F(1, 38) = 4.02$, $p = .05$. There was no main effect of age group, but the Age Group × Feedback interaction almost reached significance, $F(2, 38) = 3.00$, $p = .06$, Huyn–Feldt correction = 1.00, indicating that the delay of acceleratory recovery associated with negative feedback was more pronounced in adults compared with children.

Uninformative-same condition. In the uninformative-same condition, we examined IBI 0 and IBI 1 for participants who performed the task with response-dependent stimuli and uninformative-random stimuli. Thus, 16 younger children, 14 older children, and 11 adults were included in this analysis. The 3 (age group) × 2 (feedback) ANOVA for IBI 0 did not result in significant effects. The same analysis for IBI 1 resulted in a main effect of feedback, $F(1, 38) = 12.76$, $p < .01$, and in an Age Group × Feedback interaction, $F(2, 38) = 3.86$, $p < .05$. Post hoc Tukey comparisons for difference scores between always positive and always negative feedback showed that the adults' heart rate slowed significantly less than young children's heart rate for negative feedback, whereas adults did not differ from older children, and older children did not differ significantly from younger children.

Sequential Effects

To examine sequential effects, the data in the uninformative-random condition were averaged according to four separate conditions and focused on the last feedback in the sequence: negative feedback trials preceded by negative feedback trials, negative feedback trials preceded by positive feedback trials, positive feedback trials preceded by positive feedback trials, and positive feedback trials preceded by negative feedback trials, based on the same stimuli and the same responses. (For example, the negative–positive sequence could mean that on the first occasion, a house stimulus was followed by a left-hand response and negative feedback. On the next occasion, the house stimulus was again followed by a left-hand response but this time resulted in positive feedback.

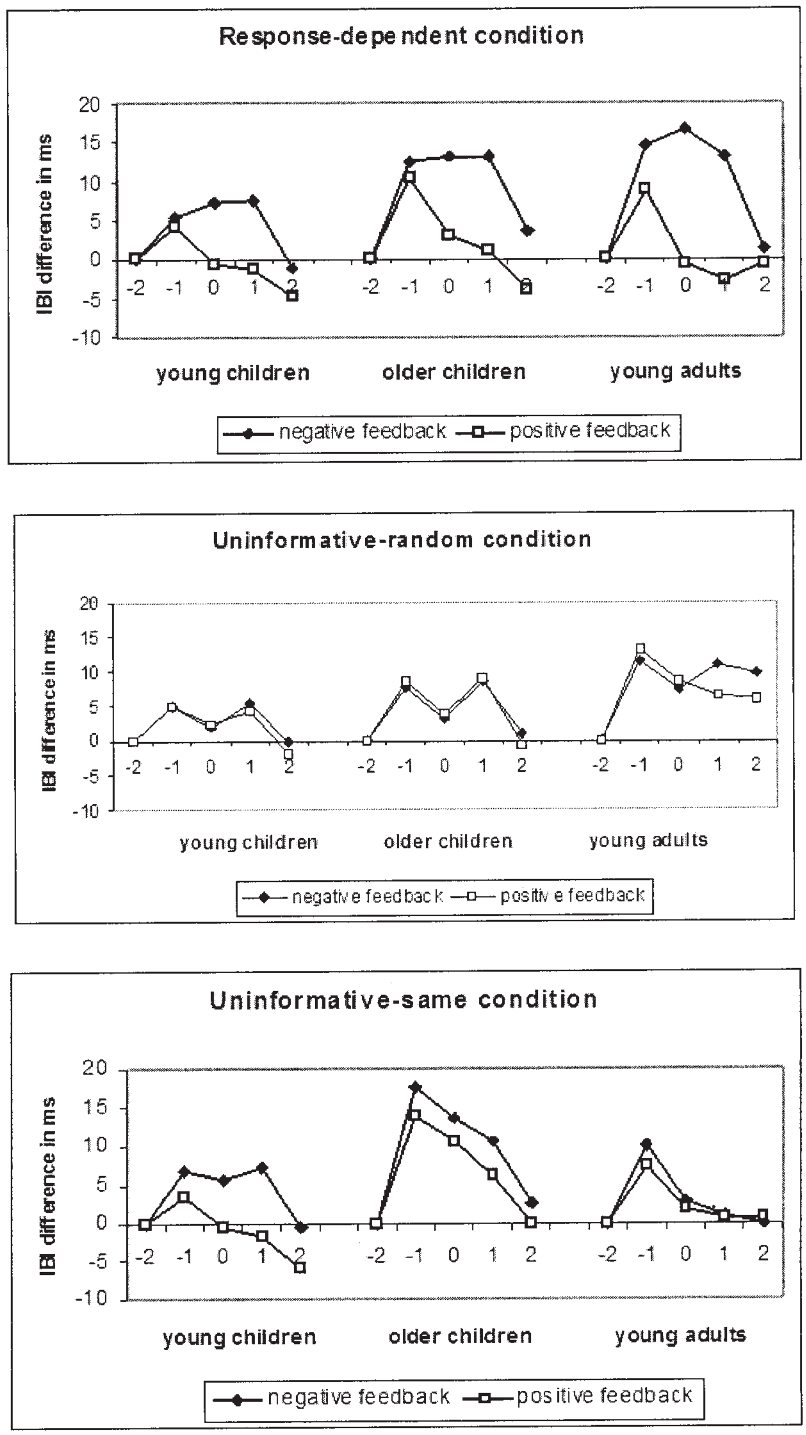


Figure 5. Cardiac responses associated with negative and positive feedback in the response-dependent condition, uninformative-random condition and uninformative-same condition for each age group. IBI = interbeat interval.

Thus, the stimulus and response were the same, but the feedback changed from negative to positive.) By focusing on the last feedback in the sequence, it is possible to separately examine the effect of valence of feedback (positive vs. negative) and changing of the feedback according to the previous trial (same feedback vs. alternate feedback). Note that consecutive encounters could be separated by trials associated with a different stimulus and/or response. Figure 4 shows the temporal pattern of IBI responses for IBI −2 to IBI 2. Given that effects only occurred at IBI 1 in the uninformative-random condition, the dependent variable was the subtraction value of IBI 1 relative to IBI −2.

The 3 (age group) × 2 (same/alternate) × 2 (feedback valence) repeated measures ANOVA for IBI 1 resulted in a significant effect of same/alternate, $F(1, 9) = 7.64$, $p < .05$. As can be seen in Figure 4, heart rate slowed for alternating feedback compared with same feedback. Separate comparisons for same and alternating feedback revealed that, when feedback was alternating, heart rate slowing was similar for the three age groups, as indexed by a non-significant age group effect, $F(6, 105) = 1.14$, $p = .34$. In contrast, when feedback was similar as on the previous encounter of the stimulus, heart rate slowing was less pronounced for adults than for children, $F(6, 105) = 2.86$, $p < .015$.

Relation With Performance

The next set of analyses aimed at examining the relation between heart rate slowing and actual performance. The analysis focused on the response-dependent condition, given that in this condition the participants could take advantage of the feedback provided to them to adjust subsequent performance. Using a median split procedure, participants were categorized into good performers and moderate performers on the basis of their percentage correct responses within each age group. A univariate ANOVA performed on the percentages of correct responses revealed that performance was significantly better for good performers (85%) than for moderate performers (68%), $F(1, 81) = 41.23$, $p < .01$. The 2 (performance level) × 2 (feedback) repeated measures ANOVA for IBI 0 resulted in a main effect of feedback, $F(1, 79) = 50.20$, $p < .01$. There was no main effect of performance level, but there was a significant Performance Level × Feedback interaction, $F(1, 79) = 8.76$, $p < .01$. Separate comparison for each performance group showed that heart rate slowed for negative feedback relative to positive feedback for moderate performers (7.9 ms vs. 1.4 ms), $F(1, 39) = 8.89$, $p < .01$, as well as for good performers (15.9 ms vs. 0.2 ms), $F(1, 40) = 48.49$, $p < .01$. Separate ANOVAs done for negative and positive feedback revealed that performance groups differed significantly in heart rate slowing for negative feedback, $F(1, 79) = 4.75$, $p < .05$; good performers had larger heart rate slowing than moderate performers. There was no difference in heart rate response between good and moderate performers for positive feedback, $F(1, 79) = 0.32$, $p = .57$.

A similar 2 (performance group) × 2 (feedback) ANOVA for IBI 1 resulted in a main effect of feedback, $F(1, 79) = 35.35$, $p < .01$. There was no main effect of performance level, but there was a significant Performance Level × Feedback interaction, $F(1, 79) = 6.76$, $p < .05$. Again, separate ANOVAs for positive and negative feedback yielded no difference between performance groups in heart rate response associated with positive feedback (0.1 ms for good performers and −1.9 ms for moderate performers), $F(1, 79) = 1.22$, $p = .27$. In contrast, for negative feedback heart rate slowing was larger for good performers (15.5 ms) than for moderate performers (6.9 ms), $F(1, 79) = 5.36$, $p < .05$.

To examine to what extent these differences were related to age group or performance level, the difference score between heart rate slowing associated with negative feedback and heart rate slowing associated with positive feedback was correlated with the percentage correct responses in the response-dependent condition twice. First, the bivariate correlation analysis for the difference score at IBI 0 resulted in a significant correlation between heart rate difference and percentage correct responses ($r = .40$, $p < .01$). Next, a partial correlation analysis, in which effects of age were partialed out, also resulted in a significant correlation ($r = .33$, $p < .01$). The scatter plot for each age group is presented in Figure 6. Finally, the correlations between percentage correct responses and heart rate difference at IBI 1 were not significant ($p > .10$).

Together, these results demonstrate that the amount of heart rate slowing following detection of an incorrect response and performance level are positively related. This effect seems to be independent of effects of age, given that the partial correlation controlling for age group remained significant. These effects were largest for IBI 0.

Discussion

This study examined developmental change in feedback processing using heart rate changes to augment behavioral measures of performance monitoring. This research was inspired by results from the literature on concept learning and WCST performance reporting that with advancing age, children perform more successful on feedback-learning tasks (Chelune & Thompson, 1987; Diamond, 2002; Zelazo et al., 1996). Consistent with initial reports using the WCST (Chelune & Baer, 1986), our behavioral results show that all participants used the information provided by the feedback for regulating their performance. Performance level, however, was lower in children, suggesting that children did not use feedback to improve their performance as effectively as adults (see also Kendler, 1995; Perner & Lang, 2002; Welsh et al., 1991; Zelazo et al., 1996).

Heart rate measures were used to deepen our understanding of the developmental change in performance monitoring. In previous experiments, we obtained evidence to suggest that heart rate is sensitive to a mismatch between intended actions and actual performance outcomes and between anticipated events and novel events (Crone et al., 2003; Somsen et al., 2000). This sensitivity is reflected in heart rate deceleration with negative and unexpected feedback, whereas heart rate accelerates for positive feedback. These findings led us to conclude that heart rate is sensitive to the activity of a performance monitoring system, which is invoked whenever the need arises for top-down activation of relevant processing structures (Jennings & Van der Molen, 2002; Somsen et al., 2000).

The current results revealed that, as in previous studies from our laboratory (Crone et al., 2003; Somsen et al., 2000), the detection of an incorrect response in the response-dependent condition was associated with heart rate slowing in adult participants. Most important, this slowing was less pronounced for young children, as predicted by the inefficient monitoring hypothesis. This result suggests that, although children may attempt to improve their performance on the basis of positive and negative feedback, the system that should indicate that previous performance was incorrect and requires adjustment may be less active or more variable. This interpretation is consistent with the finding that sustained heart rate slowing following negative feedback in the response-dependent condition correlated positively with performance level, independent of age.

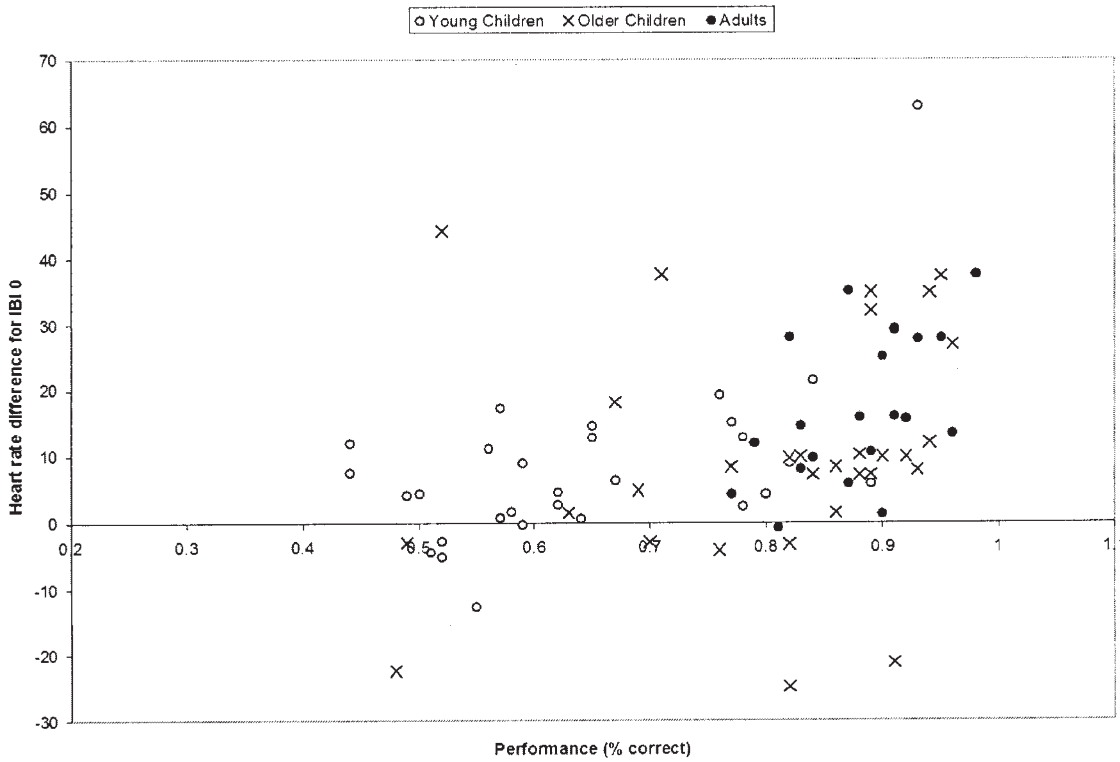


Figure 6. Scatter plot of heart rate difference at Interbeat Interval 0 (IBI 0) between negative feedback and positive feedback conditions and proportion of correct responses. Age groups are plotted separately.

The uninformative feedback conditions provide further insights into children's processing of performance feedback. In the uninformative-same condition, two stimuli were followed by the same feedback (always positive or always negative) irrespective of the response given to the stimulus. In this condition, the heart rate of adult participants did not differentiate between positive and negative feedback indicating that they soon found out that the feedback associated with these two stimuli was irrelevant. In contrast, children's heart rate was slower for negative feedback relative to positive feedback, indicating that they continued to extract meaning from the fake feedback. This finding indicates that children are actively seeking the information needed to improve their performance. Unlike adults, however, they are less efficient at differentiating between valuable and fake information that is provided to them. Alternatively, children's heart rate slowing associated with negative feedback may suggest that they respond to the valence of the feedback rather than the fake information provided by the feedback (for a similar finding in adults, see Van der Veen et al., 2004). This latter interpretation can be ruled out by the findings that emerged from the uninformative-random condition, in which two of the stimuli were followed by random positive or negative feedback. In this condition, children's heart rate did not differentiate between positive and negative feedback, suggesting that the valence of the feedback does not contribute to the heart rate pattern associated with feedback.

In the uninformative-random condition, children's heart rate tended to slow to both positive and negative (fake) feedback. In adults, heart rate showed a somewhat more pronounced slowing associated with negative feedback relative to positive feedback. These data were submitted to a sequential analysis comparing the cardiac response pattern associated with four different sequences, that is, sequences with the same, positive feedback; sequences with the same, negative feedback; sequences with alternating, positive feedback; and sequences with alternating, negative feedback. The adult results of this analysis were consistent with Crone et al.'s (2003) previous findings in showing that alternating feedback was associated with heart rate slowing whereas feedback did not seem to affect the cardiac response when it was the same as the feedback provided at the previous encounter of the stimulus. This adult pattern of findings is consistent with the suggestion that heart rate is sensitive to violation of the task representation derived from previous performance (Somsen et al., 2000). Unlike adults, children's heart rate slowed to both alternating feedback and feedback that was the same on a previous encounter of the stimulus. Children's heart rate slowing is consistent with the hypothesis that they are actively monitoring the feedback but the indiscriminate slowing to both alternating and repeating feedback suggests that their use of this (fake) information for hypothesis testing is immature (Esposito, 1975; Kendler, 1995; Spiker & Cantor, 1979).

Consistent with previous work (Crone et al., 2003), we found that heightened deceleration may occur very early; presumably following early recognition that negative feedback is coming. A comparison across conditions showed that heart rate slowing in the response-dependent condition occurred earlier (starting at IBI 0) than heart rate slowing in the uninformative-random condition (starting at IBI 1). Following the learning of the S-R mapping, participants do not have to await the feedback stimulus to know that they were wrong (see also Holroyd & Coles, 2002). For the response-dependent condition, this may suggest that heart rate slowing was already initiated following an incorrect response, suggesting that not only feedback monitoring but also error monitoring is sensitive to age-related change (see also Davies, Segalowitz, & Gavin, 2004). In contrast, for the uninformative-random condition, feedback cannot be predicted until actually presented, resulting in heart rate slowing at IBI 1. In the uninformative-same condition, young children's heart rate slowing following negative feedback also occurred later (starting at IBI 1) than did heart rate slowing in the response-dependent condition (starting at IBI 0). This is interesting because in this condition, the stimulus may already be predictive of positive and negative feedback. The fact that adults showed no heart rate slowing following negative feedback in the uninformative-same condition whereas children did suggests that children, contrary to adults, may not have realized that one of the stimuli consistently resulted in negative feedback.

An important advantage of the use of psychophysiological measures is that it allows for a more detailed examination of what seems to be overall differences in performance level between age groups. Behavioral data in this study, as well as in previous studies, show that in response-dependent conditions, children do not learn as readily from performance feedback as adults. This deficit of learning from performance feedback occurs in the context of overall lower performance patterns. An important question is whether this performance deficit is specific to the domain of feedback processing or is indicative of a more general age difference in performance (see Chapman, Chapman, Curran, & Miller, 1994, for a similar discussion). The heart rate data are convincing in supporting the hypothesis of a specific feedback-processing deficit in young children for two reasons. First, if children would be less responsive to the task manipulations in general, then we would expect that their heart rate is equally responsive to all types of feedback. In contrast, we observed that children are less responsive to error and feedback in the response-dependent condition but more responsive to uninformative feedback. This pattern supports the hypothesis that children fail to assess whether the feedback is relevant for future performance adjustment. Second, partial correlations showed that in the response-dependent condition, heart rate responses are sensitive to performance adjustments also within age groups. These results indicate that heart rate differentiation following positive and negative feedback is not specifically related to age. The current results show that heart rate responsiveness depends specifically on the extent to which individuals use performance feedback for the purpose of future performance adjustments.

In conclusion, our psychophysiological approach has helped us to resolve a major hindrance in the interpretation of findings from developmental studies of feedback processing in which only behavioral measures were used. The WCST, for example, is a classic test to examine adaptive behavior when feedback indicates that performance should be adjusted. However, the complexity of the task makes the interpretation of performance outcomes sometimes difficult. Using heart rate indices measured around the time that feedback monitoring should take place, we found evidence that children do monitor feedback outcomes but do so less selectively than adults, which could account for poor adjustments of behavior. This approach may help resolve why children perform poorly on rule and reversal learning paradigms, and may also account for individual differences in performance between children.

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