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Preschoolers' use of feedback for flexible behavior: Insights from a computational model

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ABSTRACT

This study addressed preschoolers' cognitive flexibility in an inductive task requiring response feedback processing to infer relevant task goals. A total of 63 4- to 6-year-olds were tested on a perceptual matching task in which they needed to switch attention among three colors. A computational model was designed to track down how responses to positive and negative feedback changed as children progressed through the task. The results showed that children's differential response to positive and negative feedback developed with age. In addition, age differences in feedback responding increased as the task unfolded. These findings are interpreted as reflecting an increase in flexibility with age in terms of growing efficiency in feedback processing.

Introduction

Executive control encompasses a variety of processes that underlie goal-directed behaviors and plays a key role in cognitive acquisitions occurring in various domains such as theory of mind (e.g., Carlson & Moses, 2001), problem solving (e.g., Senn, Espy, & Kaufmann, 2004), language (e.g., Deák, 2000), arithmetical skills (e.g., Bull & Scerif, 2001), and reading (e.g., van der Sluis, de Jong, & van der Leij, 2007). Cognitive flexibility is one of the most widely acknowledged contributors to executive control (e.g., Diamond, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000; St. Clair-Thompson & Gathercole, 2006). It involves the ability to adaptively select, among multiple representations for an object, multiple strategies, or multiple task sets, the one that best fits the features of a given situation as well as the ability to switch among them as a function of relevant environmental

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changes (e.g., Chevalier & Blaye, 2006; Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Jacques & Zelazo, 2005). Recent research suggests that cognitive flexibility requires (a) determining the goal to be reached and, accordingly, (b) selecting—maintaining or switching—relevant processing modes and stimulus representations (e.g., Gruber & Goschke, 2004; Miyake, Emerson, Padilla, & Ahn, 2004).

Cognitive flexibility dramatically improves during the preschool period (e.g., Deák, 2000; Espy, 1997; Jacques & Zelazo, 2001; Smidts, Jacobs, & Anderson, 2004; Zelazo, Müller, Frye, & Marcovitch, 2003). For instance, performance drastically improves over this period on the Dimensional Change Card Sort (DCCS) (Zelazo, 2006), in which children must switch between sorting bidimensional objects (e.g., red rabbit, blue boat) by shape or color. On this task, most 4- and 5-year-olds successfully switch sorting dimensions, whereas most 3-year-olds perseverate on the initial sorting dimension even after being explicitly instructed to switch to the other dimension. This improvement has mainly been assumed to reflect the development of switching per se (e.g., Espy & Bull, 2005; Kirkham, Cruess, & Diamond, 2003; Rennie, Bull, & Diamond, 2004), although it may also reflect increasing efficiency in setting and maintaining relevant task goals. Consistent with the latter hypothesis, success is achieved earlier on deductive tasks of flexibility in which children are explicitly told which task goal is relevant (e.g., Chevalier & Blaye, 2008; Zelazo et al., 2003) than on inductive tasks in which they need to determine it from instructional cues (e.g., Deák, 2000; Jacques & Zelazo, 2001). Moreover, recent findings showed enhanced performance in switching tasks when goal-setting demands were alleviated using transparent cues rather than the usual arbitrary cues (Chevalier & Blaye, in press). In many everyday life situations, there are no cues indicating that the goal has changed and the initial behavior is no longer relevant. Instead, goal changes must often be inferred from behavioral outcomes and external evaluations that serve as feedback. In such cases, cognitive flexibility may greatly depend on how efficiently response feedback is processed (e.g., Zanolie, Van Leijenhorst, Rombouts, & Crone, 2008). The current study addressed preschoolers' cognitive flexibility when task goals must be set on the basis of response feedback.

Early work on discrimination learning has suggested that feedback processing improves during childhood (e.g., Bell & Livesey, 1985; Esposito, 1975), and recent findings suggest that some kind of feedback processing is successfully achieved at 3 years of age in the DCCS, which requires switching on the basis of explicit verbal instructions (Bohlmann & Fenson, 2005). However, little is known about preschoolers' flexibility in situations that require using feedback to both infer the relevant task goal and adjust responses accordingly. The Wisconsin Card Sorting Test (WCST) (Grant & Berg, 1948) is undoubtedly the most emblematic of such situations. It requires sorting cards according to color, shape, or number on the basis of response feedback. After a series of successful trials, a switch in sorting dimension occurs and children must use feedback to discover and maintain the new sorting dimension until the next switch. The WCST is generally not administered before 6 or 7 years of age (e.g., Huizinga & van der Molen, 2007; Smith-Seemiller, Arffa, & Franzen, 2001; Somsen, 2007), and the most recent manual for the WCST does not provide normative data for children younger than 6½ years of age (Heaton, Chelune, Talley, Kay, & Curtiss, 1993). Studies conducted on older children found performance improvement until adolescence (e.g., Chelune & Baer, 1986; Somsen, 2007). Moreover, school-age children have been shown not to process feedback as efficiently as adults do on a probabilistic learning task (Crone, Jennings, & van der Molen, 2004). In the light of these findings, one may suspect that preschoolers may have difficulty in behaving flexibly on the basis of feedback processing. Actually, the very few studies that used the WCST with preschoolers showed performance improvement between 4 and 6 years of age (e.g., Cianchetti, Corona, Foscoliano, Contu, & Sannio-Fancello, 2007; Welsh, Pennington, & Groisser, 1991), suggesting that flexible behavior involving feedback processing increases over this age range. More specifically, using a modified version of the test (MCST or MWCST) with more appropriate features for young children (e.g., reduced number of trials), Cianchetti and colleagues (2007) observed, between 4 and 7 years of age, an improvement in the number of categories achieved (i.e., runs of correct responses) as well as a steep drop in perseverative errors (which decreased more slowly later on), whereas "failures to maintain set" decreased linearly during childhood.

As illustrated by Cianchetti and colleagues' (2007) study, performance in the WCST has traditionally been indexed in terms of numbers of categories achieved, perseverative errors, and failures to maintain set. However, criteria used to define errors, especially perseverative ones, have largely varied (e.g., Barceló & Knight, 2002; Milner, 1963; Nelson, 1976; see Cianchetti et al., 2007, for a comparison of four different criteria for perseverative errors). Similarly, the difficulty of consistently maintaining a sorting dimension has generally been indexed by failures to maintain set errors, but it can also be measured in terms of distraction errors (i.e., errors based on a dimension different from the one used in the previous trial) (Barceló & Knight, 2002). Errors are sometimes defined regarding the response given on the immediately preceding trial (e.g., Barceló & Knight, 2002) and sometimes as a function of the previously relevant dimension (e.g., Milner, 1963). Such diverging criteria for errors classification result from a priori theoretical assumptions and hamper comparisons among studies. Most important, the computation mode of such traditional indexes fails to capture any performance change as children progress through the task.

We designed an inductive flexibility task adapted for preschoolers to investigate the dynamic change in performance throughout the task. In the inductive version of the Preschool Attentional Switching Task (PAST) (Chevalier & Blaye, 2008), three objects with different shapes and colors (e.g., a blue cat, a yellow flower, and a green car) were displayed on each test card, and children needed to indicate the shape of the object in the relevant color. As in the WCST, the relevant color needed to be maintained across a series of trials (i.e., a phase), and changes in relevant colors needed to be inferred on the basis of response feedback. The PAST is more appropriate for use with preschoolers than the standard WCST because (a) the number of test trials is limited to 30, (b) there is no ambiguous feedback, and (c) switches are intradimensional rather than extradimensional. In addition to the type of switching (intra- vs. extradimensional), the PAST also differs from the DCCS in two main ways. First, the switch in dimensions and the newly relevant rules are explicitly announced and repeated on the DCCS, whereas the version of the PAST being used here requires inferring the relevant color on the basis of response feedback, which is more demanding in terms of goal setting and maintenance. Second, the DCCS involves only one switch, whereas the inductive PAST allows up to four switches. This difference is important because it has been argued that switching back and forth requires more efficient executive control than switching just once (Davidson, Amso, Cruess, Anderson, & Diamond, 2006), suggesting that executive demands may increase as a function of the number of past switches. Thus, the PAST allows investigation of performance changes from phase to phase.

Performance may change throughout the PAST because of increasing demands on executive control. More specifically, relying on the dissociation between distractor interference (i.e., irrelevant information competing for entering working memory) and proactive interference (i.e., previously relevant but now irrelevant information needing to be suppressed from working memory) (Friedman & Miyake, 2004), it may be argued that consistent maintenance of the initial sorting color (Phase 1) in the PAST involves only resistance to distractor interference. Switching to and then maintaining a second color (Phase 2) also necessitates inhibitory control so as to resist the proactive interference from the previously reinforced criterion. Finally, subsequent switches (Phase 3 and upward) may be even more demanding when they involve reactivating (i.e., switching back to) previously *actively* inhibited colors (e.g., Mayr & Keele, 2000). Therefore, an increase in executive demands throughout the task may result in performance decline.

Alternatively, children's performance may change throughout the task because of changes in feedback processing partly independent of executive demands (see also Crone et al., 2004). Throughout the task, children may learn to extract an increasing amount of information from the feedback. More specifically, while completing the very first categories, children experience that a positively reinforced color remains relevant for a series of trials and reciprocally irrelevant colors must be ignored during the same time. Later in the task, children may infer from negative feedback that the related color will remain irrelevant for several trials and, therefore, must be strongly inhibited, which would make perseveration less likely. Conversely, they may infer from positive feedback that the relevant color will remain so for a series of trials and should be strongly activated. Such feedback-based modulation of inhibition/activation and anticipation of future color switches would result in performance improvement throughout the task.

The current study aimed at (a) testing preschoolers' performance in a new measure of cognitive flexibility (the inductive PAST), (b) assessing flexibility development in this age range when flexible behavior relies on feedback processing, and (c) investigating children's feedback processing. More specifically, we used a computational modeling method (Dauvier & Juhel, 2006) to capture children's differential responses to positive and negative feedback as well as feedback processing development with age and change throughout the task. The computational model assumed that response selection among the three possible colors was probabilistically achieved according to the activation level of each color. The activation level of each color changed as children progressed through the task as a function of received feedback. Separate parameters quantified the increase in activation level after positive feedback and quantified the decrease in activation level after negative feedback. A feedback sensitivity parameter and its change with age were estimated for each color during each phase. The model is further described in the next section.

Method

Participants

A total of 63 4- to 6-year-olds (mean age = 60.2 months, *SD* = 7.5, range = 48–71, 32 girls and 31 boys) participated in this study. They were recruited from a preschool located in a small town in the south of France. Most participants were Caucasian and came from middle-class backgrounds, although race and socioeconomic status data were not collected. Parental consent was received for all of them. Children were tested individually in a quiet room in their preschool.

Materials

A card displaying four patches of color (green, blue, yellow, and red) and a card displaying four noncolored shapes (cat, flower, car, and rabbit) were used to ensure that children could discriminate the colors and shapes used in the PAST (Chevalier & Blaye, 2008). Materials for the PAST encompass three response cards (6 × 6 cm), a set of 33 test cards (21 × 15 cm), and a puppet. Each response card showed a black-and-white drawing of a flower, a black-and-white drawing of a cat, or a black-and-white drawing of a car. Each test card displayed three vertically arranged bidimensional objects. Objects had different colors and shapes (e.g., a blue cat, a green car, and a yellow flower), so that each object on the test card could match only one response card and vice versa. Color–shape and top–bottom arrangements were counterbalanced across test cards.

Procedure

Children sat beside the experimenter at a table. They interacted in French. The instructions reported here have been translated into English. To ensure that children could discriminate the colors and shapes that would be used during the rest of the test session, the experimenter put the card displaying patches of colors/shapes in front of children and successively asked them to point at each color/shape (e.g., "Show me the blue one," "Now show me the green one"). All children successfully recognized the four shapes and colors.

Children then proceeded to the PAST. In this inductive version, children were told that they would play a card game with a puppet. The three response cards were put in front of children, and one test card was put farther away on the table. The PAST was introduced as follows:

> In this game, you must put one of these small cards [response cards] here [beside the test card]. If you play the Blue Game, you must choose the small card that is like the blue picture here [test card]. Look, here the blue picture is a car, so you must move the car here. If you play the Green Game, you must choose the small card that is like the green picture here [test card]. Here the green picture is a flower, so you must move the flower here. If you play the Yellow Game, you must choose the small card that is like the yellow picture here [test card]. Here the yellow picture is a cat, so you must move the cat here. You'll have to find which color the puppet wants to play. The puppet may want to play the Blue Game, the Green Game, or the Yellow Game. To find the color it wants to play, you must pay close attention to what it says. When you play the right color,

> it will say, “Yeah, this is the right color!” [the experimenter makes the puppet hop on the table]. It means you have found the right color and you must go on playing that color. When you play a wrong color, it will say, “Boo, this is not the right color!” [the experimenter bows the puppet down]. It means the puppet wants to play another color. You must guess which color it wants to play and then keep on playing that color. But the puppet will sometimes want to change the color of the game. You’ll have to find the new color the puppet wants to play and go on playing that new color until it wants to change again.

The instructions were repeated if necessary. Then three demonstration trials were jointly completed by children and the experimenter. On the first demonstration trial, a test card was put on the table and the experimenter asked children to guess the color the puppet wanted to play. If children did not answer, the experimenter proposed one color and selected the corresponding response card. The feedback on the first demonstration trial was always negative. The experimenter further explained that such feedback meant that the selected color was not the relevant one and another one should be selected on the next trial. On the second demonstration trial, another color was tried and positive feedback was given. The experimenter emphasized that it meant the relevant color had been found and needed to be played again on the third demonstration trial.

After completion of the three demonstration trials, the test phase started. On each test trial, a test card was put on the table above the previous test card that was no longer visible. Children were asked to respond by selecting one of the three response cards. Then feedback was given by the puppet (positive feedback: “Yeah, this is the right color! Go on playing that color”; negative feedback: “Boo, this is not the right color! It’s another color”) while the response card was still selected. There were 30 test trials. The relevant color was changed after a series of five consecutive correct responses. Switches in colors were not explicitly announced, but the first error after a switch received special negative feedback (“Boo, now I want to change the color!”).

A new phase started each time a change in relevant color occurred (after five consecutive correct responses). There could be up to five different phases. Color order was counterbalanced across participants. The relevant color during Phase 1 was coded c1. The other two colors were coded c2 and c3. The relevant color during Phase 2 was coded c2. Then c1 was relevant again during Phase 3. c3 became relevant during Phase 4. Finally, c2 was relevant again during Phase 5.

Children’s performance scoring

Children’s performance was first scored as a function of the following indexes:

(a) *Phases achieved* (*maximum* = *5*). This corresponds to the number of times participants consistently sorted according to the relevant color on five consecutive trials.
(b) *Percentage of successful trials per phase.* Participants could not detect the change in relevant color before receiving their first negative feedback. Therefore, on the very first trial of a phase, responses based on the previously relevant color were considered as correct, and other responses were considered as incorrect.

Computational model

The current model rests on the following assumptions. First, feedback processing differs as a function of feedback valence. Second, because previous studies using deductive tasks showed that the previous status of sorting criteria influences children’s performance (e.g., Zelazo et al., 2003), feedback processing is here assumed to differ according to color status (relevant or irrelevant) during the previous phase. Third, feedback processing changes from phase to phase but remains the same within a given phase. This assumption, which is consistent with the traditional method of phase analysis in this research field, may be seen as an oversimplification because a learning phenomenon could appear within a phase and, hence, modify the sensitivity to feedback. However, allowing within-phase changes in feedback processing would at least double the number of parameters and, thus, lead to intractable computations given the methodology used in this article. Fourth, the only form of individual differences considered in the current model is children's age. This means that the model attempts to catch the psychological processes at the group level given a specific age.

The model is based on a set of psychologically sensible parameters grounded on a limited set of theoretical assumptions (these are further discussed in the Discussion section). These assumptions are rather simple and psychologically plausible. Therefore, in contrast to traditional analyses based on theoretically equivocal error types, analyses based on the current computational model should lead to parameter values that can be readily interpreted in terms of psychological processes with limited risks of erroneous interpretations of the nature of those processes.

According to the model, the probability of a response is determined by its level of activation (a_{ict}):

$$a_{ict} = a_{ict-1} + \beta_{1cp}(PFBc) + \beta_{2cp}(NFBc). \tag{1}$$

The activation level of a color c ($c = 1, \ldots, C$) for a child i ($i = 1, \ldots, N$) when responding to the trial t ($t = 1, \ldots, T$) is equal to the activation level of this color before the last feedback (a_{ict-1}) if this feedback concerned another color. It is equal to the previous activation level plus a quantity β_{1cp} if color c has been positively reinforced by the last feedback. This parameter can then be interpreted as a sensitivity parameter to positive feedback. Finally, the activation level is equal to the previous activation level plus a quantity β_{2cp}, which should be negative, if that color has just been negatively reinforced. *PFBc* and *NFBc* are indicator variables for positive and negative feedback, respectively. The value of *PFBc* or *NFBc* is 1 if the last feedback was positive or negative, respectively, and reinforced color c, and it is 0 otherwise. To study the change in feedback processing as the task unfolded, distinct parameters were estimated for each Phase p ($p = 1, \ldots, P$).

The model contains $P \times C$ parameters coding for the sensitivity to positive and negative feedback. Each parameter is split into two parts: an intercept $\gamma_{\bullet 0}$ and a coefficient corresponding to effect of age $\gamma_{\bullet 1}$:

$$\beta_{1cp} = \gamma_{10cp} + \gamma_{11cp}(AGE) \tag{2}$$

$$\beta_{2cp} = \gamma_{20cp} + \gamma_{21cp}(AGE). \tag{3}$$

The parameter γ_{20cp} represents the group mean variation of the activation of color c after negative feedback concerning this color. The parameter γ_{21cp} represents the effect of age on the sensitivity to negative feedback for color c during Phase p. A negative value of this parameter means that the activation level of color c decreases more after negative feedback for older children than for younger children. To facilitate the interpretation of parameters, *AGE* has been standardized.

The probability that the observed response (x_{it}) of child i to trial t is a particular color c depends on the level of activation of this color comparatively with the activation levels of other colors. A logistic transformation ensures that the value is positive and ranges between 0 and 1 and that the sum of the three probabilities (corresponding to the three colors) is 1. This model can be considered as a special case of multinomial logistic regression (Nerlove & Press, 1973) with fixed effects. To ensure identifiability of the model, activation values at $t = 1$ (a_{ic1}) are set to 1. This constraint is different from that generally used in multinomial logistic regression and simply means that, prior to the first feedback, activations of the three colors are equal:

$$p(x_{it} = c) = \frac{\exp(a_{ict})}{\sum_{c=1}^{c} \exp(a_{ict})}. \tag{4}$$

Assuming that responses are independent across children and are locally independent for each child given the model, the likelihood of the model, as a function of the whole set of β_{1cp} and β_{2cp} and given the whole dataset X of observed responses, is

$$L(\beta_{1cp}, \beta_{2cp} \mid X) = \prod_{i=1}^{N} \prod_{t=1}^{T} \sum_{C=1}^{C} p(x_{it} = c) I_{ict}, \tag{5}$$

where I_{ict} is an indicator variable that is 1 if the observed response $x_{it} = c$ and 0 otherwise. The log-likelihood function is

$$\ln L(\beta_{icp}, \beta_{2cp} \mid X) = \sum_{i=1}^{N} \sum_{t=1}^{T} \ln \sum_{c=1}^{C} p(x_{it} = c) I_{ict} \tag{6}$$

Parameter estimation was made by maximizing the log-likelihood using Microsoft Excel's solver, which uses a quasi-Newton–Raphson algorithm. A 95% confidence interval was computed for each parameter using a likelihood profile procedure (Meeker & Escobar, 1995) provided by PopTools (Hood, 2006), an Excel add-in. Confidence intervals allowed a fast examination of the contribution of each parameter to the fit of the model and a simpler presentation than traditional step-by-step model comparisons.[1]

During each phase, one color was positively reinforced and the other two colors were negatively reinforced. Only one type of parameter was estimated for each color during each phase. For example, c3 was never positively reinforced during the first three phases; thus, no parameters relative to positive feedback for c3 were estimated during these three phases.

Results

Children's performance analyses

To analyze children's performance, children were split into two age groups: 4- to 5-year-olds ($n = 27$, mean age = 52.6 months, $SD = 3.4$, range = 48–59) and 5- to 6-year-olds ($n = 36$, mean age = 66.1 months, $SD = 3.3$, range = 60–71). Children passed on average 2.59 phases ($SD = 1.43$) out of a maximum of 5 phases, and there was no age difference (4- to 5-year-olds: $M = 2.37$, $SD = 1.44$; 5- to 6-year-olds: $M = 2.75$, $SD = 1.42$). For each phase (i.e., series of trials with the same relevant color), percentages of children reaching (i.e., at least one trial was administered with the newly relevant color) and passing (i.e., successful response selection based on the relevant color on five consecutive trials) are provided in Table 1.

Complementarily, we examined the proportion of successful trials according to phase and age group. A repeated-measures analysis of variance (ANOVA) revealed significant effects of age, $F(1, 53) = 4.02$, $p = .05$, partial $\eta^2 = .07$, phase, $F(4, 148) = 4.32$, $p < .01$, partial $\eta^2 = .10$, and Age × Phase interaction, $F(4, 148) = 5.52$, $p < .01$, partial $\eta^2 = .13$. Given low sample sizes during Phases 4 and 5, separate phase-by-phase analyses and nonparametric tests are recommended. Mann–Whitney tests and t tests (Table 2) and bootstrap analyses (Efron & Tibshirani, 1994) of confidence intervals showed that the highest age effect occurred during Phase 4. The nonsignificant age effect during Phase 5 probably relates to the lack of statistical power due to low sample size ($n = 4$ for 4- to 5-year-olds; $n = 12$ for 5- to 6-year-olds).

The relevance of accuracy rates here can be called into doubt. When a phase was not completed by a child, the mean accuracy rate (percentage correct) was computed on the basis of the first trials only. Because those trials were frequently failed, this results in underestimating accuracy values. This bias probably accounts for the drop in accuracy rates from Phase 2 to Phase 5 for 4- to 5-year-olds. The most important conclusion emerging from children's performance analyses is that the age effect seems to increase throughout the task. The current analyses show only separate pictures of children's performance during each phase of the PAST. In contrast, computational modeling analyses allow further investigation of the dynamics of the change in responses to feedback throughout the task.

Output of the computational model

The residual deviance, computed as minus twice the log-likelihood, is an estimation of the model discrepancy. It follows a χ^2 distribution with degrees of freedom equal to the residual degrees of free-

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[1] If the confidence interval of a given parameter does not encompass 0, a likelihood ratio test would tell us that the model including this parameter is significantly better than the model excluding this parameter. AIC (Akaike Information Criterion) comparison for these models would lead to the same interpretation. Notice that likelihood profile can be asymmetrical around the optimal value (Meeker & Escobar, 1995), especially if the probability distribution used in the model is not symmetrical, as in the case of the multinomial distribution used here. Thus, an estimated parameter is not necessarily the midpoint of its confidence interval.

Table 1
Percentages of 4- to 5-year-olds and 5- to 6-year-olds reaching and passing each phase (success criterion = five consecutive correct responses).

		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
4- to 5-year-olds	% Reaching	100	81	74	59	15
	% Passing	81	74	59	18	4
5- to 6-year-olds	% Reaching	100	92	75	61	33
	% Passing	92	75	67	36	6
Combined	% Reaching	100	87	75	60	25
	% Passing	87	75	63	29	5

Note. "Reaching" means that the previous phase was successfully completed and at least one trial was administered with a newly relevant color. "Passing" means that children successfully based responses on the relevant color on five consecutive trials. The percentage of children reaching Phase n might not be strictly identical to the percentage of children passing Phase $n - 1$ because some children may have reached the success criterion on Phase $n - 1$ on the very last trial of the task.

Table 2
Mean percentages and standard deviations of successful trials per phase for 4- to 5-year-olds and 5- to 6-year-olds.

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
4- to 5-year-olds	74.9 (26.3)	83.7 (17.4)	78.3 (16.2)	68.5 (22.2)	61.6 (36.3)
	$n = 27$	$n = 22$	$n = 20$	$n = 16$	$n = 4$
5- to 6-year-olds	73.5 (22.5)	84.3 (14.3)	84.9 (14.3)	86.8 (13.3)	89.3 (11.9)
	$n = 36$	$n = 33$	$n = 27$	$n = 22$	$n = 12$
Cohen's d	−.06	0.04	0.43	1	1.03
Student's t test (df)	.23 (61)	−.15 (53)	−1.48 (45)	−3.17 (36)	−2.54 (14)
	$P = .81$	$P = .88$	$P = .14$	$P < .01$	$P = .02$
Mann–Whitney test	491.5	334	187	84.5	11
	$P = .63$	$P = .90$	$P = .09$	$P = .02$	$P = .10$

Note. Standard deviations are in parentheses in first two rows. Degrees of freedom (df) are in parentheses in fourth row.

dom of the model and, thus, provides a test of the overall model fit (Faraway, 2006). Here there are three possible responses, consequently the degrees of freedom for one observation is 2, and the total residual degrees of freedom is twice the number of observations minus the number of estimated parameters ($df = 3762$). The deviance of the model is 3426.3. The test tells us that the model's predictions do not differ significantly from the data and that the model fits the data sufficiently well, $\chi^2(3762) = 3426.3$, $p > .90$. Another useful criterion is the comparison of our model with the simplest model, in this case a constant model where the three responses always have the same probability: 1/3. As expected, the constant model does not fit the data, $\chi^2(3780) = 4152.7$, $p < .01$. The deviance is reduced by 17.5% from the constant model to the model of interest. This value can be interpreted in the same way as R^2 in a regression model (Faraway, 2006). It is also χ^2 distributed and can be tested and interpreted similarly to an F test in a regression model. Here the reduction of deviance is highly significant, $\chi^2(18) = 726.4$, $p < .01$. Our model can be considered to fit the data adequately.

Parameter values for each color in each of the first three phases are shown in Table 3. Feedback influence on the activation level of the related color was considered as significant when the 95% confidence interval excluded 0. Parameter values indicate increase or decrease in *activation level* after positive or negative feedback; as such, they can be below −1 or above 1. Depending on the activation levels of all colors, the *probability* of selecting a given color ranged from 0 to 1, with the probabilities of all three colors always adding up to 1. Parameter values and color probabilities are computed on the basis of participants' real performance. However, these values are illustrated in Fig. 1 for *fictive* participants 4 and 6 years of age (−1.5 *SD* from mean age and 1.5 *SD* from mean age, respectively) who would have received the same series of feedback (see Appendix A). This procedure is analogous to the use of predicted values in a regression model for illustrative purposes.

Table 3
Parameter values indexing the influence of positive and negative feedback on the activation level of all three colors for Phases 1–5.

	Phase 1 (786 responses)		
	c1 FB+	c2 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.136**	.038	−.007
	(.100, .172)	(−.019, .079)	(−.069, .039)
$\gamma_{\bullet 1}$ (*AGE*)	.016	−.010	−.016
	(−.022, .054)	(−.068, .048)	(−.081, .008)
	Phase 2 (425 responses)		
	c2 FB+	c1 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.417**	−**.689**	−**.206**
	(.333, .504)	(−.870, −.490)	(−.414, −.010)
$\gamma_{\bullet 1}$ (*AGE*)	−.005	−**.366**	.064
	(−.096, .060)	(−.596, −.154)	(−.110, .235)
	Phase 3 (378 responses)		
	c1 FB+	c2 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.649**	−**3.479**	−**1.14**
	(.454, .866)	(−4.090, −2.910)	(−1.670, −.681)
$\gamma_{\bullet 1}$ (*AGE*)	**.211**	−**.661**	−**.483**
	(.020, .396)	(−1.150, −.225)	(−.967, −.016)
	Phase 4 (234 responses)		
	c3 FB+	c1 FB−	c2 FB−
$\gamma_{\bullet 0}$	**.575**	−**5.823**	−**1.584**
	(.351, .836)	(−6.466, −5.230)	(−2.557, −.761)
$\gamma_{\bullet 1}$ (*AGE*)	.111	−**2.266**	−.701
	(−.105, .339)	(−2.850, −1.702)	(−1.505, .065)
	Phase 5 (67 responses)		
	c2 FB+	c1 FB−	c3 FB−
$\gamma_{\bullet 0}$	**1.526**	−5.717	−**5.642**
	(.818, 2.571)	(−9.027, .002)	(−7.407, −4.140)
$\gamma_{\bullet 1}$ (*AGE*)	.003	−**3.702**	−**2.952**
	(−.547, .003)	(−6.111, −.124)	(−4.240, −1.694)

Note. FB+, positive feedback; FB−, negative feedback. The 95% confidence intervals are reported in parentheses. Significant parameter values (0 excluded from the confidence interval) are reported in bold.

The computational modeling analysis shows that, during Phase 1, positive feedback following responses based on the relevant color (c1) significantly affected responses by increasing the activation level of c1 in subsequent trials. Each time positive feedback was received for c1, its activation level on the next trial increased by .136. In contrast, negative feedback related to c2 and c3 had no significant influence on subsequent responses. Age interacted with none of these parameters. In sum, the modeling analysis suggests that children were sensitive only to positive feedback for the relevant color during Phase 1 and feedback responses did not differ with age.

During Phase 2, feedback related to all three colors had a significant influence on responses. Positive feedback for responses based on c2 significantly increased by .417 the activation level of c2 on the next trials. By contrast, negative feedback for c3 significantly decreased by −.206 the activation level of c3 on the next trials. More importantly, negative feedback for c1 (i.e., the color that was previously relevant) significantly decreased by −.689 the activation level of c1 on subsequent trials, and this parameter was significantly modulated by age (−.366). A negative feedback for c1 resulted in a de-

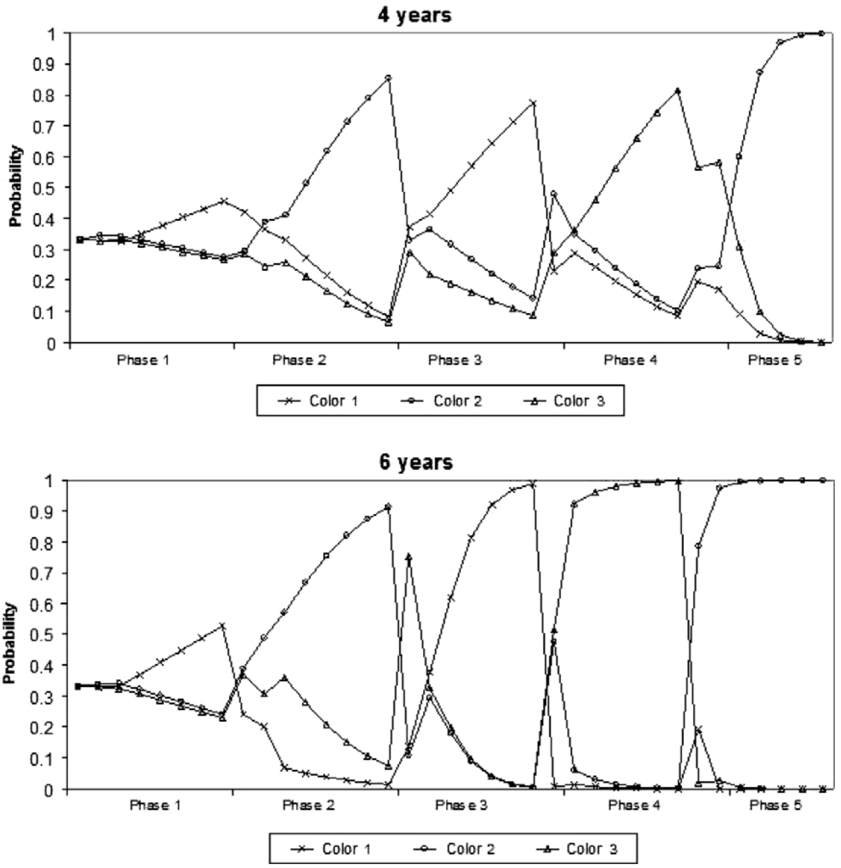

Fig. 1. Change in color probabilities across Phases 1–5 as a function of feedback for fictive 4- and 6-year-old participants receiving exactly the same series of feedback (cf. Appendix A).

crease by only −.140 (−.689 + [−1.5 × −.366]) for a 4-year-old, whereas it resulted in a decrease by −1.055 (−.689 + [1.5 × −.366]) for a 6-year-old. This is illustrated in Fig. 1 by the steep decrease of c1 probability on the very first trials of Phase 2 for the fictive 6-year-old. In contrast, the decrease of c1 probability during Phase 2 for the fictive 4-year-old is much slower, resulting in c1 always being more probable than c3 for children of this age, whereas it is the reverse at 6 years of age, suggesting that perseveration was more probable at 4 than at 6 years of age. In sum, the computational modeling analysis suggests that, after a first switch in relevant color, children's responses were significantly affected by feedback regarding all three colors, and responses to negative feedback for the formerly relevant color were especially acute in older children.

During Phase 3, the computational modeling analysis suggests that feedback related to all three colors significantly influenced responses, and age significantly modulated the influence of each of them. After positive feedback, the activation level of c1 increased more readily for a 6-year-old (.966) than for a 4-year-old (.333), resulting in a steeper increase in the probability of selecting c1 at 6 than at 4 years of age (Fig. 1). Negative feedback for c3 made its activation level decrease more rapidly for a 6-year-old (−1.865) than for a 4-year-old (−.416). This is illustrated in Fig. 1 by a steeper decrease of c3 probability at 6 years of age—despite an initial sudden rise—than at 4 years of age. Finally, although direct comparisons of interactions between age and color feedback were nonsignificant, age tended to particularly affect the influence of negative feedback for c2 (i.e., the previously relevant color). Negative feedback for c2 made its activation level decrease by −4.471 for a 6-year-old and by −2.488 for a 4-year-old, resulting in a steep decline of the probability of selecting c2 during the very first trials of Phase 3 at 6 years of age, whereas this decline was slower at 4 years of age. In sum, according to the analysis, it seems that all feedback types significantly influenced children's responses, and the influence of feedback for all colors was modulated by age, with older children benefiting more than younger children from both positive and negative feedback.

Parameters values for Phases 4 and 5 were computed on a limited set of data because nearly half of the participants (40%) did not reach Phase 4 and only 29% of them passed it (recall that the task ends after 30 trials). Similarly, 75% of the participants did not reach Phase 5 (5% passed it). The limited data set for Phases 4 and 5 has three main consequences. First, confidence intervals are widened, making it harder to detect significant effects. Second, the sample is less representative of the original sample of participants because the least cognitively advanced children did not reach these phases. The homogenization of the sample makes it harder to reveal age effects. Finally, many participants who reached these phases failed to complete them because of limitation on the number of trials, which biases the data during these phases toward the very first trials. Given this poor reliability, parameter values for Phases 4 and 5 must be interpreted with caution.

During Phase 4, the computational modeling analysis shows that feedback related to all three colors significantly influenced response probabilities. A negative feedback for c2 resulted in a decrease in the activation of c2 by −1.584. In contrast, the activation level of c3 significantly increased by .575 after positive feedback. These effects were not modulated by age. Negative feedback for c1 (i.e., the previously relevant color) resulted in a significant decrease in activation (−5.823) that was significantly modulated by age (−2.266). The analysis suggests that the decrease was steeper at 6 years of age (−9.222) than at 4 years of age (−2.424). According to the computational modeling analysis, response to negative feedback for the previously relevant color increased from Phase 3 to Phase 4 for the oldest children but remained roughly the same for the youngest children.

During Phase 5, positive feedback for c2 made its activation increase significantly (1.526), but this was not modulated by age. Negative feedback for c1 had no significant effect overall, but its effect was significantly modulated by age (−3.702), with a stronger change in activation level at 6 years of age (−9.419) than at 4 years of age (−.164). Finally, negative feedback for c3 (i.e., the previously relevant color) significantly affected its activation level (−5.642), and this effect was significantly modulated by age (−2.952). Negative feedback had a stronger effect at 6 years of age (−10.070) than at 4 years of age (−1.214). In sum, the analysis suggests that, during Phases 4 and 5, age mostly affected the effect of feedback regarding the previously relevant color.

Discussion

This study investigated the development of 4- to 6-year-olds' cognitive flexibility in an inductive version of the PAST that required inferring the relevant task goal on the basis of response feedback. Results showed that this task was adapted for use with children in this age range, and age only modulated performance late in the task. A computational model was then used to further assess performance development with age and change throughout the task. The analyses suggest two main conclusions. First, children's responses seem to be influenced differently by positive feedback for the relevant color, negative feedback for the formerly relevant color, and negative feedback for the other irrelevant color, and responses to feedback did change across phases. Second, age seems to increasingly modulate feedback processing efficiency throughout the task. These results showed that the use of computational models to investigate children's responses allows finer-grained descriptions of performance changes over age and throughout the task than do traditional indexes. Moreover, they complement previous findings on the deductive version of the PAST (in which the relevant color is repeated before every trial [Chevalier & Blaye, 2008]) that showed an important development of flexible behavior between 3 and 4 years of age but ceiling performance later on. Although the deductive and inductive PAST cannot be compared directly because of many different features (e.g., number of trials, presence/absence of compatible trials, number of switches), the current study on the inductive PAST suggests that flexible behavior keeps on improving after 4 years of age in situations that require using feedback to infer and maintain relevant task goals.

The analysis of children's responses by means of the computational model used in the current study suggests that children responded differently to feedback depending on their valence and the status of related colors. During Phase 1, positive feedback for the relevant color (c1) had a significant effect on activation levels, whereas negative feedback for the two alternative irrelevant colors had no significant influence, suggesting that children responded only to positive feedback. Indeed, Phase 1 mainly required inferring and consistently maintaining the relevant color in the face of the interference created by the two irrelevant colors. Positive feedback for the relevant color was especially useful because it directly signaled which task was relevant and to be selected on subsequent trials, whereas the same amount of information could only be inferred, using negative feedback, from the combination of *both* irrelevant colors. The especially informative status of positive feedback during Phase 1 may have led children to pay particular attention to it. During subsequent phases, children first needed to discover from negative feedback that the formerly relevant color was now irrelevant and then switch to the newly relevant color and maintain it consistently. Thus, negative feedback for the formerly relevant color played a key role in signaling that a switch was now required, and consistently this type of feedback was especially influential over activation levels during Phases 2 to 5. As a whole, the computational modeling analyses suggest that preschoolers selectively process the most informative feedback types.

The absence of significant response to negative feedback during the first phase may seem at odds with findings of negative priming in some flexibility measures for preschoolers (Chevalier & Blaye, 2008; Müller, Dick, Gela, Overton, & Zelazo, 2006; Zelazo et al., 2003). On such measures, 3-year-olds encountered special difficulty in switching to a sorting criterion that was previously ignored, as compared with a neutral criterion that was not present before the switch occurred. If children are willing to inhibit irrelevant information during the first phase, why don't they consider negative feedback that incites them to do so? Actually, these findings are inconsistent only if one considers that negative priming results from voluntary inhibition. Yet it may also result from automatic inhibition (e.g., Harnishfeger, 1995), hence explaining why negative priming can be observed in infants whose voluntary inhibition is still immature (e.g., Amso & Johnson, 2005). If negative priming is related to an automatic phenomenon, there is no reason to expect children to respond significantly to negative feedback during the first phase of the PAST.

The second main outcome of the computational modeling analysis was the differentiation of feedback processing efficiency with age as children progressed throughout the task. According to the analysis, feedback influence did not interact with age at all during Phase 1. During Phase 2, age only affected the influence of negative feedback related to the previously relevant color. Finally, during Phase 3, age affected feedback related to all three colors. During Phases 4 and 5, age modulation on feedback for the previously relevant color kept increasing, whereas age effects on other feedback types were not consistent, possibly relating to the poor reliability of parameter values due to limited data for Phases 4 and 5. The differentiation of feedback processing efficiency with age across phases may be accounted for by at least two alternative—albeit not mutually exclusive—explanations: increase in executive demands or increase in efficiency of feedback processing across phases. The increase in executive demands across the first three phases may have increasingly penalized the youngest children whose executive control is the least efficient. Phase 1 only required active maintenance in the face of distractor interference, whereas Phase 2 also involved inhibition to resist the proactive interference of the previously attended color and Phase 3 added the special requirement of reactivating a previously actively inhibited color. Consistent with this interpretation, maintenance of initial criteria is successfully achieved by 3 years of age on the DCCS (e.g., Zelazo et al., 2003) and, to a lesser extent, on the deductive version of the PAST (Chevalier & Blaye, 2008), whereas inhibitory control has been shown to develop substantially during the preschool period (e.g., Espy, 1997; Gerstadt, Hong, & Diamond, 1994) and reactivation failures have been observed in both preschoolers (Chevalier & Blaye, 2008; Müller et al., 2006) and adults (Dreisbach & Goschke, 2004; Maes, Damen, & Eling, 2004; Mayr & Keele, 2000).

Alternatively, feedback processing efficiency differentiation with age across phases may reflect age difference in feedback processing per se. Actually, except for the minority of participants (13%) who failed to complete the first phase, most 4- to 6-year-olds could use feedback to infer information about what should be done on the very next trial. However, as they progressed through the task, children may have increasingly used past experience with the task (e.g., regularities in phase length) to infer an increasing amount of information from feedback (e.g., a positively reinforced color will remain relevant for a while) and, accordingly, modulate color activation or inhibition. Refinement in feedback processing may increase with age, hence making perseveration less likely for older children than for younger children. Such learning about how to efficiently resolve the task is generally beneficial, but it may be temporarily detrimental at the beginning of Phase 3. Older children may have inferred from c1 being relevant during Phase 1 and c2 being relevant during Phase 2 that the first negative feedback for c2 meant not only that c2 was now irrelevant but also that c3 was relevant because it had never been relevant so far, hence resulting in the sudden rise of the probability of c3 for the fictive 6-year-old child in Fig. 1.

According to a strict executive interpretation, older and younger children's feedback processing efficiency would increasingly differ across phases because performance of younger children, whose executive control is relatively poor, would decrease (i.e., parameter values would get closer to 0) as executive demands increased, whereas older children's performance would remain relatively stable. In contrast, the feedback processing interpretation predicts that because older children process feedback more informatively (by relating it to previous experience on the task) than younger children, the sensitivity to feedback of older children should increase more across phases (i.e., parameter values getting further away from 0) than that of younger children. Actually, parameter values for negative feedback decreased across phases, whereas parameters values for positive feedback increased across Phases 1 to 5 for the oldest children. They did so from Phase 1 to Phase 2 and remained about the same during subsequent phases for the youngest children. Therefore, the outcomes of the modeling analysis suggest that responses to feedback improved for all children and even more so for older children, and this speaks to an increasing ability to efficiently process feedback with age.[2]

The claim here is not to discard any contribution of executive demands but rather to stress that differentiation in feedback processing with age did occur across phases. We consider that executive control is relevant here precisely because information inferred from feedback needs efficient executive control to be applied, children who are motivated by negative feedback to exert strong inhibition over a series of trials can do so only if their inhibitory control is efficient enough. Nonetheless, the refinement in feedback processing suggests that, with age, children improve at using feedback to set and maintain the relevant task goal as well as anticipate subsequent goal changes. As such, the current findings complement recent evidence showing that goal-setting abilities not only play an important role in adults' flexibility (e.g., Miyake, Emerson, Padilla, & Ahn, 2004; Gruber & Goschke, 2004; Miyake et al., 2004) but also contribute substantially to flexibility development (Chevalier & Blaye, in press).

Our findings are also compatible with ideas developed by Marcovitch and Zelazo (2006, 2009) within the hierarchical competing systems model (HCSM). This model hypothesizes that flexibility development relates to an increase in the level of reflection on the content of a conscious representational system that leads to new responses and overrides irrelevant prepotent responses based on a habit system. Reflection is thought to increase with experience and to develop during childhood. The HCSM may explain why, in the current study, children started to respond significantly to negative feedback only after the first change in relevant color. The surprising failure following the color change may have alerted children to the importance of negative feedback (i.e., increase in reflection on negative feedback) and, thus, motivated them to now deeply process this information. Similarly, as the task unfolded, children may have gained reflection on all feedback types, progressively increasing feedback processing efficiency. Because reflection is thought to develop with age, reflection gains may have been even higher for the older children. Therefore, the HCSM offers an interesting account of children's increasing ability to set and maintain task goals on the basis of response feedback with age and experience with the inductive PAST.

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[2] Because parameters were estimated for each phase, including only children who passed the previous phase, one may argue that parameter change relates to selection of the children whose executive control was the most advanced rather than improvement in feedback processing. We reestimated parameter values for all three phases, including only the sample of children who reached the third phase, and we still observed the same change across phases, although the age effect for negative feedback for Phase 3 fell short of significance (see Appendix B). Therefore, participant selection could not fully account for parameter change.

Compared with models based on only discrete change assumptions, one of the main interests of our model, which is probabilistic in nature, is that it can reveal both gradual changes in color probabilities, as observed during the first phases of the task, and more sudden variations, as evidenced in parameter values of the simulation for older children during Phases 4 and 5. In contrast, a model based on only discrete change assumptions would show only sudden variations and, thus, fail to capture intraindividual change from gradual to sudden variations throughout the task. The flexibility of probabilistic models such as ours in depicting different kinds of performance change suggests possible interpretations in terms of the involvement of two learning modes at different stages of the task: associative learning accounting for gradual changes and more reflective controlled learning (based, e.g., on better goal setting) evidenced through sudden changes.

Finally, although the assumptions of the current computational model allowed us to draw important conclusions about the processes underlying preschoolers' use of feedback for flexible behaviors, some of these assumptions are probably too strong. At least two paths of improvement can be suggested for future models. First, feedback processing might change not only as children move on to a new phase but also as they proceed from trial to trial within each phase[3]; this is especially probable because, according to the HCSM, reflection on the task may occur anytime during the task. Second, it is highly plausible that feedback processing and switching performance differ not only as a function of age but also as a function of other interindividual variables (e.g., working memory capacity, inhibitory control). Future models of children's developing flexibility should aim at addressing these two aspects.

The current study showed that 4- to 6-year-olds can make successful use of response feedback to infer relevant task goals and, accordingly, behave flexibly. Moreover, it brought evidence showing that feedback processing efficiency changed greatly and was increasingly mediated by age as children progressed through the task. These results suggest that children interpret feedback on the basis of previous task experience, and this ability develops during the preschool period. Finally, this study illustrated the heuristic value of computational models for the study of cognitive flexibility development.

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Appendix A. Series of positive and negative feedback that the fictive participants received for each color during the five phases of the task.

Trial	Phase	Color					
		c1		c2		c3	
		FB+	FB−	FB+	FB−	FB+	FB−
1	1	0	0	0	0	0	0
2	1	0	0	0	1	0	0
3	1	0	0	0	0	0	1
4	1	1	0	0	0	0	0
5	1	1	0	0	0	0	0
6	1	1	0	0	0	0	0
7	1	1	0	0	0	0	0
8	1	1	0	0	0	0	0
9	2	0	1	0	0	0	0
10	2	0	0	1	0	0	0

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[3] We thank an anonymous reviewer for this suggestion.

Appendix A. (*continued*)

Trial	Phase	Color					
		c1		c2		c3	
		FB+	FB−	FB+	FB−	FB+	FB−
11	2	0	1	0	0	0	0
12	2	0	0	1	0	0	0
13	2	0	0	1	0	0	0
14	2	0	0	1	0	0	0
15	2	0	0	1	0	0	0
16	2	0	0	1	0	0	0
17	3	0	0	0	1	0	0
18	3	0	0	0	0	0	1
19	3	1	0	0	0	0	0
20	3	1	0	0	0	0	0
21	3	1	0	0	0	0	0
22	3	1	0	0	0	0	0
23	3	1	0	0	0	0	0
24	4	0	1	0	0	0	0
25	4	0	0	0	1	0	0
26	4	0	0	0	0	1	0
27	4	0	0	0	0	1	0
28	4	0	0	0	0	1	0
29	4	0	0	0	0	1	0
30	4	0	0	0	0	1	0
31	5	0	0	0	0	0	1
32	5	0	1	0	0	0	0
33	5	0	0	1	0	0	0
34	5	0	0	1	0	0	0
35	5	0	0	1	0	0	0
36	5	0	0	1	0	0	0
37	5	0	0	1	0	0	0

Note. FB+, positive feedback; FB−, negative feedback. c1 was relevant during Phases 1 and 3, c2 was relevant during Phases 2 and 5, and c3 was relevant during Phase 4.

Appendix B. Parameter values estimated on the sample of children who reached the third phase.

	Phase 1 (357 responses)		
	c1 FB+	c2 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.211** (.157, .242)	.059 (−.089, .218)	−.156 (−.324, .001)
$\gamma_{\bullet 1}$ (*AGE*)	.002 (−.042, .045)	−.005 (−.146, .186)	−.099 (−.223, .023)
	Phase 2 (374 responses)		
	c2 FB+	c1 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.481** (.381, .589)	−**.923** (−1.206, −.657)	−.188 (−.415, .039)

(*continued on next page*)

Appendix B. (*continued*)

	Phase 2 (374 responses)		
	c2 FB+	c1 FB−	c3 FB−
$\gamma_{\bullet 1}$ (*AGE*)	−.029 (−.169, .112)	−**.355** (−.666, −.147)	.079 (−.181, .256)
	Phase 3 (378 responses)		
	c1 FB+	c2 FB−	c3 FB−
$\gamma_{\bullet 0}$	**.673** (.458, .916)	−**3.794** (−4.520, −3.100)	−**.981** (−1.578, −.460)
$\gamma_{\bullet 1}$ (*AGE*)	**0.221** (.004, .457)	−0.628 (−1.180, .217)	−.485 (−.997, 0.020)

Note. FB+, positive feedback; FB−, negative feedback. The 95% confidence intervals and numbers of available responses are reported in parentheses. Significant parameter values (0 excluded from the confidence interval) are reported in bold.

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