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ARTICLE

Training kindergarten children on learning from their mistakes

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Abstract
This study investigated whether feedback on their errors and speed improves kindergarten children's performance in an executive function (EF) task. Children from Switzerland ($N = 213$, 49% female, $M_{age} = 6.4$ years) were tested in the Hearts and Flowers task pre- and post-training and trained either on a variant of this task with ($n = 71$) or without feedback ($n = 72$), or on a control learning task ($n = 70$). The feedback group performed more efficiently than the no-feedback group during the intervention and partially also in the post-test. Both EF training groups performed more efficiently than the control group in the post-test. These results suggest that kindergarten children detect and monitor their errors and even get better at it given the opportunity to practice. Moreover, they benefit additionally from external feedback. Integrating feedback into computerized cognitive training (and learning apps) could be a potential avenue for interventions in school settings.

KEYWORDS
cognitive control, executive functions, feedback, Hearts and Flowers, intervention, post-error slowing

BACKGROUND

Executive functions (EF) are top-down processes that guide goal-directed behaviour. They are mainly composed of inhibition, working memory (WM), and shifting (Diamond, 2013). Because these processes are crucial elements of many everyday and academic tasks, it is no surprise that they predict many life outcomes, such as academic achievement, social adjustment, and adult wealth and health (Blair & Razza, 2007; Moffitt et al., 2011). Fortunately, research has shown that EFs are malleable in childhood and can be trained through different interventions such as classroom activities, physical activity, and

Statement of Contribution

What is already known on this subject?

- Executive functions (EF) can be trained in young children through repetitive practice at increasing difficulty.
- Feedback within a single session has been effective in supporting EF of 3-year-olds, but not older children.

What does the present study add?

- Repeated feedback over weeks improved 5- to 7-year-olds' EF more than just increasing practice difficulty.
- Children's efficient orchestration of the involved sub-processes also improved through repeated feedback.
- Integrating feedback into computerized cognitive training is found feasible.

computerized cognitive training (for a review, Diamond & Ling, 2020). One crucial aspect of efficient intervention approaches is the engagement in repetitive practice at increasingly higher difficulty levels (Diamond & Ling, 2016). What remains unknown is whether, in addition to repeatedly practicing at progressively more challenging levels, providing feedback on their mistakes may improve children's monitoring, thereby improving their orchestration of the different EF subprocesses and, thus, EFs overall. In other words, can kindergarten children learn from their mistakes? The current study aimed to answer this question and implemented computerized cognitive training with or without feedback on errors.

Among different intervention approaches, computerized training is the most widely researched, with robust success in improving all three EF components in children (Bergman Nutley et al., 2011; Liu et al., 2015; Thorell et al., 2009; for a review, Diamond & Lee, 2011; for a meta-analysis, Cao et al., 2020), and as effective as non-computerized training (Scionti et al., 2020). Computerized training interventions are generally shorter-term and more time- and cost-efficient compared to curriculum-based interventions (Traverso et al., 2015). In principle, such interventions can be used as a learning app, enabling widespread use and offering cost-effective learning opportunities, for example, during a pandemic, for disadvantaged or chronically sick children, or when teacher–student ratios are problematic. Relying on their comparable effectiveness and administering efficiency, we developed and evaluated a computerized training programme to investigate the effect of giving feedback on children's errors in improving their monitoring. Our overarching goal was to pave the way for developing a child-appropriate, scientifically based and evaluated learning app that targets monitoring skills and that could be used in both typical and atypical populations.

Additional feedback on performance might help children monitor their performance and/or reduce goal-maintenance demands (Oeri et al., 2019). So far, only a few studies have investigated the effect of feedback on children's EFs, specifically on shifting and inhibition, and within a single session, but not in more extended training. Their overall evidence is somewhat contradictory. Feedback was generally effective in 3-year-olds (Bohlmann & Fenson, 2005; Van Bers et al., 2014), but not necessarily in 4-year-olds (Oeri et al., 2019) or 5-year-olds (Bohlmann & Fenson, 2005). Six-year-olds monitored their performance better when they were required to estimate their own feedback (i.e., evaluate their responses themselves), but not when given direct feedback (i.e., that their response is correct, incorrect, or too late) or no feedback (Hadley et al., 2020). While one-session feedback may be effective in younger children who are more open to support due to their less developed EFs (Cao et al., 2020), older children may still benefit from feedback when given repeatedly over a number of increasingly challenging sessions. Additional pair activities engaging 8.5-year-old children in metacognitive monitoring, such as evaluating task demands, the difficulty of different test trials, possible task strategies, and sources of interference, led to greater gains in some trained EF tasks but not in near- or far-transfer tasks (Kubota et al., 2023). Even when monitoring is not explicitly trained, the repeated feedback on accuracy and speed could bring about a systematic task approach in which children internalize the feedback to subsequently evaluate their responses on their own and possibly automatize monitoring processes. Given that an effect of feedback has been documented on both inhibition (Hadley et al., 2020; Oeri et al., 2019) and shifting components of EF (Bohlmann & Fenson, 2005; Van Bers et al., 2014), the current study investigates these two EF components.

Most EF, as well as everyday tasks, do not only demand children to be as accurate as possible but also as fast as possible. Thus, feedback is not only needed on the accuracy but also the speed of children's answers. To our knowledge, no studies have provided feedback on both the accuracy and speed of children's answers in EF training to examine whether it improves children's EF, except for a recent study from our group (Heemskerk & Roebers, 2024). This study implemented a similar intervention with 1st graders over six sessions, similarly giving no feedback or feedback on children's speed and accuracy. The control group engaged in training on a learning task. Results showed that the EF training improved children's performance compared to the control training; however, providing feedback did not result in a statistically significant additional improvement, despite showing a trend in the expected direction. We reasoned that the duration of the training might have fallen short of generating the expected impact, especially considering the common finding in the EF literature that more practice (more sessions of training) leads to better outcomes (Diamond & Ling, 2016, 2020). Therefore, we doubled the number of sessions in the current study.

As a crucial part of EF, monitoring one's performance, recognizing errors, and adjusting the speed of responding accordingly to perform well in cognitive tasks is essential. Throughout development, children learn to find a better balance between accuracy and response speed in cognitive tasks. They learn to maintain a high accuracy while responding overall faster (Brewer & Smith, 1989; Davidson et al., 2006; Roebers, 2022). A task strategy to achieve this could be to search for the speed limits until one makes an error and downregulate speed after the error. This is known as post-error slowing, and it is an important indicator of error monitoring and control adjustments in multi-trial cognitive tasks (Laming, 1979; Rabbitt, 1966). Here, we explored whether we could support developmental progression by facilitating self-monitoring and this task strategy. Feedback on children's errors and response speed should help with better monitoring and control adjustments, consequently changing the post-error slowing towards smoother speed adjustments.

Post-error slowing (PES) has been consistently documented in adults and a growing number of studies has been documenting it in children as well, from an age as young as 3 to 4 (Brewer & Smith, 1989; Dubravac et al., 2020; Ger & Roebers, 2023a, 2023b; Jones et al., 2003; Roebers, 2022), and in different task and conflicts (Brewer & Smith, 1989; Dubravac et al., 2020; Ger & Roebers, 2023a; Jones et al., 2003; Roebers, 2022). Studies also suggest that a greater magnitude of PES is associated with better overall task accuracy, at least in young children (Ger & Roebers, 2023a; Steinborn et al., 2012). Yet we are far from understanding what the optimal level of post-error slowing may be for optimizing overall task performance. One piece of evidence that may be informative is that younger children show more exaggerated post-error slowing in the form of slowing down extremely after an error compared to older children and adults (Brewer & Smith, 1989; Dubravac et al., 2020, 2022; Roebers, 2022). It indicates that slowing down after an error, but not too much (i.e., optimizing the magnitude of post-error slowing), may be an ability that develops with age. In parallel, interventions targeting children's successful detection of errors may be expected to change the magnitude of post-error slowing, keeping the overall accuracy and reaction time constant. Despite the increasing focus on PES, studies are only beginning to investigate how PES may be influenced by targeted interventions on children's error monitoring. Heemskerk and Roebers (2024) did not find an EF training-induced change in PES in the inhibition block of an EF task (i.e., Hearts and Flowers) in first-grade children. It remains to be discovered whether and how PES would change in kindergarten children after longer training in both inhibition and shifting components.

In children, inhibition and shifting components of EF are typically closely related to other general cognitive abilities such as WM, which is also often categorized as another EF component, or nonverbal intelligence (Brydges et al., 2012; Duan et al., 2010; Ger & Roebers, 2023b). Due to the training's visuospatial and mainly nonverbal nature, we respectively measured visuospatial WM and nonverbal intelligence and controlled for these factors to ensure that any improvements observed in inhibition and shifting are not due to pre-existing differences in these cognitive abilities among the children. Further, we evaluated if these background variables would impact the effectiveness of the training by addressing individual differences.

In sum, the current study asked whether EF training with feedback on children's errors and speed leads to a greater improvement in their performance in an EF task (increased rate correct, that is, number of correct responses per second, and a greater change in PES) compared to EF training with no feedback and a control training. To this end, we carried out a pre–post design where we assessed children's performance in an EF task (Hearts and Flowers) pre- and post-training and randomly assigned children to either of these three conditions, consisting of 12 training sessions: EF training with Feedback, EF training with no feedback and control training. The EF training was based on a variant of the Hearts and Flowers task and the control training on a learning and memory task. Children's performance in the Flower and Mixed blocks of the Hearts and Flowers task were analysed separately for EF's inhibition and shifting components. We expected that both EF training with and without feedback would lead to a greater improvement in EF than the control training, and the EF training with feedback would lead to a greater improvement than without feedback. We did not expect a different pattern between EF's inhibition and shifting components. For PES, we expected the same pattern of differences between the training groups but we did not have a specific prediction for the direction of change, namely, whether PES reduces or increases. We additionally explored the trajectory of children's performance throughout the EF training with and without feedback as further evidence for the effect of feedback.

METHOD

Participants

Data from 213 kindergarten children from Switzerland between the ages of 5.8 and 7.7 years were included in the analyses. Children in Switzerland begin their formal education at the age of 4 with 2 years of kindergarten, which is included in the 11 years of mandatory schooling. The lessons follow a national curriculum and are conducted by professionally trained educators. Sample characteristics are presented separately for each of the three training groups (EF training with feedback, EF training without feedback, and control group) in Table 1. Children came from urban and rural areas of central Switzerland and mainly from families of lower- to upper-middle class. They were recruited by contacting interested kindergarten teachers. Parents of participating children gave written informed consent. The study was approved by the local ethics committee and was conducted in accordance with the Declaration of Helsinki.

TABLE 1 Sample characteristics in each group.

Group	*N*	Mean age	SD age	Min age	Max age	Sex (% female)
EFT FB	71	6.46	0.40	5.75	7.50	49
EFT NOFB	72	6.48	0.36	5.83	7.67	49
CT	70	6.39	0.32	5.75	7.08	50

Abbreviations: CT, Active control training; EFT FB, executive function training with feedback; EFT NOFB, executive function training without feedback.

Materials

Tablet computers were used to administer the tasks (Samsung Galaxy Tab S4 and Samsung Galaxy Tab A7). The tasks were implemented as apps to run on Android. Responses were automatically registered for accuracy and reaction time (RT) in milliseconds. Children responded via external buttons in the Hearts and Flowers task and the EF training (intervention) tasks, and by tapping on the touchscreen in the remaining tasks.

Tasks

EF: Hearts and Flowers Task

The Hearts and Flowers task was modified from a study by Diamond et al. (2007). The task consisted of three blocks presented in a fixed order: Hearts, Flowers, and Mixed. In the Hearts (congruent) block, children saw a heart on either the left or right side of the screen in each trial and had to press the corresponding button on that side. This block included 24 trials and established a dominant response. In the Flowers (incongruent) block, children saw a flower on either side and had to press the button on the opposite side. This block included 36 trials and required inhibiting the previously established dominant response. In the Mixed block, heart and flower trials were presented in a pseudo-randomized order, with a flower trial always surrounded by heart trials. The Mixed block included 48 heart (congruent) trials and 12 flower (incongruent) trials, and required switching between rules. Children's data were excluded from the analyses block-wise in the Hearts and Flowers task if they committed 50% or more errors ($n = 20$) to ensure that the only children included in the analytic sample were those who understood the block's rules and were sufficiently attentive. Such exclusion criteria have commonly been used in the previous literature (Camerota et al., 2019; Roebers, 2022). Further details about the task are provided in the Supporting Information.

In terms of executive function (EF) indices, we focused on the Flowers and Mixed blocks of the Hearts and Flowers task to assess the inhibition and shifting components, respectively. We calculated the mean reaction time (RT), and the mean accuracy as the proportion of correct answers. Although accuracy has been the most widely used measure from the Hearts and Flowers task as the EF score, speed has been documented to be an additionally informative measure for younger children, primarily when they perform at a high level (Camerota et al., 2019, 2020). Given that our intervention aims at improving both the accuracy and speed, we calculated a rate correct score (RCS) as an index incorporating both components by dividing the accuracy by the mean RT in seconds. As a means of quantifying trial-by-trial control adjustments, we calculated post-error slowing (PES) using the traditional method of subtracting the mean RT of correct post-error trials from the mean RT of correct post-correct trials, in units of milliseconds (Dutilh et al., 2012).

Visuospatial Working Memory (WM)

This was assessed with a modified forward position span task, adapted from Frick and Möhring (2016). In this task, a 4 × 4 grid was used, and a mole appeared at different locations within the grid. The child was asked to reproduce the locations in the same order. Performance in forward and backward spatial span tasks have been documented to be highly correlated in children (Aeschlimann et al., 2017) and arguments exist that these tasks do not necessarily tap different concepts like short-term storage and WM (Unsworth & Engle, 2007). Therefore, we used a more age-appropriate forward span task as an index of WM. The span (i.e., number of locations) was incremented from two to seven if the child correctly answered at least three of six trials at each span length. The outcome variable was accuracy, that is, the sum score of correct trials. The total score ranged from 0 to 36.

Nonverbal intelligence

The German adaptation of the Odd-Item Out subtest from the Reynolds Intellectual Assessment Scale (RIAS; Reynolds & Kamphaus, 2003) was used to assess fluid intelligence (i.e., nonverbal IQ). Children were presented with sets of five to seven pictures, and their task was to identify the picture that did not fit. Before the test trials, the children received instructions and completed three practice trials, with feedback provided for incorrect responses. As the outcome variable, a sum score of correct answers was used. The subtest included 51 items, allowing scores to range from 0 to 51.

Intervention

Children were randomly assigned to either executive function training with feedback (EFT FB), executive function training without feedback (EFT NOFB) or active control training (CT). The executive function training consisted of 12 sessions, in which a variant of the Hearts and Flowers task with different stimuli, cover story, and background music were implemented. Difficulty increased both within a session and across sessions. The three main blocks, congruent, incongruent and mixed were constant in each session, and from the 4th session on, an additional mixed block was introduced. Different from EFT NOFB, EFT FB provided feedback on errors and speed. Namely, when the child gave an incorrect response, a smiley appeared on the screen with a voice saying 'Oops, that was a mistake' and the background music paused until the next correct answer. Additional feedback was given when the child gave an incorrect response for consecutive trials or answered too slowly in a given trial. Further details of the training are provided in the Supporting Information. Similar to the pre- and post-test, RCS and PES were calculated and analysed in each block for intervention results.

Design and procedure

The study was designed as a pre–post intervention. Kindergarten classes were randomly assigned to either the EFT or CT. Within the classes assigned to EFT, children were randomly assigned to either the feedback or no feedback groups. The data were collected in two waves, in the spring semester of 2022 and 2023, respectively. In all testing sessions, including the pre-test, post-test, and intervention, children were tested in small groups in a quiet room in their kindergarten (the same throughout the intervention) and individually worked on tablet computers to solve the tasks. Children heard pre-recorded instructions through headphones. The pre-test was carried out on two separate days with a maximum of 4 days in between (except for the children who were absent and needed to catch up in the next test session). The testing on each pre-test day lasted about an hour. The 12 intervention sessions were administered over 6–8 weeks, each lasting 20–25 min. At the end of each intervention session, children received a sticker to place on the corresponding session on their game passports. Children were allowed to catch up on up to two intervention tests in a single testing session. The post-test was carried out in 1 day and the children were tested again with the Hearts and Flowers task. Once the post-test was completed, children were awarded a symbolic medal and participation certificate for supporting research. Moreover, each class received 300 Swiss Francs (CHF) as a reimbursement.

Data analysis

This study was not pre-registered. The anonymized data and analysis script can be found at: https://osf.io/p4k2r/. Data were analysed using R [version 4.3.2] (R Core Team, 2020), and the packages 'brms'(Bürkner, 2017) and 'emmeans' (Lenth et al., 2022).

We first analysed whether children's RCS and PES changed as a function of measurement point (pre-test: T1 vs. post-test: T2) and group (EF FB, EF NOFB, CT), while controlling for age, gender, visuospatial WM score and nonverbal intelligence score, separately for each relevant task block (Flowers, Mixed). To this end, we used a Bayesian linear mixed effects model using the default settings of the 'brms' package. The outcome variable was the RCS or PES, and the fixed effect variables were the measurement point, group, their interaction, age, gender, visuospatial WM score and nonverbal intelligence score (and additionally RCS for predicting PES), and participant ID as a random intercept. Regarding the categorical variables, the reference level was pre-test (T1) for measurement point, CT for group, and female for gender. To follow up on the significant effects, we calculated estimated marginal means using the 'emmeans' function (please see Supporting Information for model outputs). For the significance of an effect, we relied on the 95% Credible Intervals (CI; between lower Highest Posterior Density (HPD) and upper HPD) for the estimate. We interpreted the effect to be significant if the CI did not include 0.

We then analysed the intervention data to study the trajectory of RCS and PES between the EFT groups with and without feedback. We similarly used a Bayesian linear mixed effects model where the only difference was the session as a continuous predictor instead of the factorial measurement point, again separately for the incongruent, mixed, and second-level mixed blocks. We calculated estimates of slopes of the session trend for each group (EFT FB vs. EFT NOFB) using the 'emtrends' and 'emmip' functions from the 'emmeans' package, respectively.

RESULTS

Preliminary *t*-tests showed that, at the pre-test, boys scored higher on the RCS than girls in both the Flowers, $t(197) = -2.71$, $p = .007$ and the Mixed block of Hearts and Flowers, $t(205) = -2.80$, $p = .006$, therefore, gender was included in the analyses. Moreover, a Wilcoxon test showed that girls exhibited greater PES than boys in the Flowers block of Hearts and Flowers ($W = 3807$, $p = .025$), therefore, gender was included only for the Flowers block in the PES analyses. Children did not differ in age, $F(2, 210) = 1.20$, $p = .303$, visuospatial WM, $F(2, 210) = 0.47$, $p = .628$ or nonverbal intelligence measures, $F(2, 210) = 0.95$, $p = .390$ across the three groups, but all these measures were included as control measures in the main analyses.

Descriptive statistics

We present the descriptive statistics of the Hearts block in the Hearts and Flowers task and the congruent block in the EF training, however, these blocks are not included in the analyses given that they do not necessarily assess the EF but are used to establish a pre-potent response in children. The descriptive statistics of the accuracy, RT and RCS from the Hearts and Flowers task at both the pre-test and post-test are presented in Figure 1, and the accuracy (score) from the visuospatial WM and the nonverbal IQ tasks are presented in Table 2. The descriptive statistics of the accuracy, RT and RCS from the intervention sessions for the EFT FB and EFT NOFB groups are visually presented in Figure 2. Please note that only the RCS was used in the statistical analyses to address the research questions. Although RCS is calculated by dividing the number of correct answers by RT, we include descriptive statistics for accuracy and RT to help readers understand how these components contribute to the RCS.

Pre-test–post-test results

These results address whether children's RCS and PES change as a function of measurement point (pre-test: T1 vs. post-test: T2) and training group (EF FB, EF NOFB, CT), while controlling for age,

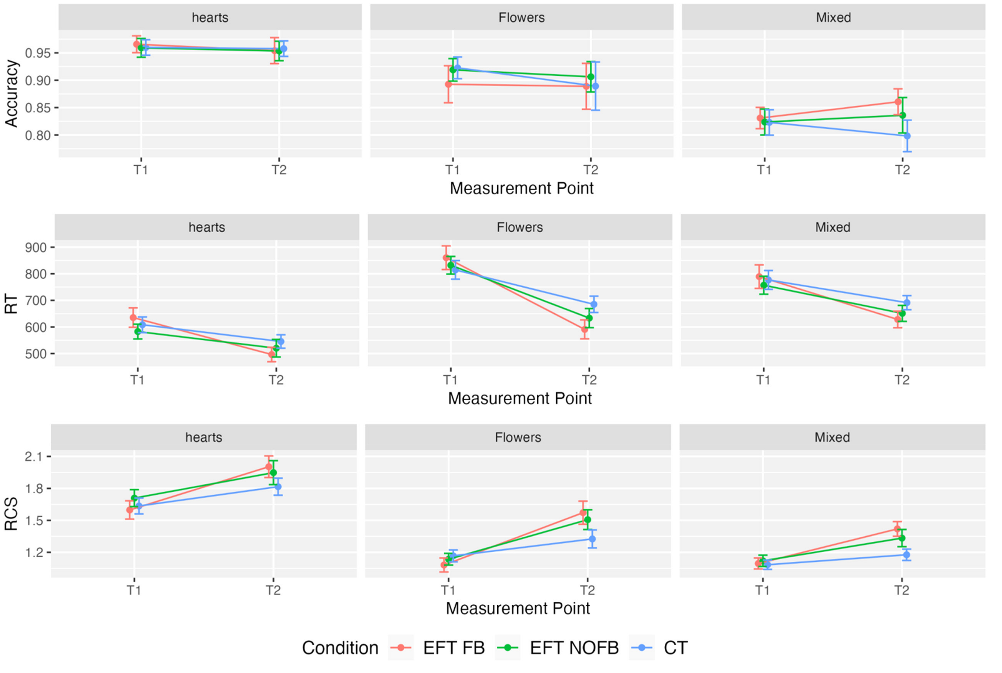

FIGURE 1 Descriptive statistics of the Hearts and Flowers scores. *Note*: Error bars represent 95% confidence intervals. RTs in milliseconds.

TABLE 2 Descriptive statistics of visuospatial WM and nonverbal intelligence.

	EFT FB		EFT NOFB		CT	
	M	***SD***	***M***	***SD***	***M***	***SD***
Visuospatial WM	7.89	3.12	7.97	2.97	8.33	2.49
Nonverbal intelligence	15.6	5.44	15.9	5.04	16.8	4.61

Note: The maximum score was 36 in the visuospatial WM task and 51 in the nonverbal intelligence task. Accuracy is the sum score of correct trials in the respective tasks.

gender, visuospatial WM score and nonverbal intelligence score, respectively in the Flowers block (i.e., inhibition) and Mixed block (i.e., shifting).

Flowers block

Below we present the pre-test–post-test results for the Flowers Block.

RCS

The pairwise comparisons of the estimated marginal means from the model predicting RCS showed that the groups did not differ from each other at T1 (Table 3). However, at T2, both EFT FB and EFT NOFB groups scored higher in RCS than the CT group, while they did not differ from each other (Table 3). Moreover, all groups increased their RCS from T1 to T2 (Figure 3a).

PES

The pairwise comparisons of the estimated marginal means from the model predicting PES showed that the groups did not differ from each other either at T1 or T2. For all three groups, PES decreased

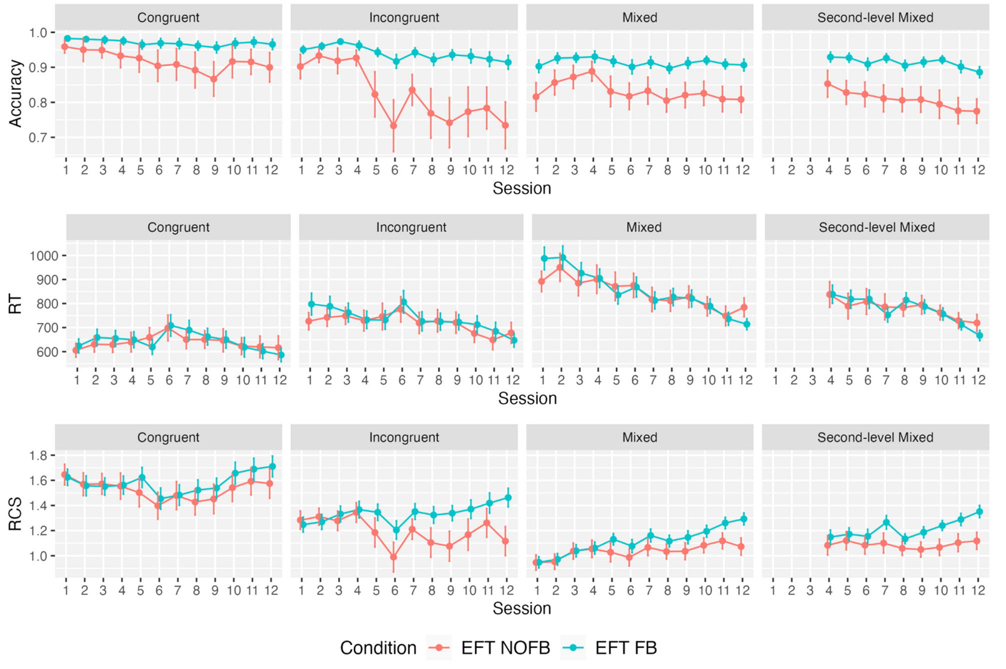

FIGURE 2 Descriptive statistics of the intervention sessions.

TABLE 3 Summary of the pairwise comparisons from the Bayesian mixed model predicting RCS in the Flowers and Mixed Block.

	Estimate [lower.HPD, upper.HPD]	
Contrast	**Flowers block**	**Mixed block**
Measurement point T1		
CT – EFT NOFB	0.04 [−0.07, 0.14]	−0.04 [−0.12, 0.05]
CT – EFT FB	0.08 [−0.03, 0.19]	−0.01 [−0.10, 0.07]
EFT NOFB – EFT FB	0.05 [−0.06, 0.16]	0.02 [−0.06, 0.10]
Measurement point T2		
CT – EFT NOFB	−0.18 [−0.29, −0.07]	−0.16 [−0.24, −0.08]
CT – EFT FB	−0.25 [−0.36, −0.15]	−0.25 [−0.33, −0.17]
EFT NOFB – EFT FB	−0.07 [−0.19, 0.03]	−0.09 [−0.17, −0.00]

Note: Results are averaged over the levels of gender. The point estimate is displayed as the median. HPD interval probability is 0.95.

in magnitude from T1 to T2, with no difference in the magnitude of the difference between the groups (Figure 4a).

Mixed block

Below we present the pre-test–post-test results for the mixed block.

RCS

The pairwise comparisons of the estimated marginal means from the model predicting RCS showed that the groups did not differ from each other at T1 (Table 3). However, at T2, both EFT

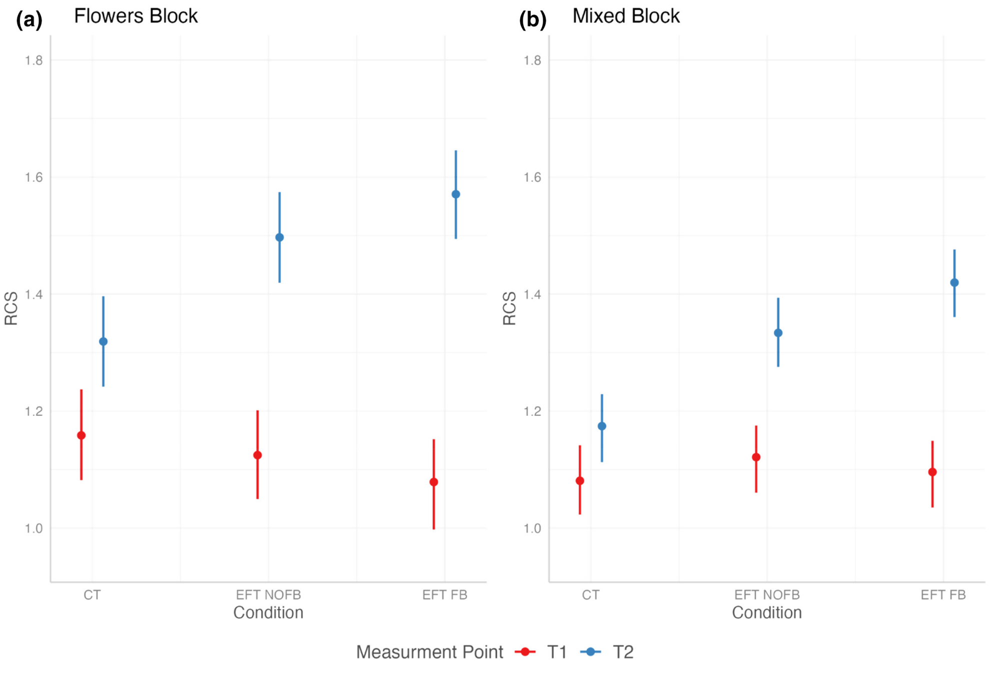

FIGURE 3 Predicted values of RCS in the (a) Flowers and the (b) Mixed Block. *Note*: The error bars represent 95% CI.

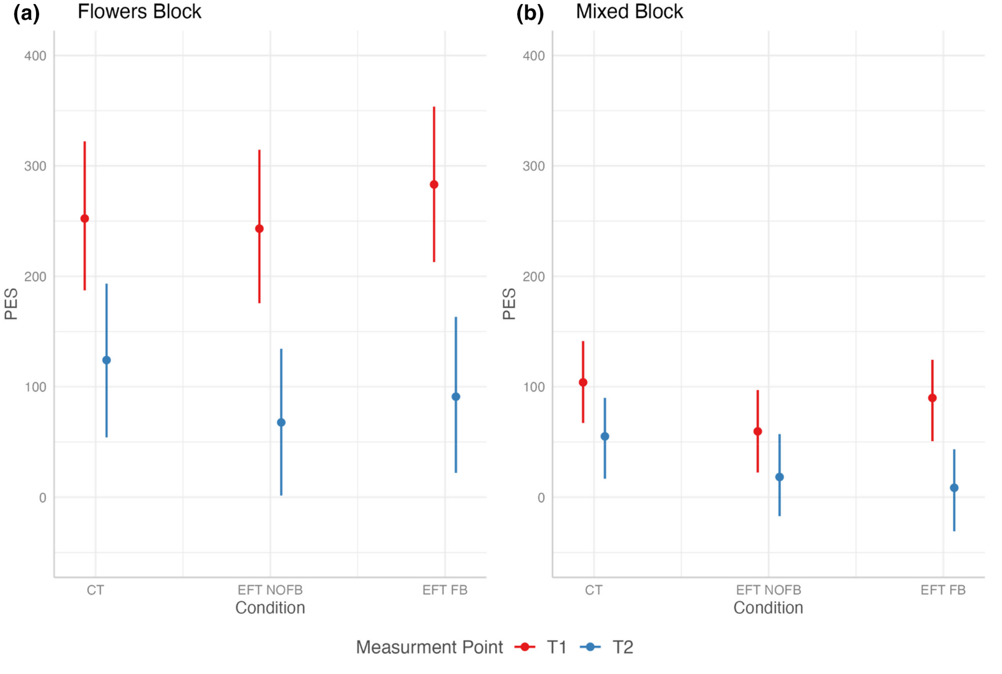

FIGURE 4 Predicted values of PES in the (a) Flowers and the (b) Mixed Block. *Note*: The error bars represent 95% CI.

FB and EFT NOFB groups scored higher than the CT group, and the EFT FB group scored higher than the EF NOFB group (Table 3). Moreover, all groups increased their RCS from T1 to T2 (Figure 3b).

PES

The pairwise comparisons of the estimated marginal means from the model predicting PES showed that the groups did not differ from each other either at T1 or T2. The change in PES from T1 to T2 also did not differ between the groups. However, PES significantly decreased only for the EFT FB group (Figure 4b).

Intervention results

The following results address whether the trajectories of children's RCS and PES in each block (incongruent, mixed and second-level mixed) throughout the 12 EF training sessions differ as a function of feedback.

RCS

The linear trends (slopes) for RCS as a function of session and for each group and the comparisons of the slopes between the groups are given in Table 4 and visualized in Figure 5. As seen in this table and figure, children in the EFT FB group showed a significant increase in RCS in all blocks, whereas children in the EFT NOFB group showed an increase only in the mixed block. The difference between the slopes of EFT FB and EFT NOFB groups (contrast) was significant in all blocks.

TABLE 4 Slopes of RCS as a function of session per group and slope differences between groups.

	Estimate [lower.HPD, upper.HPD]		
Block	**EFT FB**	**EFT NOFB**	**Contrast**
Incongruent	0.01 [0.01, 0.02]	−0.02 [−0.02, −0.01]	0.03 [0.02, 0.04]
Mixed	0.03 [0.02, 0.03]	0.01 [0.01, 0.01]	0.02 [0.01, 0.02]
Second-level mixed	0.02 [0.02, 0.03]	0.00 [−0.00, 0.01]	0.02 [0.01, 0.03]

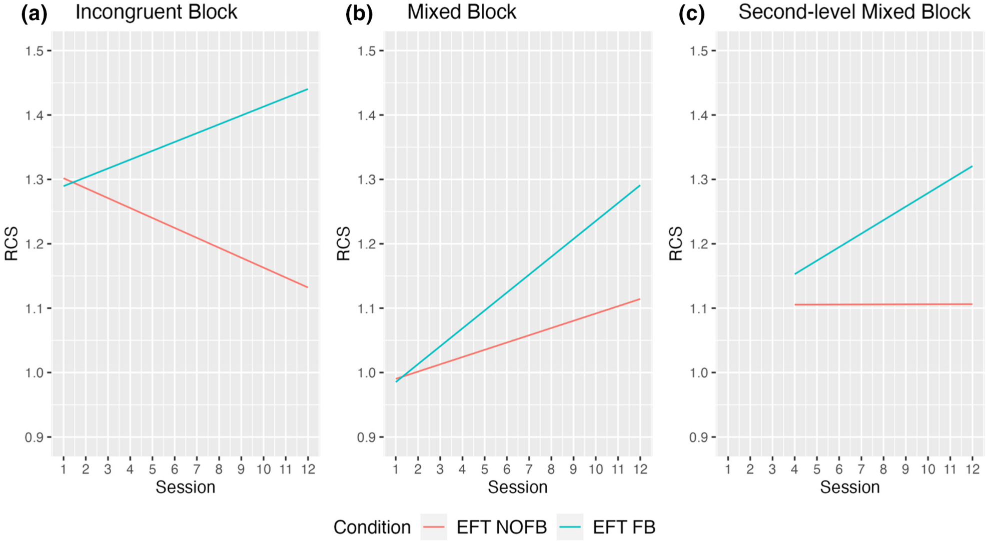

FIGURE 5 Predicted slopes of RCS in the (a) Incongruent, (b) Mixed and (c) Second-level mixed blocks.

PES

The linear trends (slopes) for PES as a function of session and for each group, and the comparisons of the slopes between the groups are given in Table 5 and visualized in Figure 6. As seen in this table and figure, only children in the EFT FB group showed a significant decrease in the magnitude of PES, and only in the mixed, and second-level mixed blocks. The difference between the slopes of the EFT FB and EFT NOFB groups (contrast) was significant only in the mixed block.

DISCUSSION

This study examined whether computerized EF training with feedback on errors and speed leads to improvements in an EF task to a greater extent than the same EF training without feedback or active control training in kindergarten children. Findings revealed that all three trainings increased children's accuracy per second (rate correct score; RCS) from pre- to post-test for both inhibition and shifting blocks of the EF task, however, EF training increased it more than the control training. Moreover, EF training with feedback increased it more than without feedback for the shifting block of the EF task. In addition, all three trainings reduced children's post-error slowing (PES) from pre- to post-test in the inhibition block, however, only the EF training with feedback reduced PES in the shifting block. In fact, in this block, EF training with and without feedback reduced it more than the control training, and EF training with feedback reduced it more than without feedback. Intervention results illustrated that the feedback gradually built up its effect throughout the 12 sessions of EF training. Specifically, RCS showed a steeper slope of increase with feedback, not only for the shifting but also for the inhibition block. PES was meaningfully reduced only with feedback, in the shifting block.

TABLE 5 Slopes of PES as a function of session per group and slope differences between groups.

	Estimate [lower.HPD, upper.HPD]		
Block	**EFT FB**	**EFT NOFB**	**Contrast**
Incongruent	−5.18 [−12.00, 1.72]	−0.18 [−6.40, 6.59]	−4.92 [−14.40, 4.89]
Mixed	−8.88 [−13.54, −4.24]	1.19 [−3.12, 5.40]	−10.10 [−16.10, −4.17]
Second-level mixed	−8.62 [−14.90, −2.60]	−4.01 [−9.70, 2.25]	−4.61 [−13.40, 3.98]

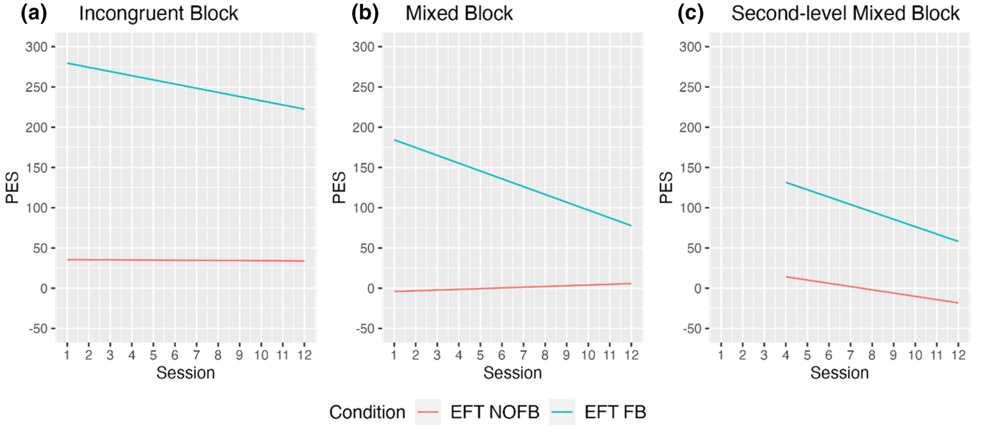

FIGURE 6 Predicted slopes of PES in the (a) Incongruent, (b) Mixed, and (c) Second-level mixed blocks.

This is the first study to show that giving children feedback on errors and response speed in a multi-trial EF task improves the shifting performance in a variant of that EF task. This aligns with and, in several ways, extends the handful of previous studies that documented feedback to be effective in improving the performance of children younger than 4 or 5 years old in various EF tasks (Bohlmann & Fenson, 2005; Oeri et al., 2019; Van Bers et al., 2014). First and foremost, previous work documented the benefit of feedback within a single testing session. In the present approach, we showed that when feedback was given over several sessions throughout a training programme, children were able to internalize this feedback and exhibit improved performance even when the feedback was no longer present during testing. Children presumably adopted a task approach where they systematically evaluated their responses for accuracy and adjusted their response speed accordingly. This resonates well with the importance of reflecting on one's own performance in promoting performance monitoring (Hadley et al., 2020; Zelazo & Carlson, 2020). Second, previous work has shown feedback to be effective only in children younger than 5. The current study shows that 5- to 7-year-old children also can benefit from repeated feedback over several sessions. Third, for shifting, giving feedback on the errors and response speed was similarly effective as giving feedback only on the correctness of answers (Bohlmann & Fenson, 2005; Van Bers et al., 2014). However, for inhibition, for which the current study did not find an additional effect of feedback, giving explicit feedback on the correct answers might be crucial (Oeri et al., 2019). Comparing the effectiveness of feedback on correct answers versus feedback on errors using an identical task could be an interesting future direction.

A previous study from our group did not find feedback to be effective in a training programme with six sessions, administered over 3 weeks with children 1 year older (Heemskerk & Roebers, 2024). The two main differences between this and the current study are the 1-year age difference and the doubled number of training sessions. Both factors could have contributed to the divergence of these findings, and with the current data, we cannot tease them apart. However, both factors are very likely to have contributed given the common finding in the EF literature that a greater amount of training results in more favourable outcomes (Scionti et al., 2020; Takacs & Kassai, 2019) and that computerized EF training is more effective in younger children (Cao et al., 2020). From the monitoring literature, we would expect that feedback facilitates self-monitoring which in turn may get automated over many practice sessions.

The improvement in performance due to feedback is reflected not only in the RCS (i.e., rate correct score – number of accurate responses per second) but also in PES (i.e., post-error slowing). PES is a good indicator of error monitoring and cognitive control. It has been receiving more attention in developmental literature recently. Yet this is the first study to show that training with feedback on errors and response speed reduces children's PES in a shifting task, keeping their rate correct constant. This suggests that feedback might help children adjust their response speed more efficiently throughout a multi-trial task, given that children can slow down less after errors without having to compromise their overall accuracy and speed. At the same time, children's PES was reduced in all groups in the inhibition task. This may suggest that when the task is not very demanding (inhibition is presumably easier than shifting), a quick adaptation to errors, and hence a smoother speed adjustment post-error, may be possible by merely solving the same task a second time. In contrast, for more demanding tasks, children of this age may require additional external feedback on errors and response speed to adapt their adjustments. Research shows that younger children show somewhat exaggerated post-error slowing compared to older children and adults, perhaps as an indication of developing cognitive control (Brewer & Smith, 1989; Dubravac et al., 2020, 2022; Roebers, 2022). Here, feedback may resemble the development by age because after training with feedback children showed reduced post-error slowing. However, it may not necessarily mean that less PES is better just because PES is reduced by increasing age. In fact, in kindergarten age, it has been shown that a greater PES is associated with higher overall accuracy (Ger & Roebers, 2023a). Future studies should reconcile these findings by focusing more on the mechanisms by which PES changes during development and what a reduction in the magnitude of PES may suggest.

What is important to keep in mind while interpreting the current improvements is that during the intervention, we used a variant of the EF task that we used for the pre- and post-assessments. This may suggest that the improvements we observed are task-specific, although the variation in stimuli between training and assessment was intended to mitigate the potential for mere rote learning. In fact, in each training session, children needed to make their decisions based on a new set of stimuli. Moreover, if the improvements observed post-training were solely due to automatization, we would expect no significant difference between the EF training groups with and without feedback at the post-test. However, the data show that the feedback group not only achieved higher RCS but also demonstrated less PES, suggesting that feedback provides a distinct advantage in enhancing how children engage with and perform the task. This indicates that the feedback does more than facilitating mere task familiarity; it actively contributes to the development of more effective task strategies and error monitoring. Our approach can therefore be considered more as a 'proof-of-principle' than just another intervention study that reveals informative effects for future interventions.

One strength of the current study is having an active control group that trained on a related but different ability (i.e., learning and memory) and similarly received feedback on the accuracy of answers. The better performance of children in the EF training groups compared to this control group ensures that the effects are not simply due to time, engaging in any training (i.e., cognitive stimulation), receiving feedback on the accuracy of responses, or any combination of these. Rather, it is the practice and the training where one receives feedback specifically on errors and response speed in a multi-trial speeded accuracy task. In addition, other general cognitive abilities, specifically, visuospatial WM and nonverbal intelligence, were controlled for in the analyses. This ensures that the observed improvements were due to the training itself and not to pre-existing individual differences in these general cognitive abilities. From an individual differences perspective, our results suggest that all children benefited similarly, independent of their visuospatial WM capacities or nonverbal intelligence. This is an important and practically relevant finding for the suitability of a computerized learning app.

A second strength lies in the feasibility of the current training programme. Our tablet computer-based training programme allows individualized training during class time, whereby children receive pre-recorded instructions through headphones. Hence, it requires less personnel and is practical to administer simultaneously to multiple children in small groups. The game-like nature of the tasks makes it very engaging, and children solve the tasks over several sessions with high motivation. With these features, such a training programme could be easily implemented in school settings and developed further into learning apps targeting a wide range of users.

Limitations and future directions

The current study has some limitations. First, we did not test for related skills at the post-test for practical reasons. Therefore, it is an open question whether the effects we found transfer to non-trained tasks tapping related cognitive skills such as WM. This also includes the real-world consequences of such training. Often the arbitrary and decontextualized nature of computerized training makes it difficult for the effects to transfer to real-world activities (Diamond & Ling, 2020). Second, we did not test for long-term effects. It is crucial to understand whether the cognitive gains persist over time, as this has implications for the educational practicality and effectiveness of the intervention in real-world settings. Spaced practice (i.e., shorter training sessions over longer training time) appears to result in longer-term effects than massed practice (Diamond & Ling, 2020). Our training constituted spaced practice with 20–25-min sessions over 6–8 weeks. In that sense, it could be expected to show longer-term effects, although this must be empirically tested. A promising future direction is to test the effect of feedback on various transfer tasks including real-world activities and conduct follow-up assessments.

CONCLUSION

Children learn from their mistakes when they repeatedly engage in a task, but particularly so when we provide them with feedback on these mistakes. This learning entails improving accuracy and speed as well as better adjusting the response speed after mistakes in a multi-trial cognitive task. The feedback is particularly effective when the task is to switch between different rules, rather than just to inhibit a pre-potent response. These findings imply that tablet computer-based EF training with feedback on errors and response speed may be helpful for children to develop an efficient orchestration of the involved sub-processes. Importantly, it was found to be feasible for implementation in school settings or development into learning apps to improve kindergarten children's EF in a certain task.

AUTHOR CONTRIBUTIONS

Ebru Ger: Conceptualization; writing – review and editing; formal analysis; project administration; methodology; visualization; writing – original draft; investigation; supervision. **Claudia M. Roebers:** Funding acquisition; conceptualization; writing – review and editing; project administration; methodology; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OSF at https://osf.io/p4k2r/.

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