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Hearts, flowers, and fruits: All children need to reveal their post-error slowing

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ABSTRACT

Slowing down responses after errors (i.e., post-error slowing [PES]) is an established finding in adults. Yet PES in young children is still not well understood. In this study, we investigated (a) whether young children show PES in tasks with different types of cognitive conflict and differing demands on executive functions, (b) whether PES is adaptive and efficient in the sense that it is associated with better task performance, and (c) whether PES correlates between tasks. We tested 4- to 6-year-old children on the Funny Fruits task (FF; $n = 143$), a Stroop-like task that incorporates semantic conflict and taxes children's inhibition skills, and the Hearts and Flowers task (HF; $n = 170$), which incorporates spatial conflict and taxes children's inhibition skills in its incongruent block and taxes both inhibition and cognitive flexibility (rule-switching) skills in its mixed block. A subgroup of children were tested on both FF and HF ($n = 74$). Results revealed that, first, children showed PES in FF and both blocks of HF, indicating that PES occurs in both types of conflict and under varying executive demands. Second, PES was associated with task accuracy, but only for FF and the mixed HF. Third, a between-task association in PES emerged only between FF and the mixed HF. Together, these findings indicate that PES is still a developing strategy in young children; it is present but only adaptive for, and correlates between, semantic inhibition and spatial flexibility.

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Introduction

In many everyday situations, we are faced with the challenge to flexibly modify our thoughts and behaviors in the face of conflicts, termed as *cognitive control* (Braver, 2012; Nigg, 2017). This challenge is there not only for adults but also already for young children. For instance, children need to inhibit their desire to run faster if this leads them to trip and fall on a gravel road.

Cognitive control is closely related to "lower-level" executive functions[1] (EFs) such as working memory, inhibition, interference control, and cognitive flexibility (set/task shifting or rule switching; Nigg, 2017). Children's ability to employ cognitive control predicts several life outcomes such as academic success and adult health and wealth (Blair & Razza, 2007; Moffitt et al., 2011). Researchers try to assess children's cognitive control in laboratory settings by using tasks that induce cognitive conflict and/or errors. Traditionally, children's average accuracy and reaction time in these tasks are used as indicators, with a consensus that the former is more suitable for younger children and the latter is more suitable for older children (Diamond et al., 2007). Nevertheless, recent attempts have challenged this tradition (Camerota et al., 2019, 2020). Going beyond these measures and more closely inspecting the course of a task on a trial-by-trial basis proves to be promising in understanding whether and how cognitive control is manifested in young children (Roebers, 2017).

One prominent indicator of cognitive control, derived from trial-by-trial performance adjustments, is post-error slowing (PES), namely, taking longer to respond after committing an error. PES is an established phenomenon in adults indicating error detection. Several studies suggest that it also already exists in children as young as 3 to 4 years of age, albeit in a more exaggerated fashion (Brewer & Smith, 1989; Dubravac et al., 2020; Fairweather, 1978; Gupta et al., 2009; Jones et al., 2003; McDermott et al., 2007; Smulders et al., 2016; Thaqi & Roebers, 2020). That is, younger children slow down more dramatically right after an error compared with older children and adults. PES seems to increase until around 7 to 9 years of age and then starts to decline until adolescence (de Mooij et al., 2022; Gupta et al., 2009; Jones et al., 2003; Schachar et al., 2004). Children appear to initially employ reactive control and start to employ the more efficient proactive control (i.e., find a good speed of responding by balancing speed and accuracy from the beginning) only from 8 years of age onward (Chevalier et al., 2015; Niebaum & Munakata, 2020). As another indication of more efficient post-error adjustment, the variability in response times decreases from 5 to 15 years of age (Brewer & Smith, 1989).

Domain-general versus domain-specific accounts of cognitive control

Whether cognitive control is a domain-general or domain-specific ability from the outset is a curious question developmental psychologists can address by studying children. At least two dimensions of cognitive control may be informative in studying this: the type of control component and the type of cognitive conflict. PES in children has often been assessed using a single cognitive control task with a certain type of conflict, which taxes a certain type of control component. However, in young children, it remains largely unknown whether PES occurs in different types of tasks and conflicts that show different developmental timelines.

The preschool age and kindergarten age are critical in the development of PES because cognitive control shows rapid developmental progression (Gerardi-Caulton, 2000; Jones et al., 2003; Reed et al., 1984; Zelazo & Jacques, 1997). Importantly, the developmental trajectories of the different components of cognitive control, such as inhibitory control and cognitive flexibility, exhibit differences (Anderson, 2002; Davidson et al., 2006; Diamond, 2013); for example, flexibility shows a more protracted developmental progression than inhibition.

Children's efficiency of control in *semantic conflict* continues to develop throughout childhood and into adulthood (e.g., Jongen & Jonkman, 2008) and shows a significant increase only from 8 years of age onward, but not at 4 to 8 years (Archibald & Kerns, 1999; Macdonald et al., 2014), whereas

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[1] "Higher-level EF" includes reasoning, problem solving, and planning.

significant improvements in control in the face of *spatial conflict* is already observed at 6 to 11 years of age (Cao et al., 2013; Davidson et al., 2006; Roebers, 2022).

Domain-general models of cognitive control, such as Botvinick et al.'s (2001) conflict-monitoring model, propose an all-encompassing conflict-control mechanism that can be employed to handle different types of conflicts. In this model, the anterior cingulate cortex (ACC) is responsible for conflict detection and the prefrontal cortex is responsible for executive control (Botvinick et al., 2001). Various types of conflict are proposed to similarly activate these brain regions because of a shared module of cognitive control.

Supporting domain generality, research has shown that adults show control adjustments after conflicts—in other words, *post-conflict slowing*—across different conflicts (Freitas et al., 2007). Similarly, 5- to 7-year-old children were found to show post-conflict slowing consistently in three different tasks: Simon, Stroop, and Flanker (Ambrosi et al., 2016). *Post-error slowing* was also observed in tasks with demands on different cognitive control components and conflicts; for example, adults showed PES in both the Simon task, taxing cognitive flexibility in spatial conflict, and the Stroop task, taxing inhibition in semantic conflict (Dubravac et al., 2020; Forster & Cho, 2014; Notebaert & Verguts, 2011; Roebers, 2022; Wang et al., 2016). In children, only one previous study examined whether PES generalizes across distinct task demands with differing conflicts (Dubravac et al., 2022). This study tested children aged 8, 10, and 12 years and consistently found PES across three tasks: Stroop (Funny Fruits), Simon, and Flanker. Further supporting the generality of PES, the pattern of PES was similar across tasks in terms of temporal and developmental trajectories. That is, in all three tasks younger age groups similarly showed a larger slowing in the first post-error trial and a steeper decrease in slowing in the second post-error trial compared with older age groups. PES in the Stroop task was reported to be slightly higher than in the other two tasks, which was attributed to the lower error rates in the Stroop.

In contrast, domain-specific models of cognitive control, such as Kornblum's (1994) dimensional overlap (DO) model, propose that specific conflict-control mechanisms are employed for different types of conflict. For example, the conflict in the Stroop task emerges from the incongruence between task-relevant (e.g., ink color) and task-irrelevant (e.g., word meaning) stimulus features (stimulus–stimulus [S-S] conflict) (Egner, 2007; Li et al., 2017). The conflict in a Simon task emerges from the incongruence between a task-irrelevant stimulus feature (e.g., the location of the stimuli) and a response feature (e.g., press on a certain button) (stimulus–response [S-R] conflict; Egner, 2007). The mechanisms involved in processing these S-S and S-R conflicts are assumed to differ (Egner, 2008). In line with this, spatial conflict is detected faster in the brain compared with semantic conflict (Donohue et al., 2016). A recent meta-analysis of functional magnetic resonance imaging (fMRI) studies investigating S-S and S-R conflict processing (Li et al., 2017) showed that both types of processing employ common neural networks, specifically fronto-parietal and cingulo-opercular networks. However, they were also distinguished by the use of distinct neural substrates and functions. S-S conflict processing, which is often involved in semantic conflicts, was associated with different brain regions (inferior frontal cortex, superior parietal cortex, superior occipital cortex, and right anterior cingulate cortex) than those associated with S-R conflict processing (left thalamus, middle frontal cortex, and right superior parietal cortex), which is often involved in response inhibition and spatial attention. The authors thus suggested a hybrid model of cognitive control that involves both global (domain-general) and modular (domain-specific) components.

Supporting a domain-specific account, post-conflict slowing was found to be specific to the nature of the conflict in adults (Funes et al., 2010). In children, one study with 12-year-olds found Flanker (i.e., response interference) and Simon (i.e., spatial conflict) tasks to differ in modulations of control (Stins et al., 2008). To our knowledge, however, no study has found evidence for domain specificity of PES in younger children.

Prior evidence supporting either account of cognitive control exists, and hence findings are inconclusive. More central to our focus, the extent of the generality of PES is not well known in younger children. There appears to be more evidence in line with a domain-general model of cognitive control in children aged 5 years and older as outlined above. Nevertheless, during early childhood, cognitive control is still developing and has not yet reached a mature state (Gerardi-Caulton, 2000; Jones et al., 2003). Therefore, PES as an indicator of cognitive control may also be fragile and observable only under certain contexts and for certain conflicts, supporting a domain-specific account. Another overlooked aspect concerning domain generality versus domain specificity is examining control adjustments in different tasks on the individual level, going beyond the group level, namely, whether an individual's control adjustments in one task correlate with the individual's control adjustments in another task.

In the current study, we investigated inhibition and cognitive flexibility (rule switching) demands in the contexts of spatial or semantic conflict. We used the Funny Fruits task (FF; Dubravac et al., 2022; Oeri et al., 2020) as a semantic conflict (S-S) task that requires mainly inhibition in its critical block. It also represents conflict between perceptual information, the visible color of a fruit stimulus, and semantic (conceptual) information, the fruit's actual color, that must be retrieved from memory. We used the Hearts and Flowers task (HF; Wright & Diamond, 2014) as a spatial conflict (S-R) task, which requires mainly inhibition in its incongruent block and both inhibition and flexibility (and working memory) in its mixed block. It also presents conflict between a perceptual dimension, the location of the stimulus, and a motor dimension, the response side. We make two new contributions by examining, first, in what types of conflicts and executive demands young children show PES and, second, whether an individual's PES in one task is associated with the individual's PES in another task.

A domain-general account would predict PES to be observed in, show a similar temporal trajectory in, and correlate between all tasks. A domain-specific account would expect PES to show differences between tasks with either different control requirements or different types of conflicts. Accordingly, on the type of control dimension, the mixed HF, which requires additional cognitive flexibility, may dissociate (i.e., show a different pattern of presence, temporal trajectory, and correlations) from the flowers HF and FF, which only require inhibition. Or on the type of conflict dimension, FF, which poses semantic conflict, may dissociate from the flowers and mixed blocks of HF, which pose spatial conflict.

Nature of PES in children

An additional focus of this study that is rarely studied in the literature was the nature of PES in children. PES is commonly interpreted for both adults and children to be an indicator of individuals monitoring their performance and adjusting their speed after an error is detected to respond accurately (Arnett et al., 2021; e.g., Botvinick et al., 2001; Brewer & Smith, 1989). Researchers have further suggested that cognitive control mechanisms are adaptive and self-regulating (Botvinick & Cohen, 2014). This would mean that PES is adaptive to optimize the speed–accuracy trade-off; that is, slowing down after errors helps to regain focus on being accurate. Accordingly, better PES is often found to be associated with better post-error accuracy (Hajcak et al., 2003) and better overall task accuracy, which indicate better cognitive control (Steinborn et al., 2012). Although there are several accounts to explain the mechanisms underlying PES and not all propose that it is adaptive (Danielmeier & Ullsperger, 2011; Dutilh, Vandekerckhove, et al., 2012; Notebaert et al., 2009), there is considerable empirical evidence for its adaptive nature in adults (Arnett et al., 2021; Dutilh, Vandekerckhove, et al., 2012; Klein et al., 2007; Nieuwenhuis et al., 2001; Steinhauser et al., 2017).

In young children, however, it is unclear not only whether PES occurs but also whether any observed PES is adaptive. Given that important advances are taking place in cognitive control skills in general during preschool age (Carlson, 2005; Davidson et al., 2006; Rueda et al., 2004) and are especially pronounced at 4 to 6 years of age (Roebers et al., 2011; Röthlisberger et al., 2010), a greater slowing may be indicative of better development in cognitive control skills (Steinborn et al., 2012). In turn, greater slowing at these critical ages of cognitive control development may be expected to be more adaptive and thus associated with higher task accuracy (Jones et al., 2003; Tamnes et al., 2013).

To our knowledge, there is only one previous study that sampled children younger than 6 years to examine whether PES was adaptive (de Mooij et al., 2022). In children aged 5 to 13 years, not only was PES found in several different games where math (e.g., counting, division) and language (e.g., vocabulary, spelling) were practiced, but also greater PES was found to be associated with greater post-error accuracy and overall ability level in a game. PES was also found to be negatively associated with time pressure (i.e., the more time given to respond from 8 to 60 s, the more PES) and error speed (i.e., greater PES when the reaction time of the error was slower than the median reaction time of pre-error correct trials), and was greater in mathematics-related activities than in language-related activities. This suggests that although PES may be observed in various tasks and may be adaptive, different task contents may also lead to differences in the magnitude of PES (see also Dubravac et al., 2022).

Currently, it is not known whether different cognitive control components, such as inhibition and cognitive flexibility; and different domains of conflict, such as semantic and spatial conflict, play a role in the manifestation of PES in young children and specifically children younger than 6 years.

The current study

This study focused on PES in 4- to 6-year-old children and addressed three research questions: (1) whether PES occurs in only specific tasks with specific types of conflict or whether it may manifest itself in different types of conflict and show a similar temporal trajectory (adaptations of response speed beyond the first trial after the error), (2) whether PES is adaptive in the sense that it is associated with better task performance and whether it is adaptive for only certain tasks or conflicts, and (3) whether individuals' PES in different types of tasks and conflicts correlate with each other. We hypothesized, based on previous evidence pointing to a domain-general control mechanism (Botvinick et al., 2001) and empirical evidence in children in favor of that (de Mooij et al., 2022; Dubravac et al., 2022), that (1) PES would occur in FF and both blocks of HF and show a similar temporal trajectory across tasks. Again, following a domain-general account and based on empirical evidence pointing to the adaptive nature of PES in both adults (Dutilh, Vandekerckhove, et al., 2012) and children (de Mooij et al., 2022), we expected that (2) PES would be associated with task accuracy for FF and both blocks of HF. Finally, we expected (3) correlations between each of the three tasks. However, given that cognitive flexibility includes not only inhibition but also working memory and thus shows a later and longer developmental progression than inhibition (Anderson, 2002; Davidson et al., 2006; Diamond, 2013), we expected the correlation in PES between the two tasks that exclusively tax inhibition (i.e., FF and the flowers HF) to be stronger.

Method

Participants

The data came from the pretest measurement of a larger intervention project. Children aged 4 to 6 years were tested on HF (n = 143) and FF (n = 170). Of these two samples, a subsample was jointly tested on both tasks (n = 74). Table 1 presents the characteristics of each sample. An additional 18 children in the HF sample were tested but excluded from the analyses because they had no error in any of the blocks (n = 1), had 40% or more errors in any of the blocks (n = 15), did not complete the task (n = 1), or were outside of the target age range (n = 1).[2] An additional 9 children in the FF sample were tested but excluded from the analyses because they had no error (n = 2) or had 40% or more errors (n = 5) in the critical incongruent block or were outside of our target age range (n = 2). We excluded the children who did not make any errors because we would not be able to calculate PES measures for them. We excluded the children who made many errors ($\geq$ 40%) to ensure including only those who understood the task well. Children were recruited from urban and rural areas of central Switzerland and came predominantly from families of lower- to upper-middle class. Recruitment was carried out by contacting kindergarten teachers who were interested in participating. Written informed consent was obtained from the parents of participating children. The study was approved by the local ethics committee and was conducted in accordance with the Declaration of Helsinki.

Tasks

Hearts and Flowers task

An adapted version of HF (Diamond et al., 2007) was used. The flow and stimuli of the flowers and mixed block of the task are presented in Fig. 1A. In this task, children needed to press either the left or

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[2] In Switzerland, children normally attend 2 years of kindergarten and go through an assessment at the end of the second kindergarten year to determine whether they are ready to start primary school or should repeat a further year in kindergarten. In our sample, those over 80 months of age were attending their third year and were excluded considering that this extra year of kindergarten might have an influence on their cognitive skills.

Table 1
Sample characteristics.

Sample	N	Mean age in months (*SD*)	Age range	% Female
Hearts and Flowers	143	66.6 (7.14)	52–79	46
Funny Fruits	170	66.5 (6.97)	52–79	48
Joint subsample	74	66.7 (6.63)	53–78	46

right external button, depending on the prompting stimulus (a heart or a flower) that appeared on the screen. The task consisted of three blocks in the following fixed order: a congruent block with a heart, an incongruent block with a flower, and a mixed block with both congruent (heart) and incongruent (flower) trials. In the congruent (hearts) block, there were 12 heart trials. In each heart trial, children saw a heart on either the left- or right-hand side of the screen and were asked to press the button on the corresponding side (i.e., press the left button if the heart appears on the left and vice versa). The hearts block served to establish a prepotent response of pressing the same side. In the incongruent (flowers) block, there were 36 flower trials. In each flower trial, children saw a flower on either the left- or right-hand side of the screen. This time, they were asked to press the button on the opposite side (i.e., press the left button if the flower appears on the right and vice versa). The flowers block served to induce spatial conflict. In the mixed block, 48 heart (congruent) and 12 flower (incongruent) trials were presented in a pseudo-randomized order, with the constraint that a flower trial always came in between two heart trials or followed a heart trial as the last trial. The mixed block is assumed to trigger rule switching.

Instructions and four practice trials for each of the hearts, flowers, and mixed blocks preceded the test trials. Trials lasted until children gave a response. For each trial, the accuracy and reaction time (RT) of the response were recorded.

Funny Fruits task

This is a semantic conflict task consisting of three blocks presented in the following fixed order: baseline, congruent, and incongruent. The flow and stimuli of the critical incongruent block of the task is presented in Fig. 1B. The baseline and congruent blocks consisted of 24 trials each, and the incongruent block consisted of 48 trials. In each trial, first, a target stimulus appeared at the center of the screen. After a brief inter-trial interval, two choices appeared on either side of the screen and remained on the screen until children pressed one of them by touching it with their index fingers. In all the blocks, the two choices were a red square and a yellow square. In the baseline block, the target stimulus was a colored square (red or yellow), and children were asked to choose the square with the matching color. In the congruent block, the target stimulus was a fruit in its usual color (red strawberry or yellow banana), and children were again asked to choose the square with the matching color. These two blocks were aimed at establishing a prepotent response and inducing a cognitive conflict in the final incongruent block. In the incongruent block, the target stimulus was a fruit in the wrong color (yellow strawberry or red banana), and children were this time asked to choose the square that matched the actual color of the depicted fruit (red banana: choose yellow). We adapted the four choice options used in previous studies (Dubravac et al., 2022; Oeri et al., 2020) into two options to make the task more suitable for younger children. Before each block started, participants did four practice trials in which they received online feedback from the experimenter. Specifically, when children made more than two errors in these practice trials, the experimenter explained the rules to them again, and then they did another round of four practice trials.

Procedure

Children were tested individually in a quiet room in their kindergarten by a trained experimenter. Children solved both tasks on a tablet computer by responding either with finger touch (Funny Fruits) or via a pair of external response buttons connected to the tablet (Hearts and Flowers). The tasks were administered on 2 different days, with a maximum delay of 8 days in between the two sessions. For children who were tested on both HF and FF, the order of these tasks was counterbalanced because this study was part of a larger intervention study where counterbalancing task order is common.

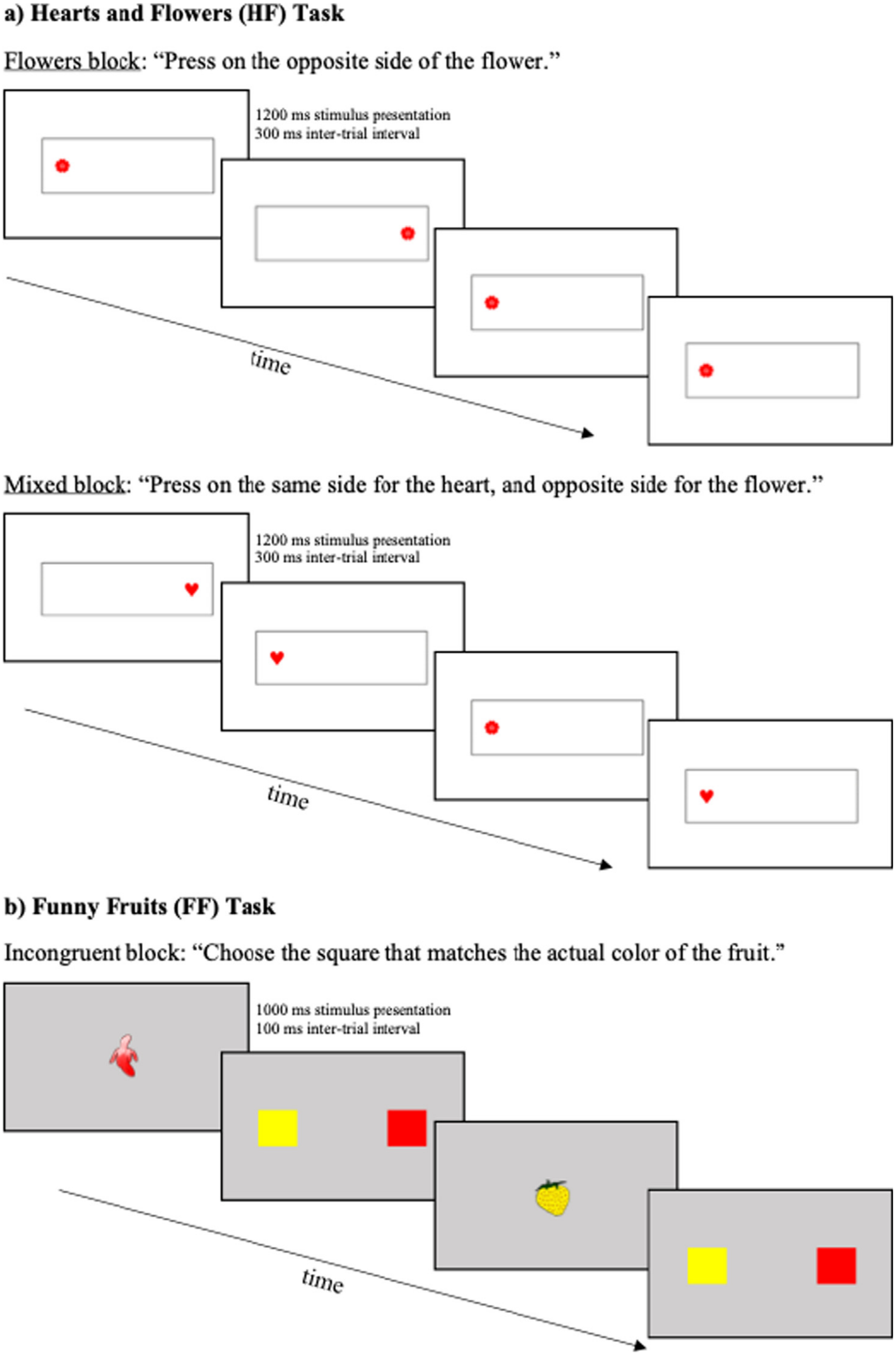

Fig. 1. Schematic representation of the Hearts and Flowers and Funny Fruits tasks.

Data analysis

All analyses were carried out in R Version 4.0.2 (R Core Team, 2020). The data from the flowers and mixed blocks of HF and from the incongruent block of FF were analyzed (The data and analysis script can be found on the Open Science Framework at https://osf.io/kpshq/.) Practice trials were not included in the analyses. RT and accuracy measures (as a percentage score: the number of correct trials divided by the total number of trials) were used. For both HF and FF, trials with RTs greater than 4000 ms were removed for being outliers, and trials with RTs less than 250 ms were removed for being too fast to be responses to the stimuli (Davidson et al., 2006; Wright & Diamond, 2014). Table 2 shows the numbers and percentages of removed trials and the numbers and percentages of children from which these trials were derived for both tasks. After these removals, 7961 trials from FF and 15,128 trials from HF were analyzed.

To answer our Research Questions 1 and 2, we conducted two sets of PES analyses. In the first set of PES analyses, we analyzed the temporal trajectory of PES. To do so, we first determined error trials that were followed by four consecutive correct trials. These trials were respectively categorized as E, E + 1, E + 2, E + 3, and E + 4, and they constituted five levels of a new variable we created as trial type. Then we categorized children's task accuracy as low or high accuracy within each block based on a median split. The median values and the number of children in each accuracy group are shown in Table 3. This binary grouping constituted a task accuracy variable. We ran three separate mixed linear models to examine whether RT changed as a function of trial type and task accuracy when controlling for age, for FF, the flowers HF, and the mixed HF, respectively. In these mixed models, participants were entered as the random intercepts, and trial type, task accuracy, and age were entered as fixed effects. Comparisons of models with and without the interaction term were used to determine whether there was a significant interaction effect. Significant effects were analyzed further with Tukey-corrected post hoc mean comparisons using the *emmeans* package in R (Lenth et al., 2022).

In the second set of PES analyses, we calculated PES using the traditional method of subtracting individuals' mean RT of correct trials following correct trials from their mean RT of correct trials following error trials (Dutilh, van Ravenzwaaij, et al., 2012). We first checked whether this PES estimate for each of the blocks was significantly above 0 using separate one-tailed one-sample *t* tests to more confidently conclude whether children engaged in PES. Then we carried out separate Pearson correlations to check whether this estimate of PES correlated with the accuracy for FF and the flowers and mixed blocks of HF, respectively. To answer our Research Question 3, we checked whether there were cross-correlations between PES in these three tasks using the subset of our sample who were tested on both FF and HF. That is, we ran separate Pearson correlations between PES in the mixed HF and flowers HF, the mixed HF and FF, and the flowers HF and FF, respectively. In this set of analyses, missing values

Table 2
Removed trials.

Task	*n* (%) trials	Derived from *n* (%) children
	>4000 ms	
Hearts and Flowers	208 (1.3%)	88 (62%)
Funny Fruits	123 (1.5%)	65 (38%)
	<250 ms	
Hearts and Flowers	108 (0.7%)	49 (34%)
Funny Fruits	76 (0.9%)	33 (19%)

Table 3
Median accuracy and numbers of children in accuracy groups based on median splits.

Task	Median accuracy	*n* low accuracy	*n* high accuracy
Funny Fruits	.89	85	85
Flowers block of Hearts and Flowers	.94	81	62
Mixed block of Hearts and Flowers	.90	73	70

that emerged because some children did not have post-error trials (i.e., no error was committed in one of the HF blocks or the post-error trial was removed because of its outlying RT) were handled via pairwise deletion.

Results

Descriptive statistics for children's accuracy and RTs in both tasks are given in Table 4 and visualized in Fig. 2. Preliminary analyses revealed that there were no gender differences in accuracy or RTs in either of the tasks. For the joint subsample, accuracy, RT, and PES measures did not differ depending on the task order in any of the tasks.

Table 4
Descriptive statistics for accuracy and RTs in HF and FF tasks.

	HF				FF	
	Flowers		Mixed			
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Accuracy	.92	.08	.88	.08	.88	.08
RT (ms)	1033.85	206.33	912.10	157.85	1221.63	258.09

Note. RT, reaction time; HF, Hearts and Flowers task; FF, Funny Fruits task.

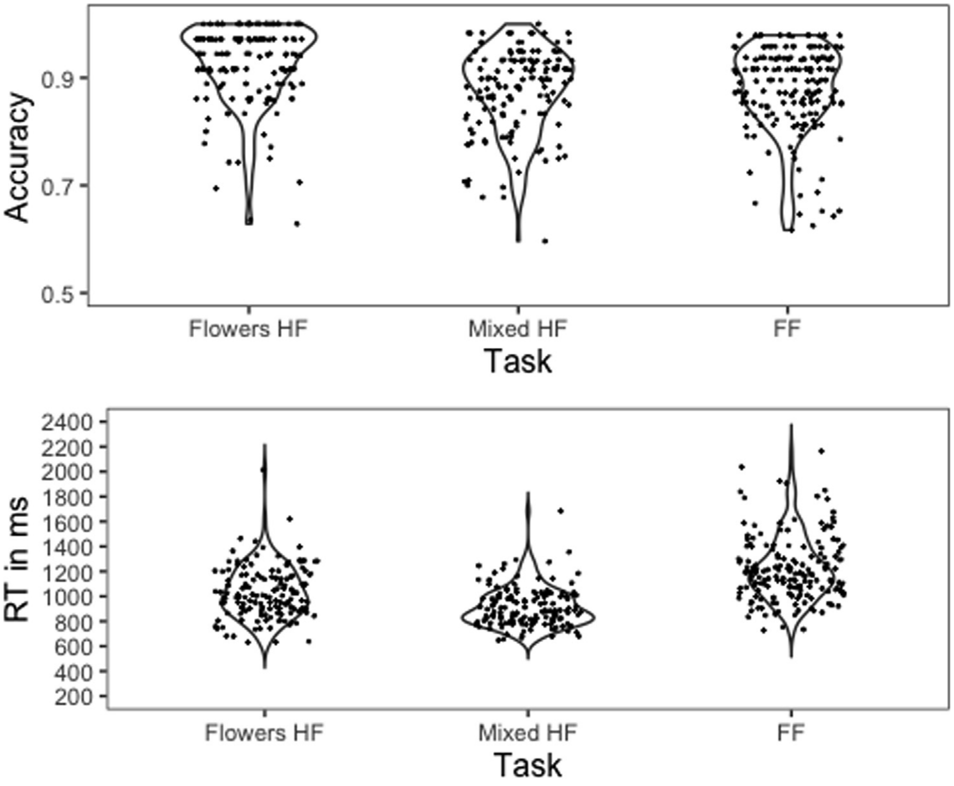

Fig. 2. Distribution of mean accuracy (top) and mean reaction times (bottom) in Hearts and Flowers (HF) and Funny Fruits (FF) tasks.

First set of PES analyses

Fig. 3 shows the RTs as a function of trial type and task accuracy for FF, the flowers HF, and the mixed HF. The analyses revealed a significant interaction between task accuracy and trial type on RT in FF, $\chi^2(4) = 10.81$, $p = .03$, and the mixed HF, $\chi^2(4) = 23.15$, $p < .001$, but not in the flowers HF, $\chi^2(4) = 2.12$, $p = .71$.

Post hoc comparisons for FF revealed no differences in the RTs between the high- and low-accuracy groups in any of the trials. For both the high- and low-accuracy groups, E + 1 and E + 2 trials were slower than the error trial (E; $p < .0001$, .05, respectively for high-accuracy; $p < .0001$, .001, respectively for low-accuracy). However, although E + 3 and E + 4 were still slower than the error trial for the high-accuracy group ($p < .05$, .01, respectively), they were not different from the error trial for the low-accuracy group. For the high-accuracy group E + 2, E + 3, and E + 4 all were faster than E + 1 (all *ps* < .0001), whereas for the low-accuracy group only E + 3 and E + 4 were faster than E + 1 ($p < .0001$, .001, respectively).

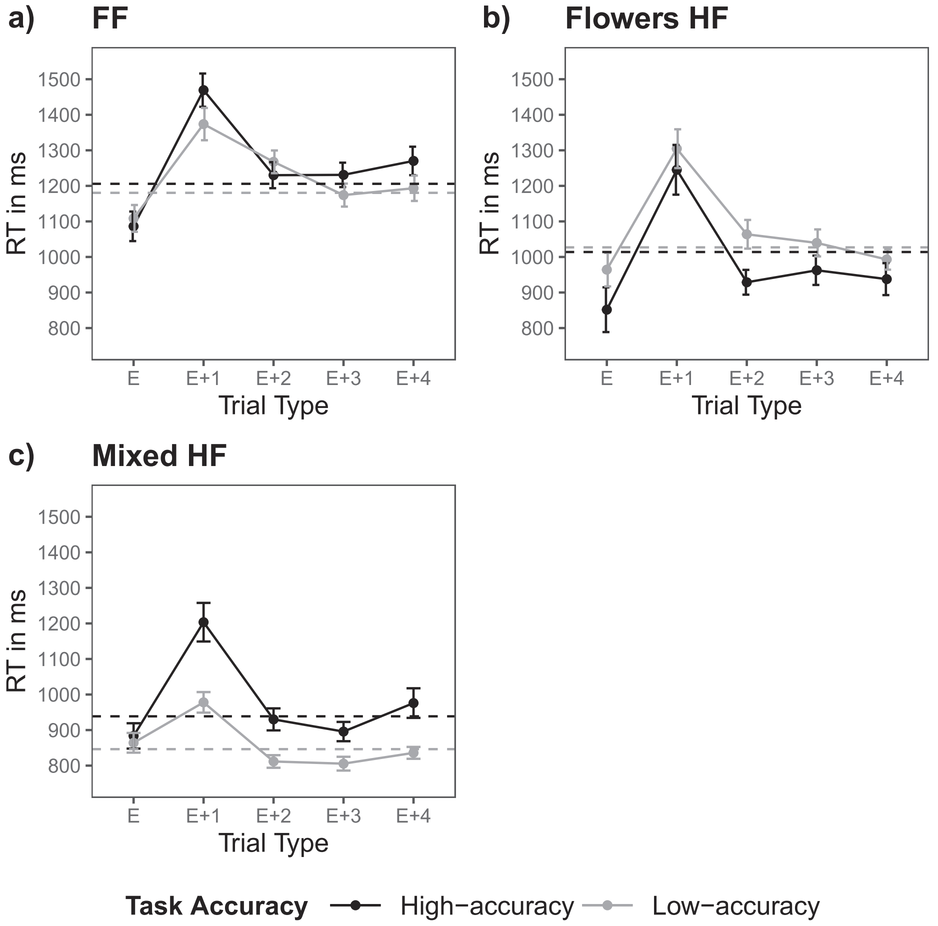

Fig. 3. Reaction times (RTs) as a function of trial type and task accuracy for the Funny Fruits (FF) task (A), flowers block of Hearts and Flowers (HF) task (B), and mixed block of HF task (C). Dashed horizontal lines represent the average RT of post-correct trials.

Post hoc comparisons for the flowers HF revealed no differences in the RTs between the high- and low-accuracy groups. E + 1, E + 2, and E + 3 were slower than E (p < .0001, .05, .05, respectively), and E + 2, E + 3, and E + 4 all were faster than E + 1 (all *ps* < .0001).

Post hoc comparisons for the mixed HF revealed differences in the RTs between the high- and low-accuracy groups only in the E + 1 trial, where the high-accuracy group was slower (p < .0001). For both the high- and low-accuracy groups, only E + 1 was slower than E (p < .0001, .01, respectively), and E + 2, E + 3, and E + 4 all were faster than E + 1 (all *ps* < .0001).

Second set of PES analyses

PES was significantly above zero for FF (M = 232, SD = 337), $t(169)$ = 9.00, p <.0001, the flowers HF (M = 282, SD = 372), $t(113)$ = 8.09, p <.0001, and the mixed HF (M = 182, SD = 288), $t(140)$ = 7.51, p <.0001. PES was also positively correlated with accuracy in FF, $r(168)$ =.16, p =.04 (Fig. 4A), and the mixed HF, $r(139)$ = .19, p = .03 (Fig. 4C), but not in the flowers HF, $r(112)$ = $-$.04, p =.70 (Fig. 4B).

Cross-correlation analyses of PES between tasks revealed that there was no correlation between PES in the flowers and mixed blocks of HF, $r(111)$ =.08, p =.39 (Fig. 5A). However, PES in FF was correlated with PES in the mixed HF, $r(70)$ =.24, p =.04 (Fig. 5B), but not in the flowers HF, $r(51)$ = $-$.07, p =.64 (Fig. 5C).[3]

Results from the flowers HF revealed a different pattern of PES in its relation to accuracy and in between-task correlations. This was contrary to our prediction based on a domain-general account, which would predict PES to be correlated with accuracy in all three tasks and PES to be correlated across all three tasks. Considering an alternative explanation that task difficulty might play a role in this pattern, we sought to compare the average accuracy in the flowers HF with the other two tasks as a follow-up exploratory analysis. A paired Wilcoxon test showed that the accuracy in the flowers HF was significantly higher than that in the mixed HF (V = 8247, p <.0001, effect size r =.54; see Table 4 for the descriptives). A two-samples Wilcoxon test showed that the accuracy in the flowers HF was also significantly higher than that in FF (V = 16862, p <.0001, effect size r =.33; see Table 4 for the descriptives).

Discussion

This study investigated the presence and nature of PES in children aged 4 to 6 years in cognitive conflict tasks that differ in the type of conflict and the type of cognitive control demand. The findings were threefold. First, in line with our hypothesis, PES was revealed across tasks and conflicts: in both the flowers (incongruent) and mixed blocks of HF, demanding inhibition, and inhibition and cognitive flexibility, respectively, in spatial conflict; and in FF, demanding inhibition in semantic conflict. This indicated the manifestation of error detection and cognitive control in the form of PES as well as the presence of PES across different kinds of cognitive conflict in young children. Yet there were some differences in the extended PES trajectories across tasks. Namely, in the flowers HF, high- and low-accuracy groups similarly slowed down after an error and speeded up after the first post-error trial. In the mixed HF, the high-accuracy group slowed down more after an error, but both groups similarly speeded up after the first post-error trial to the level of the error trial. In FF, both high- and low-accuracy groups slowed down to a similar extent in the two consecutive trials immediately following an error. However, the high-accuracy group speeded up more quickly after the first post-error trial yet remained slower than the error trial for more subsequent trials. Second, regarding its adaptive nature, PES was associated with task accuracy in FF and the mixed HF. But in contrast to our hypothesis, this was not the case in the flowers HF. Third, in contrast to our hypothesis, a between-task association in PES emerged only between FF and the mixed HF.

This is the first study to show the presence of PES in 4- to 6-year-old children across inhibition and cognitive flexibility demands and across spatial and semantic conflict. This finding is in line with

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[3] The pattern of results from the second set of analyses remained the same using alternative exclusion criteria. For the details and results, refer to https://osf.io/kpshq/.

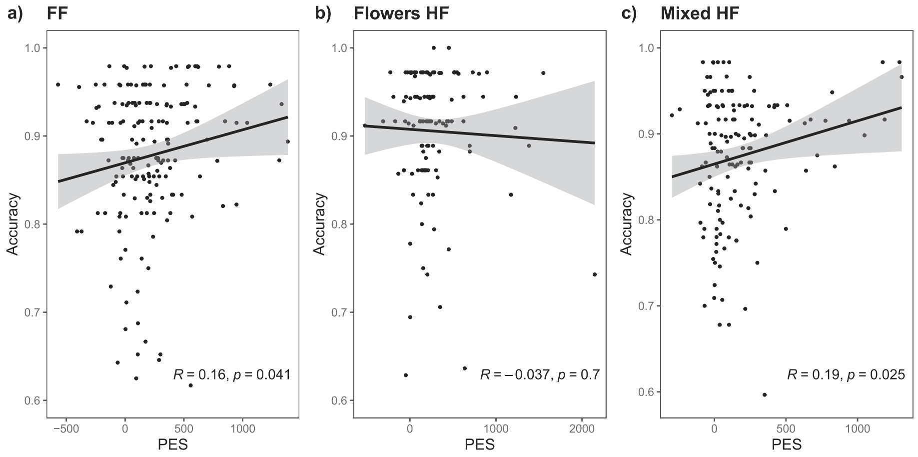

Fig. 4. Relations between post-error slowing (PES) and accuracy: (A) Funny Fruits (FF) task; (B) flowers block of Hearts and Flowers (HF) task; (C) mixed block of HF task.

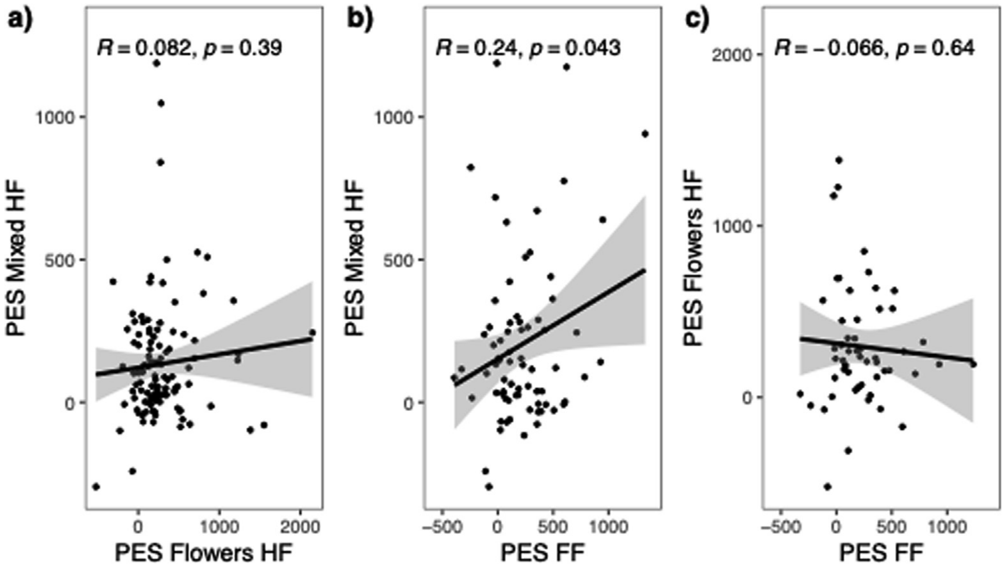

Fig. 5. Relations between post-error slowing (PES) in A) mixed HF and flowers HF, B) mixed HF and FF, and C) flowers HF and FF.

previous research with adults (Forster & Cho, 2014; Notebaert & Verguts, 2011; Wang et al., 2016) as well as with Dubravac et al. (2022), who similarly found PES to occur across Simon, Stroop, and Flanker tasks at 8, 10, and 12 years of age. PES has so far been observed earliest around 3 to 4 years of age (Jones et al., 2003). Taken together with the current findings with 4- to 6-year-olds, it is likely that from its very emergence onward PES is a control mechanism with some domain-general qualities that transcend different conflicts and task demands, in line with Botvinick et al.'s (2001) conflict-monitoring model.

Yet not all our predictions based on a domain-general account were confirmed. Specifically, our findings revealed finer differences in the extended temporal trajectory of post-error trials, in contrast to Dubravac et al. (2022), who found a similar trajectory across three tasks despite a descriptively larger magnitude of PES in the Stroop task (FF). Some of these differences in the PES trajectory emerged as a function of task accuracy (low accuracy vs high accuracy) and therefore pose some implications about the adaptive nature of PES, which we discuss further below.

In the current study, the trajectory of PES overlaps well with the established finding that young children show exaggerated PES (e.g., Dubravac et al., 2020; McDermott et al., 2007; Smulders et al., 2016; Thaqi & Roebers, 2020). Children in our study generally slowed down considerably in the first post-error trial but very quickly returned to responding very fast. However, there were also differentiations between high- and low-accuracy children, which gives us some insight into whether and in which tasks PES may be adaptive. In particular, the PES trajectory in the flowers HF was independent of task accuracy, hinting that PES was not adaptive for the type of spatial inhibition this task required. In contrast, in the mixed HF, high-accuracy children showed a greater slowing than low-accuracy children, although only in the first post-error trial. This suggests an immediate but not long-lasting adaptivity of PES for cognitive flexibility in the face of spatial conflict. Finally, in FF, although no differences emerged between the RTs of the high- and low-accuracy groups in any of the post-error trials, the high-accuracy group maintained its slowed-down response time for a longer duration. Note, however, that the magnitude of PES was nevertheless correlated with accuracy in terms of the percentage of correct answers. Taken together, this suggests that a longer-lasting PES may be more important than a greater magnitude of PES for semantic inhibition.

The adaptive nature of PES was further supported by the correlations between PES and accuracy. There were significant associations only for FF and the mixed HF. This suggests that PES may be a control mechanism that is effective in maintaining a high accuracy only for inhibiting semantic conflict and flexibly switching between rules in the face of spatial conflict, but not for *purely* inhibiting spatial conflict. This differentiation would in principle support a domain-specific account of cognitive control. Together with the evidence in support of a domain-general mechanism, this might point to a hybrid model of cognitive control that incorporates both domain-general and domain-specific components, as suggested by the meta-analysis of fMRI studies in adults by Li et al. (2017). However, the direction of relations—that is, the flowers HF dissociating from the mixed HF and FF—does not align with our expectations of what a domain-specific account would predict. Namely, on the type of control dimension, PES in the mixed HF, as requiring additional cognitive flexibility, should dissociate from PES in the flowers HF and FF, which only require inhibition. Furthermore, on the type of conflict dimension, FF, as posing semantic conflict, should dissociate from the flowers and mixed blocks of the HF. Future neuroimaging studies on samples of young children would be helpful to test a potential hybrid model.

One explanation for this differentiation in the adaptivity of PES, an alternative to a domain-specific account, may lie in the fact that the overall accuracy of the flowers HF was higher than both the mixed HF and FF. Although children did significantly slow down after errors in the flowers HF, this might not have been as influential in optimizing their accuracy as in the other two tasks because the task might have been easy enough for them to maintain a high accuracy without much need for cognitive control. We know from the literature that cognitive flexibility develops slower and later than inhibition (Anderson, 2002; Davidson et al., 2006; Diamond, 2013), and tackling semantic conflict takes longer to master compared with spatial conflict (Archibald & Kerns, 1999; Cao et al., 2013; Jongen & Jonkman, 2008; Macdonald et al., 2014). Thus, at our sampled young age of 4 to 6 years, relative to these developments, testing different control components and types of conflict might have resulted in an additional general task difficulty dimension rather than dissociation based purely on the control component and type of conflict. A tentative suggestion based on this is that, at least at 4 to 6 years of age, an individual's consistency in the level of performance adjustments may depend on how demanding a cognitive conflict task is. Intra-individual stability in PES in the same task has been shown in adults over a time spectrum ranging from 20 min to several months (Danielmeier & Ullsperger, 2011; Segalowitz et al., 2010). However, we still know very little about intra-individual stability across tasks, especially in young children. Further research is needed to understand the individual consistency of PES when confronted with various types and complexities of cognitive conflict demands. A potential future direction to disentangle task difficulty versus domain specificity underlying differences in PES could be to use a more difficult spatial inhibition task or to increase the difficulty by adopting a higher time pressure and thereby increasing the likelihood of errors. Another direction could be to exploit neuroimaging techniques to capture potential differences in the localization of brain activation in the process of PES across different tasks that could be more confidently attributed to a particular control or type of conflict component.

The apparent dissociation in the adaptive nature of PES (across tasks) may also suggest that PES is not only a response strategy to maintain an optimal speed-accuracy balance. One explanation could be that errors are not only triggering a strategically cautious slower response in the following trial (Botvinick et al., 2001) but perhaps also orienting the attention to the infrequent event of an error, thereby resulting in a longer response time (Notebaert et al., 2009). Supporting this, PES was not found to be related to accuracy in the flowers HF, which had the lowest frequency of errors. This is not to suggest that a single mechanism should explain the PES phenomenon. On the contrary, it is likely that several mechanisms are simultaneously at play in the formation of PES and that the different accounts that try to explain this phenomenon are complementary rather than competing (Danielmeier & Ullsperger, 2011; Dubravac et al., 2022).

In conclusion, this study provides evidence for the presence of PES across different task demands and cognitive conflicts in 4- to 6-year-old children using HF and FF (Stroop) tasks. Together with previous research, this is suggestive of the domain generality of cognitive control. However, more research with a wider variety of tasks and age groups is needed to corroborate these findings and their implications. The significant relations between PES and task accuracy suggest that PES manifests as an adaptive behavior at least for semantic inhibition (FF task) and cognitive flexibility in the face of spatial conflict (mixed block of HF task). In parallel, individual associations were found in the magnitude of PES between these two tasks, suggesting that whether and how well children monitor their performance might, to a certain extent, cut across cognitive conflicts.

Data availability

The data and the analysis script are available in OSF.

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