Response inhibition and adaptations to response conflict in 6- to 8-year-old children: Evidence from the Simon effect

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Abstract Several studies have shown that the Simon effect, which is the advantage of spatial correspondence between stimulus and response locations when the stimulus location is task-irrelevant, decreases with increasing response times and is affected by preceding-trial correspondence. These modulations suggest the existence of control mechanisms that adapt our behavior to current goals by responding to the conflict experienced within a trial and by preventing the recurrence of a conflict in the subsequent trial. The aim of the present study was to assess whether these control mechanisms, which are well consolidated in adults and in children older than 8 years of age, are present in children between 6 and 8 years old. To this end, we tested 32 first-grade (6–7 years) and 34 second-grade (7–8 years) children on a Simon task in which correspondence sequence was manipulated on a trial-by-trial basis. The Simon effect was larger for first- than for second-graders and decreased with increasing response times only in second-graders. Crucially, for both groups, the effect was reduced when the preceding trial was noncorresponding, and the reductions were comparable for the two groups, indicating that trial-by-trial control mechanisms are already present in first-grade children and may be dissociated from within-trial control adjustments.

Keywords Cognitive control · Response inhibition · Conflict-driven adaptations · Correspondence sequence · Simon effect

During our daily activities we are faced with a variety of environmental inputs, many of which are irrelevant for current-task performance. Successful behavior requires constant monitoring in order to select and limit processing to relevant information and to allow the cognitive system to perform the intended actions. In the field of cognitive psychology, the ability to coordinate and monitor behavior—termed *attentional control*—is studied by means of conflict-inducing tasks in which participants have to respond to a task-relevant stimulus attribute while ignoring a task-irrelevant attribute; such tasks include the Stroop (Stroop, 1935; for a review, see MacLeod, 1991), the Eriksen flanker (Eriksen & Eriksen, 1974), and the Simon (Simon & Rudell, 1967) tasks.

In the Simon task, participants are required to respond to a nonspatial feature (e.g., color) of stimuli that randomly appear on the right or on the left of fixation, by pressing a spatially defined response (e.g., a left or right response key). Although the stimulus position is task-irrelevant, faster and more accurate responses are observed when the stimulus and response positions spatially correspond (i.e., corresponding condition) than when they do not (i.e., noncorresponding condition) (e.g., Rubichi & Nicoletti, 2006; Rubichi, Nicoletti, Pelosi, & Umiltà, 2004; see Proctor & Vu, 2006; Rubichi, Vu, Nicoletti, & Proctor, 2006, for reviews). The difference between corresponding and noncorresponding trials, termed Simon effect, is composed by both facilitation and interference effects (e.g., Umiltà, Rubichi, & Nicoletti, 1999) and is usually explained by means of dual-route models that distinguish between direct or automatic and indirect or controlled processes linking perception and action (e.g., de Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990). These models hypothesize that when a stimulus appears, a slow, controlled route activates the required response on the basis of task-defined associations that connect a stimulus to a particular response, whereas a fast, automatic route activates the response that spatially corresponds to the stimulus location through preexisting stimulus–response associations, which are independent from the instructions (Barber & O'Leary, 1997). In corresponding trials, this automatically activated

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response is the same as the one indicated by the relevant stimulus feature; therefore, no competition between response codes arises. In noncorresponding trials, on the contrary, the automatically activated response and the response activated on the basis of the relevant stimulus feature are different, and a conflict arises that causes a slowing of response times (RTs) and increased numbers of errors.

As was suggested by Ridderinkhof (2002), the conflict between response alternatives may be resolved by actively inhibiting the inappropriate response. Most of the evidence supporting this view derives from the analysis of the temporal dynamics of the Simon effect. When the RT distribution is divided into quantiles, or bins, and the Simon effect is plotted as a function of bin, the effect is usually largest at the shortest RTs and decreases as RTs increase (de Jong et al., 1994; Rubichi, Nicoletti, Iani, & Umiltà, 1997; see Proctor, Miles, & Baroni, 2011, for a review). This pattern has been taken as being indicative of rapid activation of the corresponding response through the direct route; this activation then dissipates, possibly due to active inhibition of the initial activation. Since this inhibition takes time to build, it mostly affects slower responses (see, e.g., Ridderinkhof, 2002).

Crucially, the magnitude of the Simon effect does not depend only on response speed, but is also dependent on correspondence sequence, with the effect being reduced (or absent) after a noncorresponding trial (e.g., Hommel, Proctor, & Vu, 2004; Iani, Rubichi, Gherri, & Nicoletti, 2009; Soetens, Maetens, & Zeischka, 2010; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). These trial-by-trial modulations (from now on, *sequential modulations*) have been demonstrated also in the Stroop (e.g., Egner & Hirsch, 2005; Kerns et al., 2004) and in the Eriksen flanker (e.g., Gratton, Coles, & Donchin, 1992) tasks, and have been interpreted as evidence that the conflict experienced in a trial triggers a series of adjustments aimed at preventing the recurrence of the conflict in the subsequent trial (see Mansouri, Tanaka, & Buckley, 2009, for a review). As has been suggested by neuroimaging studies, these online control mechanisms may be subserved by two prefrontal areas, the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC), which have been shown to activate during performance on conflict-inducing tasks (e.g., Kerns, 2006; Liu, Banich, Jacobson, & Tanabe, 2004). Specifically, as was suggested by the conflict-monitoring hypothesis proposed by Botvinick and colleagues (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004), the ACC may be activated by the occurrence of response conflict, and its activation may serve as a signal to recruit other brain areas, such as the DLPFC, to prevent conflict in subsequent performance.

According to this account, conflict resolution within a trial and conflict adaptations reflect different and independent mechanisms. More precisely, when a conflict in a trial is detected, control readjustments within the trial itself are

triggered. This form of control is "reactive," because it is implemented only after a conflict arises. Furthermore, information about a conflict in a given trial is maintained across time and prompts an independent adaptation process that affects subsequent performance. The latter form of control can be defined as "proactive," because it represents a preventive regulation that biases the cognitive system to avoid future conflict (see Braver, Gray, & Burgess, 2007, for the distinction between proactive and reactive cognitive control). This view is, however, still debated, and it has recently been proposed that conflict adaptations evident in a given trial may simply reflect a carryover of the control adjustments that took place in the previous trial (e.g., Egner, Ely, & Grinband, 2010; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011).

Although both conflict resolution within a trial and sequential modulations have been widely studied in adults, studies on normally developing children are very few (e.g., Larson, Clawson, Clayson, & South, 2012; Nieuwenhuis et al., 2006; Stins, Polderman, Boomsma, & de Geus, 2007). Since there are indications that proactive and reactive control exhibit different developmental trajectories (e.g., Chatham, Frank, & Munakata, 2009), assessing them in the same task might allow insights into the nature of cognitive-control mechanisms and their independence.

The development of cognitive control has been assessed by means of different tasks, which are supposed to tackle different aspects of cognitive-control abilities (see Bunge & Crone, 2009; Diamond, 2013; Hsu & Jaeggi, 2013; Rueda, 2013; van den Wildenberg & Crone, 2005, for comprehensive reviews on the development of cognitive-control abilities). As regards the development of those cognitive-control abilities related to the detection and resolution of conflict, the available literature suggests that cognitive control improves rapidly between the preschool and elementary school years, with most of the changes occurring between 6 and 8–10 years of age (see, e.g., Cao et al., 2013; Friedman, Nessler, Cycowicz, & Horton, 2009; Ridderinkhof, van der Molen, Band, & Bashore, 1997). As was stated by Jongen and Jonkman (2008), however, the specific age at which cognitive control seems to be mature depends strongly on the type and complexity of the task. For instance, by employing the children's version of the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002), used to assess alerting, orienting, and executive attention (the latter of which includes cognitive control), Rueda et al. (2004) found that the ability to resolve conflict had reached adult levels of performance already by 7 years of age. With regard to the Simon task, developmental studies are very few. Overall, the size of the interference effect has been shown to decrease with age, to reach adult-like levels between the sixth and tenth years of life, with a rapid development of cognitive control from 6–7 to 8 years of age (e.g., Cao et al., 2013; Davidson, Amso, Anderson, & Diamond, 2006), whereas behavioral evidence of adaptations to prior

conflict similar to those of adult participants has been found in 12-year-old children (Stins et al., 2007). However, to our knowledge, no studies have focused on younger children, and most importantly, no developmental studies have assessed in the same task both within-trial conflict resolution and trial-by-trial adaptations to response conflict.

To investigate this issue, in the present study we tested first- and second-graders (between 6 and 8 years of age) on a Simon task in which correspondence sequence was manipulated on a trial-by-trial basis. To assess developmental differences in the handling of response conflict within a trial, we compared the two groups with regard to both the magnitude and time course of the Simon effect (e.g., Forstmann et al., 2008). To assess developmental differences in the adaptation to response conflict, we assessed whether the two groups displayed sequential modulations (i.e., modulation of the Simon effect by preceding trial correspondence).

The decision to test children between 6 and 8 years of age was driven by two main considerations. First, as stated above, cognitive control, as indexed by Simon task performance, seems to develop rapidly from 6–7 to 8 years of age, and hence, assessing this age range might allow us to detect when handling of response conflict and adaptations to response conflict reach adult-like performance. Second, we wanted to use a task as similar as possible to the task used with adult participants, testing children for approximately as many trials as is typically done in studies testing conflict adaptations in adults. This would have been harder with children younger than 6 years of age, who are normally tested using easier and shorter tasks and who normally display low accuracy rates and longer RTs (e.g., Davidson et al., 2006).

Following earlier research, we hypothesized that older children would perform better than younger children, as evidenced by faster RTs and a smaller Simon effect. Since the DLPCF and ACC, supposed to support cognitive control, are not fully developed until late adolescence or early adulthood (e.g., Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Kelly et al., 2009), one might expect that children would display different behavioral responses to conflict than do older adults, and this difference should be more evident in younger children. Furthermore, if conflict resolution within a trial and conflict adaptations reflect the same mechanism, the time course and sequential modulations of the Simon effect should differ between age groups but should show similar patterns within the age groups.

Method

Participants

Groups of 32 first-graders (15 females, 17 males; mean age 6.8 ± 0.33 years) and 34 second-graders (19 females, 15

males; mean age 7.7 ± 0.26 years) were recruited from an elementary school. All of the children were right-handed and had normal or corrected-to-normal vision.

Apparatus, stimuli, and display

Participants were tested individually in a quiet room in school. They sat in front of a 14-in. color monitor controlled by an IBM portable computer, in a dimly illuminated room, at a viewing distance of approximately 46 cm. Stimulus presentation and response collection were controlled by the E-Prime (version 2) software system. The stimuli were red or blue solid squares (3.6 × 3.6 cm), presented on a black background to the left or the right of a white fixation cross (0.6 × 0.6 cm) with an eccentricity of 5.7 cm.

Responses were executed by pressing the "ALT" key (on the left side of the keyboard) or the "CTRL" key (on the right side of the keyboard) with the left and the right index finger, respectively. The keys were covered with the appropriate colored pieces of paper, and the keyboard was located centrally with respect to the body midline.

Procedure

Children were asked to respond as quickly and accurately as possible to the color of the stimulus by pressing the key of the same color, ignoring its location. The experimenter read the instructions and ensured that they were understood by the children. Half of the participants responded to the red square with the left hand and to the blue square with the right hand, whereas the other half experienced the inverse mapping rule.

The task consisted of 128 trials divided into four blocks of 32 trials each, preceded by 20 practice trials. In each block, the trial sequence was controlled so that each trial was preceded by either a corresponding or a noncorresponding trial, with equal probabilities; this produced four different trials sequences (C–C, C–NC, NC–C, NC–NC, with italics denoting trial N).

Each trial began with the presentation of the fixation cross, followed after 1 s by the imperative stimulus, which remained visible for 3 s or until a response was made. The trial terminated if the participant did not respond within 3 s. No feedback was provided. The intertrial interval was 2 s, during which the screen was blank.

Results

For each participant, responses that were 2.5 standard deviations above or below the mean were excluded from the analyses (2.1% of trials). Correct mean RTs and arcsine-transformed error rates were submitted to two separate repeated measures analyses of variance (ANOVAs), with Group
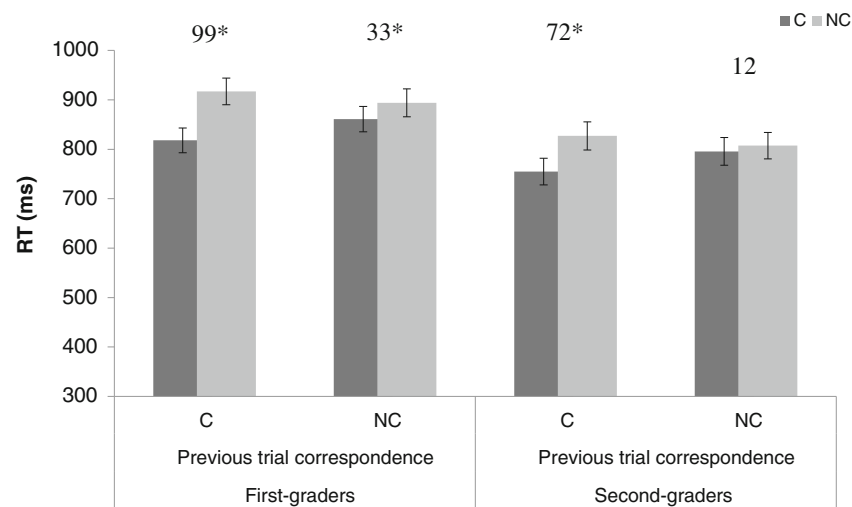
Fig. 1 Mean response times (RTs) in milliseconds for a corresponding (C) and a noncorresponding (NC) trial N, as a function of the correspondence in trial $N-1$ for first- and second-graders. Simon effects, calculated by subtracting RTs on corresponding trials from those on noncorresponding trials, are reported at the top. Error bars indicate standard errors of the means, and asterisks denote significant differences ($p < .05$)

(first-graders and second-graders) as a between-subjects factor and Current-Trial Correspondence and Preceding-Trial Correspondence as within-subjects factors.[1] The respective data are displayed in Fig. 1. When necessary, comparisons were performed using Bonferroni's test for multiple comparisons.

The RT analysis showed a main effect of group, $F(1, 64) = 4.13$, $MSE = 92,697$, $p < .05$, $\eta_p^2 = .06$, with first-graders (873 ms) responding more slowly than second-graders (796 ms). Corresponding trials (808 ms) were faster than noncorresponding trials (861 ms), as was indicated by the significant main effect of current-trial correspondence, $F(1, 64) = 88.68$, $MSE = 2144$, $p < .001$, $\eta_p^2 = .58$. In addition, responses were faster after a corresponding trial (829 ms) than after a noncorresponding trial (839 ms), as was indicated by the significant main effect of previous-trial correspondence, $F(1, 64) = 4.45$, $MSE = 2,144$, $p < .05$, $\eta_p^2 = .09$. The interaction between group and previous-trial correspondence did not reach significance, $F < 1$, whereas the interaction between group and current-trial correspondence did, $F(1, 64) = 6.48$, $MSE = 1,016$, $p < .05$, $\eta_p^2 = .06$. Post-hoc comparisons showed that the difference between corresponding and noncorresponding trials (i.e., the Simon effect) was significant for both groups (65 and 41 ms for first- and second-graders, respectively). A follow-up analysis with the effect as the dependent measure confirmed that the Simon effect displayed by first-graders was significantly different from the effect displayed by second-graders, $p < .05$. Most importantly, the interaction between current-trial

and previous-trial correspondence, indicative of sequential modulations of the Simon effect from a previous trial, was significant, $F(1, 64) = 59.48$, $MSE = 1,095$, $p < .001$, $\eta_p^2 = .48$. Overall, after a corresponding trial the Simon effect was 85 ms, whereas after a noncorresponding trial it was 23 ms. Both effects were significant. After a corresponding trial, first-graders showed a 99-ms Simon effect, whereas second-graders showed a 72-ms effect. After a noncorresponding trial, a 33-ms Simon effect was evident for first-graders, whereas a 12-ms nonsignificant effect was evident for second-graders. The reductions of the Simon effect following a noncorresponding trial were comparable for the two groups (66 and 60 ms for first- and second-graders, respectively), as was signaled by the nonsignificant three-way interaction with group, $F < 1$.

With regard to errors, the analysis revealed a main effect of current-trial correspondence, $F(1, 64) = 33.69$, $MSE = 0.01$, $p < .001$, with fewer errors in corresponding (1.8%) than in noncorresponding (4.4%) trials, and a significant interaction between current-trial correspondence and previous-trial correspondence, $F(1, 64) = 32.50$, $MSE = 0.01$, $p < .001$. Post-hoc comparisons showed that errors were highest when a noncorresponding trial was preceded by a corresponding trial, and lowest when a corresponding trial was preceded by a corresponding trial (1.1%, 5.8%, 2.4%, and 2.9% for C–C, C–NC, NC–C, and NC–NC sequences, respectively). The three-way interaction involving group did not reach statistical significance, $F < 1$.

To assess the changes in effect size across the RT distribution, we performed a distributional analysis (Ratcliff, 1979). For each group, individual RTs for corresponding and noncorresponding trials were rank ordered and divided into five bins. The mean RTs for each bin were then submitted to a repeated measures ANOVA with Group as a between-subjects

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[1] Since preliminary analyses of response times showed that participants' genders had no effect, we did not consider this factor.
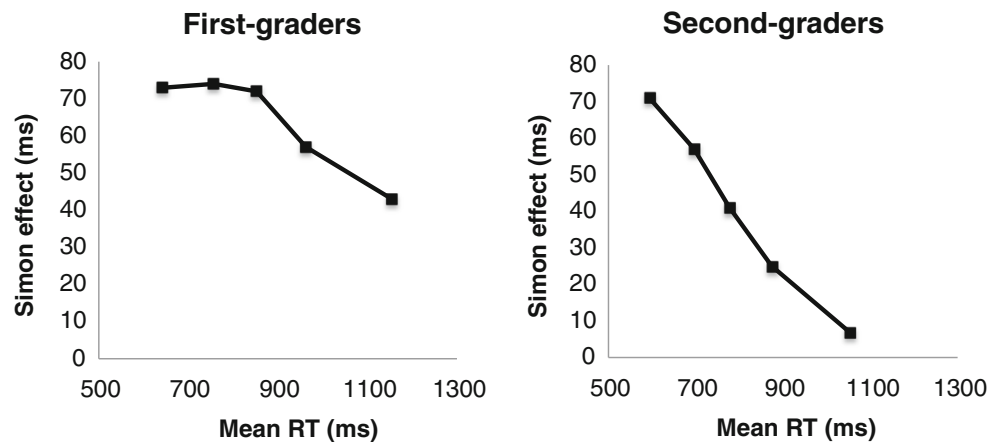
Fig. 2 Magnitude of the Simon effect (RT on noncorresponding trials – RT on corresponding trials, in milliseconds) as a function of mean RTs for first-graders (left panel) and second-graders (right panel)

factor and Bin (from 1 to 5) and Correspondence as within-subjects factors.

Besides the effects and interactions already discussed in the overall analysis, this analysis showed a significant interaction between correspondence and Bin, $F(4, 256) = 22.31$, $MSE = 535$, $p < .001$, $\eta_p^2 = .26$, which was further modulated by group, $F(4, 256) = 3.10$, $MSE = 535$, $p < .05$, $\eta_p^2 = .05$ (Fig. 2). Separate analyses by group showed that the two-way interaction was significant for both first-graders, $F(4, 124) = 5.18$, $MSE = 568$, $p < .001$, $\eta_p^2 = .14$, and second-graders, $F(4, 132) = 21.60$, $MSE = 504$, $p < .001$, $\eta_p^2 = .39$: The Simon effect was present with fast responses and decreased only slightly with increasing RTs. Post-hoc analyses showed that, whereas for first-graders the Simon effect was significant in all the bins (73, 74, 72, 57, and 43 ms from Bins 1 to 5), for second-graders it was significant in all the bins but the last (71, 57, 41, 25, and 7 ms from Bins 1 to 5), suggesting more efficient inhibition of the irrelevant spatial code in older children.

Discussion

The aim of this study was to examine response inhibition and adaptations to response conflict in normally developing children between 6 and 8 years of age. To this end, we employed a version of the Simon task that had previously been demonstrated to show strong conflict-driven adaptations in adult participants, even when stimulus and response repetitions were controlled (Iani et al., 2009).

For both age groups, response speed and accuracy were higher in corresponding than in noncorresponding trials. The advantage for corresponding trials (i.e., the Simon effect) was larger for first-graders than for second-graders, with the latter displaying an effect comparable to that found in adult participants on similar versions of the Simon task (e.g., Iani et al., 2009; Pellicano et al., 2010). The finding of a larger Simon

effect for younger children is consistent with previous studies showing that the Simon (e.g., Davidson et al., 2006), Stroop (e.g., Bub, Masson, & Lalonde, 2006), and flanker (e.g., Ridderinkhof et al., 1997) effects tend to decrease with increasing age, which suggests that the ability to deal with the conflict at the root of these interference effects improves with age.

Investigations of the time course of the Simon effect in adult participants have consistently shown that, in the case of lateralized stimuli, the Simon effect is present for the fastest responses but tends to decrease over time, with null or even inverted effects for the slowest responses (e.g., de Jong et al., 1994; Proctor et al., 2011; Rubichi et al., 1997). Although second-graders showed a similar time course, with the Simon effect starting to decrease from the second bin and disappearing at the slowest RTs, first-graders showed a significant effect across the whole RT distribution. These different time courses may suggest that the inhibition of the irrelevant spatial code is more efficient for older children. This view is consistent with findings suggesting age differences in the ability to inhibit irrelevant information in a variety of different tasks (e.g., Band, van der Molen, Overtoom, & Verbaten, 2000; Ikeda, Okuzumi, Kokubun, & Haishi, 2011; Leon-Carrion, Garcia-Orca, & Perez-Santamaria, 2004).

Despite the differences in the time courses of the Simon effect, both age groups showed adaptations to response conflict, with a larger effect after corresponding trials than after noncorresponding trials. More precisely, whereas after a corresponding trial both groups showed a significant Simon effect, after a noncorresponding trial the Simon effect was reduced but still present for first-graders, and it was nonsignificant for second-graders. Interestingly, using the same task with adult participants (20–32 years of age), Iani et al. (2009) found a 59-ms effect following a corresponding trial and a nonsignificant 4-ms effect following a noncorresponding trial. Although second-graders displayed sequential modulations more similar to those displayed by adults rather than by first-graders, it should be noted that the reductions in the

magnitude of the effect following a noncorresponding trial were comparable for the two groups.

These results are of particular relevance because they show for the first time that in the Simon task, responses to conflict occurring within a trial may be dissociated from adaptations to conflict occurring between trials, suggesting that different mechanisms may be involved that develop at different times during childhood. The findings are also consistent with studies showing that, in the Stroop task, older adults show impaired conflict resolution, as measured through Stroop interference, but spared conflict adaptations, as measured through sequential modulations (Puccioni & Vallesi, 2012).

Note that alternative explanations of sequential effects consider them as reflecting stimulus–response priming (Mayr, Awh, & Laurey, 2003) or binding effects (e.g., Spapè, Band, & Hommel, 2011), rather than conflict-driven adaptations in cognitive control. More precisely, as regards the typical Simon task, correspondence sequence is confounded with the presence of stimulus and response repetitions in consecutive trials. Indeed, whereas sequences of two corresponding trials and sequences of two noncorresponding trials are either complete repetitions of stimulus position and response or complete changes of both stimulus position and response, mixed sequences are always partial repetitions in which either stimulus position or response repeats. Since complete repetitions and complete alternations produce faster responses than do partial repetitions (e.g., Pashler & Baylis, 1991), the advantage of correspondence-level repetition may be accounted for by the repetition of specific stimulus and response features. Even though in the present study we used a version of the Simon task that has previously been shown to produce strong conflict-driven adaptations in adults, even when stimulus and response repetitions were controlled (Iani et al., 2009), we cannot exclude the possibility that the present data were influenced by repetitions, since in the Simon task it is impossible to completely disentangle binding and adaptation effects, and both may contribute to the observed behavioral effects (see Verguts & Notebaert, 2009, for an integrative account).

To conclude, the present results are in line with those of Stins et al. (2007) in showing that children's performance on a trial is affected by the conflict experienced on the previous trial. Importantly, we extended these results by showing that conflict-induced modulations are already present in 6-year-old children, even though they are not as effective in eliminating conflict as they become in older children (between 8 and 12 years of age) and are independent from adaptations to response conflict occurring within a trial. On a more general level, our results indicate that proactive forms of cognitive control emerge early in childhood. Rapid, online adjustments in cognitive control, following the occurrence of response conflict, occur despite the fact that children seem to be characterized by underdeveloped neural connections between

areas involved in executive functions in general, and conflict adaptations in particular. As was suggested by previous studies (e.g., Lamm, Zelazo, & Lewis, 2006; Larson et al., 2012; Rueda et al., 2004), in children these adaptations may be subserved by a larger overall neural activation than occurs in adults.

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