Larger between-task crosstalk in children than in adults: Behavioral results from the backward crosstalk paradigm and a diffusion model analysis

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ABSTRACT

In dual-task settings, one can find influences from Task 2 processing even on Task 1 performance, an effect referred to as the *backward crosstalk effect* (BCE). The size of the BCE has been taken as an index of how well Task 1 processing can be shielded against concurrently ongoing Task 2 processes. In the current study, we compared the size of the BCE between adults and a group of 5- and 6-year-old children. First, the BCE turned out to be larger in children than in adults. Second, both groups exhibited a comparable adjustment of behavior in response to just experienced conflict; in both groups, the BCE was smaller following conflict trials than following no-conflict trials. Third, a diffusion model analysis suggests that the source for the BCE is different in adults than in children. In particular, not parallel Task 2 response activation appears to be the source of the BCE in children. Rather, non-decisional processes appear to be responsible for the BCE in this age group. Thus, this study shows that (a) 5- and 6-year-old children can perform dual-tasks, but (b) they show slightly larger signs of between-task crosstalk, and (c) the exact reasons for this appear to be different from those responsible in adults.

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Introduction

One core component of cognitive development is increasing cognitive flexibility, and one aspect of this is multitasking (see Ionescu, 2012, for a broader discussion)—the ability to deal with more than one task simultaneously. Children tend to grow up with multitasking demands, and in everyday life both contemporary leisure and labor time require this ability (Courage, Bakhtiar, Fitzpatrick, Kenny, & Brandeau, 2015). Accordingly, there is an increased interest in the developmental trajectory of multitasking performance in children.

Multitasking in adults and children

One line of research focuses on task-switching, that is, the ability to flexibly switch between different tasks according to current environmental demands (for reviews of research with adult participants, see Kiesel et al., 2010; Monsell, 2003). In a typical experiment, participants work on two different tasks: A and B. In a mixed/heterogeneous condition, both tasks occur in a random but cued sequence (Meiran, 1996) or in a predictable sequence (Rogers & Monsell, 1995). Thus, on each trial (except the very first one) the task can be either the same as the previous one (task repetition) or not (task switch). The routinely reported response time (RT) difference between (faster) repetition and (slower) switch trials is referred to as (local) switch costs. Furthermore, a comparison of repetition trials from mixed blocks with trials from single/homogeneous task blocks also yields faster RTs in the latter; this RT difference is referred to as mixing costs or global switch costs (e.g., Mayr, 2001). Local switch costs were mainly explained via two mechanisms (which most likely are at work simultaneously). First, an active preparation for the upcoming task might be required in task switch trials (e.g., Rogers & Monsell, 1995). Consequently, increasing the interval from, for example, the task cue to the actual stimulus (i.e., the cue–stimulus interval, CSI) should reduce local switch costs, and this is the common finding. Second, the previously activated, and not yet fully decayed, task set might interfere with a new, and now required, task set (task set inertia; e.g., Allport, Styles, & Hsieh, 1994). In this case, increasing the time from a response to the next cue (i.e., the response–cue interval, RCI) should reduce switch costs, and this is also the common result.

Studies with child-friendly versions have shown that children are in principle able to perform such task-switching (for reviews, see Courage et al., 2015; Davidson, Amso, Anderson, & Diamond, 2006; Peters & Crone, 2014), with some result patterns being different from those of adults. First, mixing costs appear to be larger in children compared with adults. Second, local switch costs were found to be larger or of similar size in children (mostly 8–12 years old), perhaps depending on whether the task sequence was predictable or not (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Crone, Ridderinkhof, Worm, Somsen, & van der Molen, 2004; Kray, Eber, & Karbach, 2008; Kray, Eber, & Lindenberger, 2004). Notably, although manipulations of the CSI were similarly efficient in all age groups, children did not take advantage of a lengthened RCI. Accordingly, Cepeda and colleagues (2001) suggested that task sets do not exhibit passive decay in children as rapidly as in adults. In another study, 8- to 11-year-old children also showed larger local switch costs when the response repeats (Crone, Bunge, van der Molen, & Ridderinkhof, 2006), a finding that may also be taken to suggest a larger influence of established stimulus–response links in children compared with adults.

A second line of multitasking research addresses performance when doing two tasks (more or less) at the same time. One experimental way is to measure single-task performance in two tasks, A and B, and then to combine them into a dual-task where the respective stimuli are presented simultaneously. In the latter case, RTs are usually increased compared with the single-task RTs. Alternatively, the psychological refractory period (PRP) paradigm is used, where two stimuli are presented briefly one after another with a varying stimulus onset asynchrony (SOA) (see Pashler, 1994). RTs to the first presented stimulus are typically not affected by the SOA manipulation, but those to the second stimulus become faster the longer the SOA. This so-called PRP effect indexes dual-task costs (see Janczyk, Pfister, Wallmeier, & Kunde, 2014, for possible exceptions).

Children can successfully engage in such dual-task settings, and a central question is whether they would show specific limitations in dividing attention in such tasks. In a review, Guttentag (1989)

suggested that dual-task costs become smaller the older children become. In addition, the PRP effect was larger in 9-year-old children compared with younger adults (Surwillo & Titus, 1976). It was criticized, however, that the general performance difference between age groups in the single-task conditions was not taken into account. For example, Irwin-Chase and Burns (2000) adopted a method used by Somberg and Salthouse (1982) and reported no differences in dual-task coordination between second- and fifth-grade children (8- to 11-year-olds) when both detection tasks were given equal priority. Similarly, Anderson, Bucks, Bayliss, and Della Sala (2011, Experiment 2) did not find differences in dual-task costs between 8- and 9-year-old children and adults with an inspection time paradigm.

In sum, even young children are able to perform in task-switching and dual-task paradigms. This implies that they are able to keep two task sets available and to process them to some degree in parallel even when stimuli appear in close temporal proximity. However, this ability opens the door for between-task crosstalk, and in order to coordinate two tasks efficiently, it becomes necessary to shield one task from influences of the other task. In the present study, we examined whether this ability differs between 5- and 6-year-old children and young adults by focusing on the *backward crosstalk effect* (BCE).

Backward crosstalk and the efficiency of task shielding

In a standard backward crosstalk experiment, a colored letter stimulus (e.g., a red or green H or S) calls for two subsequent responses (e.g., Hommel, 1998). The color serves as Stimulus 1 (S1) and is responded to with a manual left/right key press response (R1), and the identity is Stimulus 2 (S2) and requires a pedal left/right response (R2). A trial is R1–R2 compatible if both responses are given on the same side (i.e., both left or both right), and it is deemed incompatible if one response is on the right side and the other is on the left side. The BCE is the observation that performance already in Task 1 is better (faster RT1s and/or fewer errors) in compatible (no-conflict) trials than in incompatible (conflict) trials. Similar findings have been reported from various other studies with different tasks and responses (e.g., Hommel & Eglau, 2002; Janczyk, Pfister, Hommel, & Kunde, 2014; Lien & Proctor, 2000; Thomson, Danis, & Watter, 2015).

The BCE indicates that both tasks are not processed completely independent of each other. Consequently, its relative size has been taken as an index of how well Task 1 processing can be shielded against parallel ongoing Task 2 processing (Fischer, Gottschalk, & Dreisbach, 2014; Fischer & Hommel, 2012; Janczyk, 2016; Plessow, Schade, Kirschbaum, & Fischer, 2012; Zwosta, Hommel, Goschke, & Fischer, 2013). Put simply, the smaller the BCE, the more Task 1 was shielded against Task 2 influences. In a very extreme case, no BCE occurs, meaning that Task 1 was completely shielded against Task 2. Variables that potentially influence the degree of task shielding include a systematic–focused versus holistic–flexible thinking style (Fischer & Hommel, 2012) and a positive versus negative mood induction (Zwosta et al., 2013). Recently, it was further shown that one very important variable for the size of the BCE in a trial *n* is the compatibility status of the immediately preceding trial *n* − 1 (Fischer et al., 2014; Janczyk, 2016): following incompatible trials, the BCE was much smaller— and in fact even absent—compared with following compatible trials. Such sequential modulation resembles the Gratton effect observed for conflict tasks such as the Stroop and Simon tasks (Gratton, Coles, & Donchin, 1992; see Egner, 2007, for a review) and suggests that a very flexible adjustment of task shielding efficiency takes place in the course of subsequent trials.

The current study

Although the BCE recently has been investigated in young and old (60- to 80-year-old) adults (Hartley, Maquestiaux, Festini, Frazier, & Krimmer, 2016; Janczyk, Mittelstädt, & Wienrich, 2016), no study to date has investigated the BCE in children. The main impression is that the older adults exhibit a BCE of the same size as young adults (Grabbe & Allen, 2012; Janczyk,

Mittelstädt, et al., 2016).[2] Given that children appear able to keep several task sets (or rules) available simultaneously, we expected to find a BCE in 5- and 6-year-old children as well.

With the current experiment, we pursued three objectives. First, we wanted to compare the magnitude of the BCE between young adults and 5- and 6-year-old children. From the comparisons with the older adults, one may derive the hypothesis that children show a BCE but of the same size as younger adults. If the BCE reflects inhibition of the second task set in case of incompatible trials, such a prediction would also be supported by the finding of similar $n - 2$ repetition costs for children and adults (Schuch & Konrad, 2016). There are, however, reasons to expect a larger BCE in children. For one, it is known that children react more slowly than young adults for other reasons than older adults do. Based on diffusion model analyses (see below for more information), Ratcliff, Love, Thompson, and Opfer (2012) concluded that both 9- to 16-year-old children and older adults apply more conservative response criteria, but only children extract stimulus information at a lower rate, in comparison with younger adults (in technical terms, see below, children exhibited a lower drift rate v). Thus, simply expecting the same behavior for both age groups does not appear to be adequate. In addition, in experiments on task-switching, response compatibility effects are often observed. That is, switch costs increase when the other task would require the same response to the current stimulus as the current task does. Such response–response crosstalk was larger for children compared with adults (Cepeda et al., 2001), suggesting that mappings of currently irrelevant tasks exert a larger influence on current task performance in children. This then suggests a larger R1–R2 BCE for children.

Second, we wanted to test whether the BCE in young children and adults can be attributed to the same mechanisms. Hence, we used diffusion model analyses (Ratcliff, 1978) to disentangle possible sources of the BCE. Diffusion models assume that evidence for a required response is noisily accumulated over time, and once a certain threshold is exceeded, a corresponding response is emitted (see also Ratcliff & Smith, 2004; Ulrich, Schröter, Leuthold, & Birngruber, 2015; Voss & Voss, 2007; Voss, Voss, & Lerche, 2015). Of importance in the current context are three parameters (see also the *variable criterion model* of Grice, 1968). The drift rate v quantifies the mean rate of evidence accumulation. The boundary separation a indicates the amount of evidence necessary to trigger a reaction. This parameter reflects whether decisions are conservative but slow or are fast but risky. A larger drift rate or a smaller separation yields faster RTs. The non-decision time parameter $t0$ reflects additional time required, for example, for perceptual and motor processes or higher cognitive processes. Another parameter of the diffusion model is, for example, the relative starting point z_r that can be used to bias decisions toward one boundary or the other. Furthermore, drift rate v, non-decision time $t0$, and the relative starting point z_r can be allowed to vary from trial to trial (parameters s_v, s_{t0}, and s_{zr}). For more information, see also Voss and Voss (2007) and Voss et al. (2015).

To estimate these parameters, diffusion models are fitted to the RT distributions for correct responses and for errors. Thus, they do not rely solely on mean RTs and mean percentages of error (PEs) but rather rely on the whole distribution of correct and erroneous responses. Diffusion models have been used to analyze task-switch performance in general (Schmitz & Voss, 2012) and also to compare 7- to 11-year-old children with adults (Schuch & Konrad, 2016; Weeda, van der Molen, Barceló, & Huizinga, 2014). In accordance with previous results, several predictions concerning differences between the two age groups can be made. Children are expected to show a longer non-decision time $t0$, a larger separation a, and a smaller drift rate v (Ratcliff et al., 2012; Schuch & Konrad, 2016; Weeda et al., 2014). Logan and Gordon (2001) suggested that evidence from the (nominally) second stimulus is already gathered during Task 1 processing, thereby leading to faster RT1s in compatible trials. This reasoning suggests a larger drift rate v in case of compatible trials compared with incompatible trials. If the BCE were larger in children than in adults, and the same mechanisms drive the BCE in both age groups, it is reasonable to expect this difference in drift rate v to be larger for children than for adults.

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[2] The results presented by Hartley and colleagues (2016) are less clear in particular with regard to response compatibility, that is, a BCE as investigated here. In their Experiment 1, these authors did not observe a typical BCE at all in older adults, but at a short stimulus onset asynchrony the descriptive BCE did not differ in size from that in younger adults. After exclusion of several participants, there were even signs of a smaller descriptive BCE in older adults, which was still not significant in itself. Furthermore, in this study median RTs were analyzed, in contrast to the more common analysis of mean RTs.

Third, we wanted to test whether the same flexibility in task shielding based on the previous trial's compatibility status can be observed in both age groups. In conflict tasks, the congruency effect is usually smaller following conflict trials than following no-conflict trials (Gratton et al., 1992; see Egner, 2007, for a review). Some preliminary evidence for the same ability in children can be taken from the existing literature. For example, Jordon and Morton (2008) showed that even 3-year-old children's performance can benefit from presentation of (irrelevant but) congruent flankers in a card-sorting task. Moreover, Larson, Clawson, Clayson, and South (2012) directly compared sequential modulations in a Stroop task in 9-year-old children with those in adults. They observed a robust conflict adaptation effect that was not modulated by age group. Thus, children at this age are apparently able to employ flexible adjustments in response to just-experienced conflict. Certainly, the current paradigm differs from standard conflict tasks such as the Stroop task. For example, whereas in standard conflict tasks the conflict is induced by an irrelevant stimulus feature, in the current paradigm both tasks need to be performed and, thus, both stimulus features are relevant. However, a similar sequential modulation is observed, and the BCE is absent following incompatible trials and is large following compatible trials, indicating a very flexible adjustment of task shielding (Janczyk, 2016), and the same flexibility was observed for the older adults in Janczyk, Mittelstädt, et al. (2016).

Method

Participants

The participants were 24 naive 5- and 6-year-old children from kindergarten in Landsberg am Lech, Germany (mean age = 5.1 years, *SD* = 0.3; 12 female), and 24 naive adults from Würzburg, Germany (mean age = 28.1 years, *SD* = 11.4; 21 female, with the majority of participants being students of psychology).[3] Children were rewarded with sweets, and adults participated for monetary compensation or course credit. Written informed consent was obtained from the participants or their parents prior to experimentation.

Stimuli and apparatus

A standard laptop (Dell M6700, 17.3-inch monitor) was used for stimulus presentation and response registration. Viewing distance between monitor and participant was approximately 60 to 70 cm. Stimuli were drawings of a tree and a flower in blue or yellow color that were presented in the middle of the black screen (~250 pixels high, ~200 pixels wide). Responses were given via response keys or pedal presses. Two response keys were placed on the table in front of the participants at a horizontal distance of 18 cm. The pedals were placed on the floor to the left and right. The exact location was individually chosen to be comfortable for the participants. Key presses were made with the left and right index fingers, and pedal presses were made with the left and right feet. In support, colorless stimuli and blue and yellow circles were placed next to the keys.

Procedure

Participants were tested in one session of approximately 20 to 45 min and were verbally instructed by a researcher, who stayed in the same room during the session. Each trial began with a small fixation cross in the middle of the screen (250 ms), followed by a blank display (250 ms). Afterward, the stimulus was presented until both tasks were completed. Task 1 was to press either the left or right key according to the stimulus identity (R1), Task 2 was to press either the left or right pedal according to the stimulus color (R2). Each trial ended with an inter-trial interval (ITI) of 1000 ms. Participants

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[3] The gender proportions are different in the two age groups (50% female in the child group and 88% female in the adult group). These proportions are in line with typical proportions in a kindergarten and among university students of psychology. Although technically referred to as a confound, there is no theoretical reason why the effects investigated here should differ between males and females.

were instructed to respond as fast and accurately as possible, first to the stimulus identity and then to the stimulus color.

Participants completed 3 practice and 10 experimental blocks. In the practice blocks, participants needed to react first only to the stimulus identity, second only to the stimulus color, and third to both the identity and color. Practice blocks and the first 2 experimental blocks were excluded from analyses. Each practice block contained 30 trials, and each experimental block contained 40 trials. Stimuli were presented in random order, and stimulus–response mappings in both tasks were counterbalanced across participants.

Half of the trials were R1–R2 compatible (key and pedal press on the same side), and the other half was incompatible (key and pedal press on different sides). If participants responded in the wrong order, chose the wrong response key or pedal, or did not give responses within 4000 ms (in practice trials within 30,000 ms), specific error messages were displayed for 1000 ms before the ITI (e.g., "Fehler in Farb-Aufgabe" [Error in color task], briefly explained by the experimenter to children). Participants were instructed to perform the tasks serially and to react as fast as possible.

Design and analysis

Trials with general errors (no response within 4000 ms, wrong response order, etc.) were excluded for all analyses (16.0% [SD = 8.6] and 1.1% [SD = 1.4] of the trials for children and adults, respectively; the majority of these errors were missed responses within the allotted time window, with a larger number in incompatible trials), as were trials with an inter-response interval less than 120 ms (4.60% and 2.87% of the trials for children and adults, respectively). For RT analyses, only trials with two correct responses were further considered. Trials were deemed outliers if the RTs deviated from the mean RT (calculated separately for each participant and R1–R2 relation condition) by more than 2.5 standard deviations. For the sequential analyses, the first trial of each block was also excluded and only trials following a correct preceding trial were considered.

Mean correct RTs and mean PEs were submitted to analyses of variance (ANOVA) with age group (children vs. adults) as a between-participants variable and repeated measures on the R1–R2 compatibility (compatible vs. incompatible). Because the magnitude of the BCE increases with increasing RT levels (e.g., Hommel, 1998), a larger BCE for children than for adults cannot be attributed unambiguously to age group but also to the overall RT level difference. Therefore, it is essential to evaluate RTs also following an appropriate transformation of the raw RTs. Thus, inferential statistics were based on logarithmic RTs, a transformation that is often applied in aging research to compensate for general slowing (see Christ, White, Mandernach, & Keys, 2001; Pritchard & Neumann, 2009; see also Faust, Balota, Spieler, & Ferraro, 1999, for a critical discussion).

Diffusion modeling

The data for Task 1 were screened for outliers following Schmiedek, Oberauer, Wilhelm, Süss, and Wittmann (2007); that is, trials with RT1s faster than 200 ms and RT1s exceeding the mean by more than 4 standard deviations (separately per participant and design cell) were identified as outliers. This procedure was repeated until no more outliers were identified (leading to an exclusion of 0.5% of the trials).[4] The *fast-dm* software (Voss & Voss, 2007) was used to estimate the parameters v, a, and $t0$ separately per participant and design cell (R1–R2 compatibility). In addition, $t0$ was allowed to vary from trial to trial (i.e., the parameter s_{t0} was not fixed to zero). The upper boundary was associated with correct responses, and the lower boundary was associated with erroneous responses. We fixed the relative starting point z_r to 0.5; that is, no bias in one direction or the other existed. Inter-trial variability of v (s_v) and of z_r (s_{zr}) were fixed to 0 (see Lerche & Voss, 2016, who showed that this improves parameter estimation in comparison with more complex models). A diffusion model was also run for Task 2 data, and the respective results are reported in Appendix B.

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[4] The basic result patterns for Task 1 (see below) remained the same when this outlier elimination procedure was applied.

Results

Task 1

Mean correct RT1s (2.52% outliers) are visualized in Fig. 1 (left panel) and summarized in Table 1. First, there was a clear difference in RTs, with children responding slower than adults, $F(1,46)$ = 556.88, $p < .001$, η_p^2 = .92. Second, in both age groups, responses were slower in R1–R2 incompatible trials compared with R1–R2 compatible trials; thus, a BCE was observed, $F(1,46)$ = 129.02, $p < .001$, η_p^2 = .74. Finally, the interaction was significant and the magnitude of the BCE was larger for children than for adults, $F(1,46)$ = 17.44, $p < .001$, η_p^2 = .27. The BCE was significant within both age groups: children, $t(23)$ = 10.13, $p < .001$, d = 2.92; adults, $t(23)$ = 5.59, $p < .001$, d = 1.61 (effect size d is corrected by multiplication with $\sqrt{2}$ here and in the following).

Mean PE1s were low and are summarized in Table 1. No effect reached significance ($Fs \leqslant 1.18$, $ps \geqslant .283$). Thus, the observed RT1 pattern was not compromised by a speed–accuracy trade-off.

Task 2

Mean correct RT2s (1.85% outliers) are visualized in Fig. 1 (right panel) and are summarized in Table 2. The RT2 pattern follows that of Task 1, with slower responses for children than for adults, $F(1,46)$ = 707.25, $p < .001$, η_p^2 = .94, and for R1–R2 incompatible trials than for compatible trials, $F(1,46)$ = 88.33, $p < .001$, η_p^2 = .66. This forward crosstalk effect (FCE) was larger for children than for adults, $F(1,46)$ = 11.12, $p = .002$, η_p^2 = .19. The FCE was significant within both age groups: children, $t(23)$ = 7.51, $p < .001$, d = 2.17; adults, $t(23)$ = 5.72, $p < .001$, d = 1.65. Mean PE2s are summarized in Table 2. Children made more errors, $F(1,46)$ = 6.79, $p = .012$, η_p^2 = .13, and more errors were made in R1–R2 incompatible trials than in compatible trials, $F(1,46)$ = 6.00, $p = .018$, η_p^2 = .12, but the magnitude of this difference was the same for both age groups, $F(1,46)$ = 2.26, $p = .140$, η_p^2 = .05.

Diffusion model analyses

The Kolmogorov–Smirnov test calculated by the fast-dm software did not reveal deviations between the empirical and predicted distributions (all $ps \geqslant .463$). Additional graphical illustrations of the model fit are given in Fig. A1 of Appendix A. Because there is no systematic deviation from the diagonal, the model fit is reasonably good to interpret the results.

Parameter means as a function of age group and R1–R2 compatibility are visualized in Fig. 2. *Boundary separation* was larger for children than for adults, $F(1,46)$ = 228.19, $p < .001$, η_p^2 = .83, and was smaller in compatible trials than in incompatible trials, $F(1,46)$ = 21.90, $p < .001$, η_p^2 = .32. This latter effect was similar in both age groups, as suggested by the nonsignificant interaction, $F(1,46)$ = 1.34, $p = .254$, η_p^2 = .03. *Drift rate* was higher in adults than in children, $F(1,46)$ = 121.52, $p < .001$, η_p^2 = .73, and was overall higher in compatible trials than in incompatible trials, $F(1,46)$ = 6.06, $p = .018$, η_p^2 = .12. These main effects were qualified by a significant Group × Compatibility interaction, $F(1,46)$ = 8.93, $p = .004$, η_p^2 = .16: the increase in drift rate was significant for adults, $t(23)$ = 2.99, $p = .007$, d = 0.86, but not for children, $t(23)$ = 0.64, $p = .529$, d = 0.18. The non-decision time $t0$ was longer for children than for adults, $F(1,46)$ = 136.39, $p < .001$, η_p^2 = .75, and was overall shorter in compatible trials compared with incompatible trials, $F(1,46)$ = 31.40, $p < .001$, η_p^2 = .41. However, this effect was qualified by the significant Group × Compatibility interaction, $F(1,46)$ = 36.90, $p < .001$, η_p^2 = .45. Whereas there was a clear decrease in non-decision time in R1–R2 compatible trials for children, $t(23)$ = 6.05, $p < .001$, d = 1.75, no difference between compatible and incompatible trials was observed for adults, $t(23)$ = 0.90, $p = .379$, d = 0.26. The inter-trial variability of the non-decision time s_{t0} was larger for children than for adults, $F(1,46)$ = 82.72, $p < .001$, η_p^2 = .64, and was overall smaller in compatible trials compared with incompatible trials, $F(1,46)$ = 10.04, $p = .003$, η_p^2 = .18. However, this effect was qualified by the significant Group × Compatibility interaction, $F(1,46)$ = 9.31, $p = .004$, η_p^2 = .17. Inter-trial variability decreased in R1–R2 compatible trials for children, $t(23)$ = 3.32, $p = .003$,
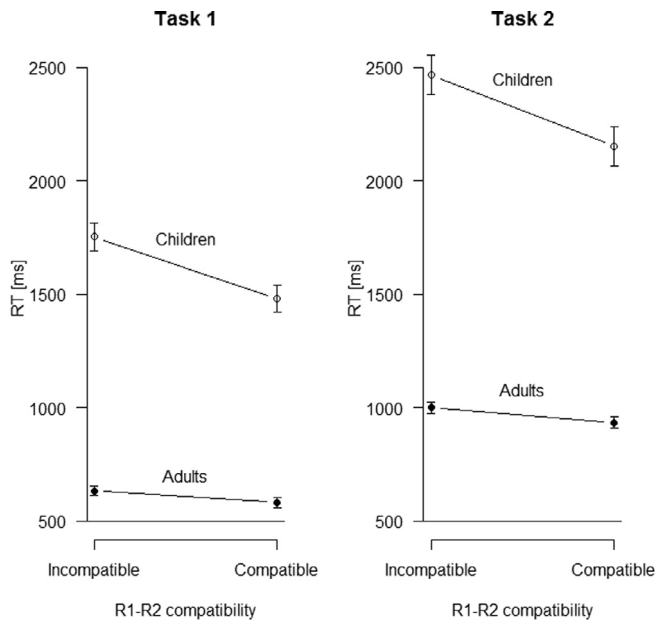
Fig. 1. Mean RTs from Task 1 (RT1, left panel) and Task 2 (RT2, right panel) in milliseconds (ms) as a function of R1–R2 compatibility and age group. Error bars are 95% confidence intervals of the difference between R1–R2 compatible and incompatible conditions, separately for each age group (see Pfister & Janczyk, 2013).

Table 1
Mean RTs from Task 1 (RT1) in milliseconds (ms) and mean percentages of error from Task 1 (PE1) as a function of R1–R2 compatibility and age group.

Age group	RT1 (ms)			PE1		
	R1–R2 compatibility			R1–R2 compatibility		
	Compatible	Incompatible	BCE (ms)	Compatible	Incompatible	BCE
Children	1480	1753	273	1.4	1.7	0.3
Adults	581	633	52	2.4	3.1	0.7

Note. Backward crosstalk effects (BCEs) were calculated by subtracting the values for the compatible R1–R2 condition from the values for the incompatible R1–R2 condition.

Table 2
Mean RTs from Task 2 (RT2) in milliseconds (ms) and mean percentages of error from Task 2 (PE2) as a function of R1–R2 compatibility and age group.

Age group	RT2 (ms)			PE2		
	R1–R2 compatibility			R1–R2 compatibility		
	Compatible	Incompatible	FCE (ms)	Compatible	Incompatible	FCE
Children	2154	2466	312	4.8	5.3	0.5
Adults	934	999	65	1.7	3.5	1.8

Note. Forward crosstalk effects (FCEs) were calculated by subtracting the values for the compatible R1–R2 condition from the values for the incompatible R1–R2 condition.
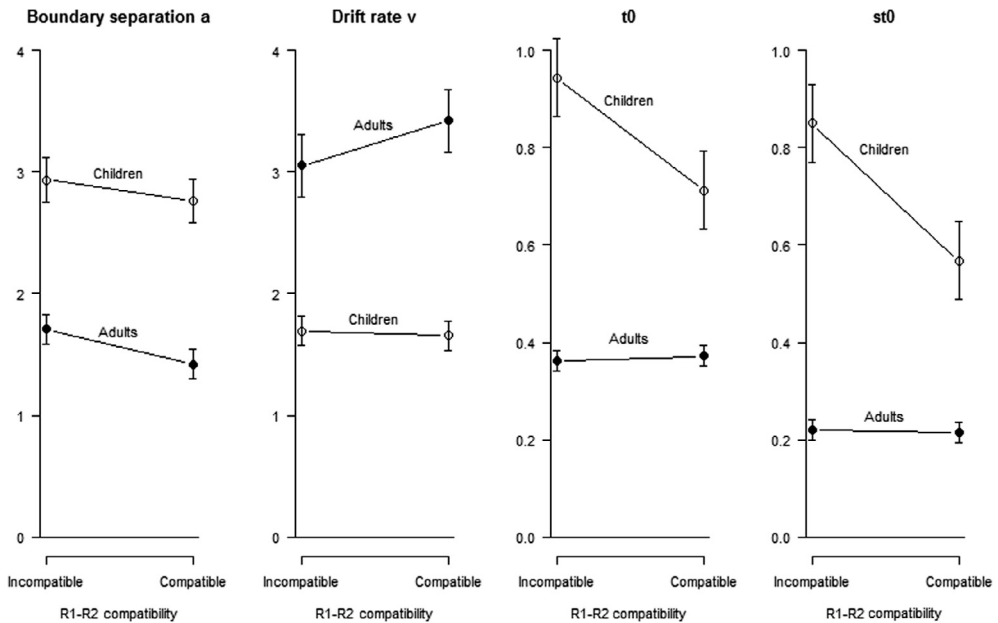
Fig. 2. Mean values of four parameters from the Task 1 diffusion model analyses as a function of R1–R2 compatibility and age group. Error bars are 95% confidence intervals of the difference between R1–R2 compatible and incompatible conditions, separately for each age group (see Pfister & Janczyk, 2013). From left to right: boundary separation *a*, drift rate *v*, non-decision time *t0*, and inter-trial variability of non-decision time s_{t0}.

d = 0.96, but no difference between compatible and incompatible trials was observed for adults, *t*(23) = 0.17, *p* = .868, *d* = 0.05.

Sequential modulations: Task 1

Mean correct RT1s (2.41% outliers) are visualized in Fig. 3 (left panel) and summarized in Table 3. Children responded slower than adults, $F(1,46) = 518.82$, $p < .001$, $\eta_p^2 = .92$, and responses were overall faster in compatible trials *n* than in incompatible trials *n;* thus, an overall BCE was observed, $F(1,46) = 104.47$, $p < .001$, $\eta_p^2 = .69$. Similar to the previous analyses, the BCE was overall larger for children than for adults, $F(1,46) = 16.11$, $p < .001$, $\eta_p^2 = .26$. Responses were also slightly faster following incompatible trials $n - 1$, $F(1,46) = 6.62$, $p = .013$, $\eta_p^2 = .13$, and this effect was larger for children than for adults, $F(1,46) = 5.79$, $p = .020$, $\eta_p^2 = .11$. Most important, the BCE was much smaller following incompatible trials $n - 1$ than following compatible trials $n - 1$; thus, a sequential modulation of the BCE was observed, $F(1,46) = 246.69$, $p < .001$, $\eta_p^2 = .84$, which was not further modulated by age group, $F(1,46) = 2.76$, $p = .104$, $\eta_p^2 = .06$.

Following compatible trials $n - 1$, the BCE was significant for adults, $t(23) = 12.74$, $p < .001$, *d* = 3.68, and for children, $t(23) = 12.35$, $p < .001$, *d* = 3.57. For children there was also a significant BCE following incompatible trials $n - 1$, $t(23) = 2.21$, $p = .038$, *d* = 0.64, whereas for adults the BCE was even reversed, $t(23) = 3.95$, $p = .001$, *d* = 1.14.

PE1s are summarized in Table 3. More errors occurred following compatible trials than following incompatible trials, $F(1,46) = 31.52$, $p < .001$, $\eta_p^2 = .41$. No other effect approached significance, and in particular the RT1 pattern was not compromised by a speed–accuracy trade-off (all other $Fs \leqslant 2.65$, all other $ps \geqslant .110$).
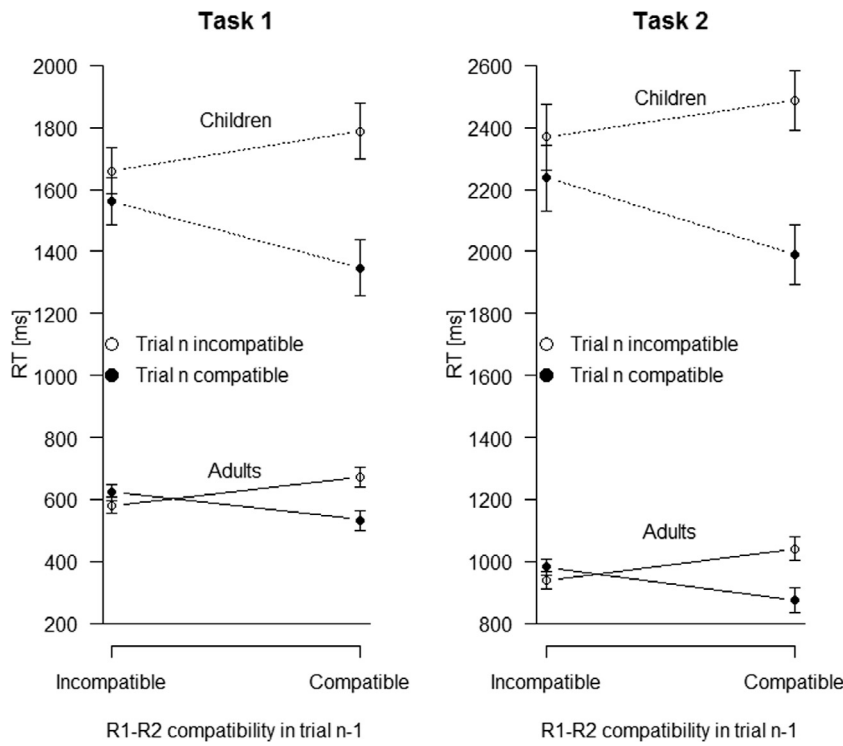
Fig. 3. Mean RTs from Task 1 (left panel) and Task 2 (right panel) in milliseconds (ms) as a function of R1–R2 compatibility in trial *n* and trial *n* − 1 and age group. Error bars are 95% confidence intervals of the difference between R1–R2 compatible and incompatible conditions in trial *n*, separately for each age group and compatibility in trial *n* − 1 condition (see Pfister & Janczyk, 2013). Note that the *y* axes of both panels have different ranges.

Table 3
Mean RTs from Task 1 (RT1) in milliseconds (ms) and mean percentages of error from Task 1 (PE1) as a function of R1–R2 compatibility in trial *n* and trial *n* − 1 and age group.

Age group	R1–R2 compatible in trial *n* − 1	RT1 (ms)			PE1		
		R1–R2 compatible in trial *n*			R1–R2 compatible in trial *n*		
		Compatible	Incompatible	BCE (ms)	Compatible	Incompatible	BCE
Children	Compatible	1347	1788	441	2.2	2.4	0.2
	Incompatible	1562	1660	98	0.7	0.9	0.2
Adults	Compatible	534	672	138	4.1	2.7	−1.4
	Incompatible	623	581	−42	0.6	1.3	0.7

Note. Backward crosstalk effects (BCEs) were calculated by subtracting the values for the compatible R1–R2 relation from the values for the incompatible R1–R2 relation.

Sequential modulations: Task 2

Mean correct RT2s (2.05% outliers) are visualized in Fig. 3 (right panel) and summarized in Table 4. The general impression of the results is as observed for Task 1. Children responded slower than adults, $F(1, 46) = 682.93$, $p < .001$, $\eta_P^2 = .94$. Responses were faster in compatible trials *n* than in incompatible

Table 4

Mean RTs from Task 2 (RT2) in milliseconds (ms) and mean percentages of error from Task 2 (PE2) as a function of R1–R2 compatibility in trial *n* and trial *n* − 1 and age group.

Age group	R1–R2 compatible in trial *n* − 1	RT2 (ms)			PE2		
		R1–R2 compatible in trial *n*			R1–R2 compatible in trial *n*		
		Compatible	Incompatible	FCE (ms)	Compatible	Incompatible	FCE
Children	Compatible	1990	2488	498	5.2	5.7	0.5
	Incompatible	2237	2369	132	3.7	6.6	2.9
Adults	Compatible	875	1041	166	1.7	4.1	2.4
	Incompatible	982	939	−43	1.2	3.3	2.1

Note. Forward crosstalk effects (FCEs) were calculated by subtracting the values for the compatible R1–R2 condition from the values for the incompatible R1–R2 condition.

trials *n;* thus, an overall FCE was observed, $F(1,46) = 81.41$, $p < .001$, $\eta_p^2 = .64$, which was larger for children than for adults, $F(1,46) = 11.86$, $p = .001$, $\eta_p^2 = .21$. Responses were slightly faster following compatible trials *n* − 1, $F(1,46) = 17.12$, $p < .001$, $\eta_p^2 = .27$, and this effect was larger for children than for adults, $F(1,46) = 10.09$, $p = .003$, $\eta_p^2 = .18$. As with the BCE in Task 1, the FCE was much smaller following incompatible trials *n* − 1 than following compatible trials *n* − 1, $F(1,46) = 199.33$, $p < .001$, $\eta_p^2 = .81$, which was not further modulated by age group, $F(1,46) = 2.03$, $p = .161$, $\eta_p^2 = .04$.

Following compatible trials *n* − 1, the FCE was significant for adults, $t(23) = 9.87$, $p < .001$, $d = 2.85$, and for children, $t(23) = 10.50$, $p < .001$, $d = 3.03$. For children there was also a significant FCE following incompatible trials *n* − 1, $t(23) = 2.64$, $p = .015$, $d = 0.76$, whereas for adults the FCE was even reversed, $t(23) = 3.07$, $p = .005$, $d = 0.89$.

PE2s are summarized in Table 4. Children committed more errors than adults, $F(1,46) = 7.47$, $p = .009$, $\eta_p^2 = .14$, and more errors occurred in incompatible trials than in compatible trials, $F(1,46) = 17.94$, $p < .001$, $\eta_p^2 = .28$. No other effect approached significance (all other $Fs \leqslant 1.62$, all other $ps \geqslant .209$).

Discussion

The BCE (Hommel, 1998) in dual-task situations shows influences of Task 2 processing already on ongoing Task 1 performance. The size of the BCE has been taken as an index of how well Task 1 processing is shielded against influences from Task 2 processing (e.g., Fischer & Hommel, 2012; Fischer et al., 2014). In the current study, we compared the size of the BCE between a group of children and a group of adults. These analyses were supplemented by a diffusion model analysis to gain further insights into the similarities and differences underlying the BCE in both age groups. A further aim was to investigate whether children would exhibit the same flexibility in adjusting their task shielding according to just-experienced conflict in a similar way as adults do (Janczyk, 2016).

RT and PE results

A first result from our study is that a BCE was clearly present for children and adults. Thus, apparently both age groups are susceptible to influences from a task that is actually to be performed only following the currently processed task. Second, the BCE was larger in children than in adults. This finding suggests that children are less able to shield a currently processed task against influences of other tasks in comparison with younger adults but also in comparison with older adults for whom a BCE of the same size as for younger adults was reported in most cases (Grabbe & Allen, 2012; Janczyk, Mittelstädt, et al., 2016; see also Hartley et al., 2016).

The BCE is usually explained by modifying the classic central bottleneck model (Pashler, 1994) in a way that the central stage is split into a parallel ongoing response activation stage that is followed by the bottleneck stage of response selection (Hommel, 1998; Lien & Proctor, 2002). In this model, the

BCE results from between-task interactions during response activation stages of both tasks. However, alternatives have been suggested that converge on the notion that some Task 2 response activation (or evidence gathered from the Task 2 stimulus) directly affects Task 1 response selection (Logan & Gordon, 2001; Thomson et al., 2015; see also Janczyk, Renas, & Durst, 2016). We come back to this when discussing the diffusion model analyses below.

Besides the BCE as such, children show—similar to (younger and older) adults (Janczyk, 2016; Janczyk, Mittelstädt, et al., 2016)—a remarkable flexibility in adjusting their behavior as a consequence of just-experienced conflict (see also Larson et al., 2012, for the Stroop task). In both age groups, the BCE was much smaller following incompatible trials than following compatible trials. One small but perhaps important difference in this adjustment between both age groups points to differences in the source of the BCE; whereas the BCE was entirely eliminated, and even reversed, following incompatible trials in adults, a remaining BCE of approximately 100 ms was still present in children. This finding indicates either that children's adjustments are less efficient or that a reason different from that in adults is responsible for the BCE—one where complete shielding is not possible.

We interpret the sequential modulations as resulting from flexible cognitive control. It is important to note, however, that explanations in terms of feature repetitions were proposed in the case of conflict tasks such as the Simon, Stroop, and Eriksen tasks (see Egner, 2007, for an overview). The same explanations do in principle also apply in the current case. However, first, even after controlling for all kinds of sequences in conflict tasks, a sequential modulation remains that can be attributed to cognitive control (e.g., Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014). Second, Experiment 2 and in particular Experiment 3 in Janczyk (2016) was run to rule out alternative explanations in terms of feature repetitions, and even in these cases the large sequential modulation survived. Thus, we believe that it cannot be explained merely by such accounts, but at the same time we concur that the effect itself needs further investigations to pinpoint its source.

Insights from diffusion modeling

To gain further insights into the mechanisms driving the BCE, which may differ between children and older adults, we applied a diffusion model to the data.[5] First, these analyses replicated several findings from previous studies that compared children's and adults' performances: children showed a smaller drift rate v, a larger boundary separation a, and a longer non-decision time $t0$ (Ratcliff et al., 2012; Schuch & Konrad, 2016; Weeda et al., 2014). Second, regarding the comparison of R1–R2 compatible and incompatible trials, both age groups showed the same reduction of the boundary separation a in compatible trials. This finding is somewhat unexpected, and Weeda and colleagues (2014) did not find an effect of task repetition versus switches on a, nor did Schuch and Konrad (2016) observe clear evidence for an effect of their task sequence comparison. However, both age groups showed this reduction in a in our study, but further research is needed to carefully analyze the reasons for this observation. Note also that for Task 2 the effect went descriptively in the opposite direction (see Appendix B). More interesting, a clear dissociation emerged for the drift rate v and the non-decision time $t0$—and it is this dissociation that suggests that the BCE in adults may have quite different sources than the BCE in children. First, as one would probably expect, we observed an increase in v in compatible trials for adults. However, the diffusion model we applied here assumes a one-stage response selection and, thus, cannot be mapped directly on the two-stage assumption made by Hommel (1998) and Lien and Proctor (2002). Alternatively, it was suggested that Task 2 response activation directly affects Task 1 response selection (Janczyk, Renas, et al., 2016; Thomson et al., 2015). Under this assumption, at least two models offer ways in which to interpret this aspect of the findings. First, similar to the model used by Ulrich and colleagues (2015), Task 2 response information is automatically activated and may add up with the (controlled) Task 1 drift, thereby yielding the higher effective drift rate in compatible trials. Second, the model of Logan and Gordon (2001) assumes that—even when Task 1 is prioritized—some S2 categorization occurs but is erroneously attributed to result from S1 and added to the Task 1 response counter.

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[5] In the following, we focus on the Task 1 diffusion model. See Appendix B for interpretations concerning the Task 2 diffusion model.

In contrast, no increase in the drift rate in compatible trials was observed in children. This suggests that no automatic Task 2 response activation took place in children during Task 1 response selection, perhaps because children tended to apply a serial strategy and loaded the Task 2 set into working memory (e.g., into the bridge in the procedural working memory account of Oberauer, Souza, Druey, & Gade, 2013) only after having selected the appropriate Task 1 response. However, and in contrast, children showed a clear decrease in *t0* in compatible trials, but this was not the case for adults. Thus, a large part of the BCE in children appears to be due to a shortened non-decision time *t0* in compatible trials (or a lengthened *t0* in incompatible trials). Because *t0* captures processes before and after response selection-related processes, it remains unclear so far which of these processes are responsible for the difference in *t0* in children. One speculation might be that in fact response selections are processed entirely in a non-overlapping and serial order in children, but the incompatibility creates motor-related interference in children. In particular, children may exhibit a stronger coupling of effectors, so that it may be more difficult to respond with, for example, the left hand when shortly after that a right foot response is required. In fact, Miller and Alderton (2006) discussed instances of BCEs where motor execution of Task 1 may be affected by Task 2 processing.

Limitations and future research

Against this background, it becomes clear that future studies should investigate the BCE in children more thoroughly and identify its underlying reasons; whatever these reasons are, they appear to be different for children and for (young) adults. Some limitations of the current study should also be noted. First, we investigated only one specific type of the BCE, namely the one depending on R1–R2 compatibility. Other BCEs, however, have been reported, for example, depending on S1–R2 compatibility (Hommel, 1998) and on whether Task 2 is a go or no-go task (Miller, 2006; see also Janczyk & Huestegge, 2016). Future studies should generalize our findings to other types of the BCE. Second, we tested only one sample of children with an age of 5 or 6 years. Clearly, this makes it impossible to explore developmental trajectories and the age when adult performance is reached. Still, we consider the results from the current study to be worthwhile and novel in the field, but we concur that future studies based on ours should overcome its limitations.

Conclusion

The current study shows that in children, as well as in adults, characteristics of a secondary task can influence Task 1 performance—the BCE (Hommel, 1998). This influence appears to be larger in children than in adults, suggesting that children are less able to shield task processing against irrelevant influences of other tasks. However, diffusion model analyses indicate that the reason for the BCE differ between children and adults, and the standard model in terms of time-overlapping response activation stages that is usually taken to account for the BCE, might not be viable for children. Future studies should aim to replicate and extend our results and to illuminate the locus of the BCE in children more thoroughly.

Acknowledgments

Appendix A.

See Fig. A1.

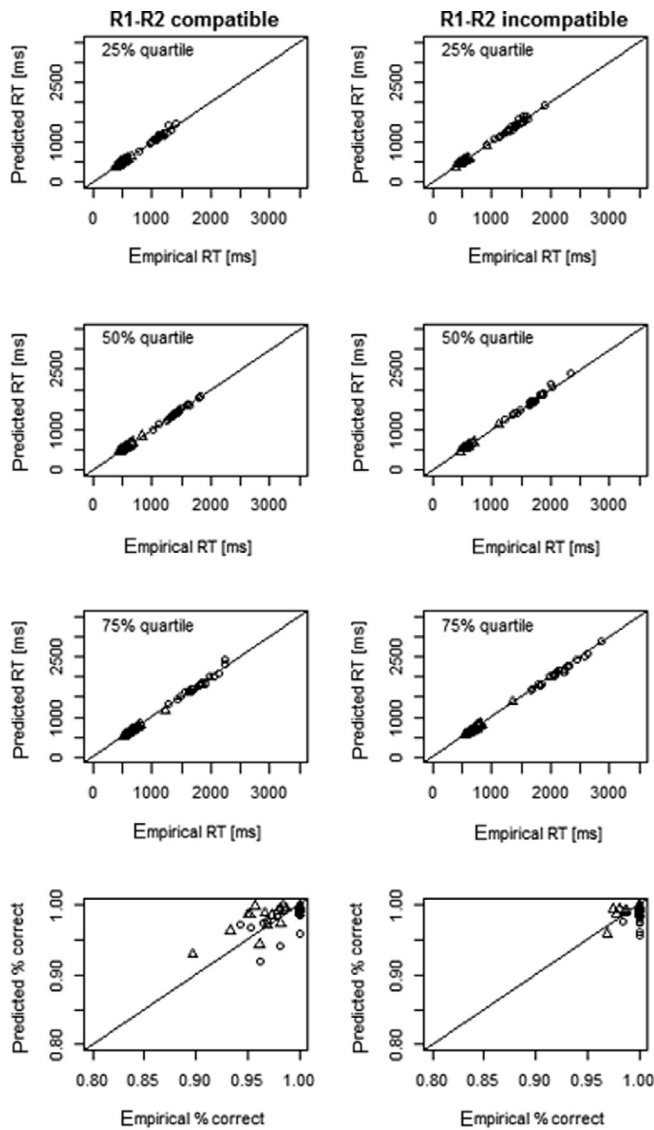**Fig. A1.** Observed RTs on the *x* axis and predicted RTs on the *y* axis (top three rows) and observed percentage correct (% correct) on the *x* axis and predicted % correct on the *y* axis (bottom row) of all participants separately for R1–R2 compatible trials (left column) and incompatible trials (right column) in Task 1. Unfilled circles represent single individuals from the child group, and unfilled triangles represent single individuals from the adult group. Perfect fit would be obtained when all data points lie on the plotted diagonal. Because only small amounts of errors were made in both age groups, RT analyses were restricted to correct trials. (For a similar approach see Voss, Rothermund, Gast, & Wentura, 2013, or Weeda et al., 2014.)

Appendix B.

This appendix summarizes the results from the application of the diffusion model to Task 2 for the sake of completeness (see Fig. B1). The data were treated as described for Task 1 (0.4% of the trials were excluded as outliers in this case). The Kolmogorov–Smirnov test calculated by the fast-dm software did not reveal deviations between the empirical and predicted distributions (all $ps \geqslant .474$).
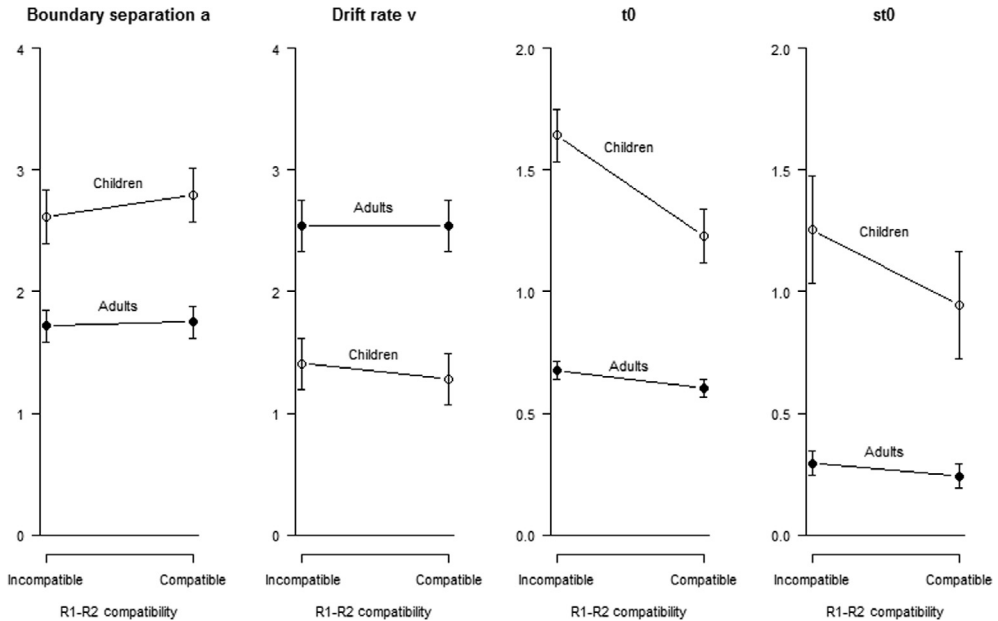
Fig. B1. Mean values of four parameters from the Task 2 diffusion model analyses as a function of R1–R2 compatibility and age group. Error bars are 95% confidence intervals of the difference between R1–R2 compatible and incompatible conditions, separately for each age group (see Pfister & Janczyk, 2013). From left to right: boundary separation *a*, drift rate *v*, non-decision time *t0*, and inter-trial variability of non-decision time s_{t0}.

Additional graphical illustrations of the model fit are given in Fig. B2 of this appendix. Because there is no systematic deviation from the diagonal, the model fit is reasonably good to interpret the results.

Results

Parameter means as a function of age group and R1–R2 compatibility are visualized in Fig. B1. *Boundary separation* was larger for children than for adults, $F(1,46) = 38.23$, $p < .001$, $\eta_p^2 = .45$, but was similar in compatible and incompatible trials, $F(1,46) = 2.87$, $p = .097$, $\eta_p^2 = .06$. The interaction was also not significant, $F(1,46) = 1.43$, $p = .238$, $\eta_p^2 = .03$. *Drift rate* was higher in adults than in children, $F(1,46) = 93.51$, $p < .001$, $\eta_p^2 = .67$, but was comparable in compatible and incompatible trials, $F(1,46) = 0.93$, $p = .341$, $\eta_p^2 = .02$. The interaction was not significant either, $F(1,46) = 0.88$, $p = .352$, $\eta_p^2 = .02$. The *non-decision time t0* was longer for children than for adults, $F(1,46) = 218.77$, $p < .001$, $\eta_p^2 = .83$, and overall was shorter in compatible trials compared with incompatible trials, $F(1,46) = 67.68$, $p < .001$, $\eta_p^2 = .60$. However, this effect was qualified by the significant Group × Compatibility interaction, $F(1,46) = 32.90$, $p < .001$, $\eta_p^2 = .42$. Thus, the decrease in non-decision time in R1–R2 compatible trials was larger for children, $t(23) = 7.30$, $p < .001$, $d = 2.11$, than for adults, $t(23) = 4.24$, $p < .001$, $d = 1.23$. The *inter-trial variability of the non-decision time s_{t0}* was larger for children than for adults, $F(1,46) = 109.66$, $p < .001$, $\eta_p^2 = .70$, and overall was smaller in compatible trials compared with incompatible trials, $F(1,46) = 10.44$, $p = .002$, $\eta_p^2 = .18$. However, this effect was qualified by the significant Group × Compatibility interaction, $F(1,46) = 5.34$, $p = .025$, $\eta_p^2 = .10$. Inter-trial variability decreased in R1–R2 compatible trials for children, $t(23) = 2.84$, $p = .009$, $d = 0.82$, and for adults, $t(23) = 2.07$, $p = .050$, $d = 0.60$.

Summary and brief discussion

Two aspects of this analysis are noteworthy. First, the decrease in boundary separation that was observed for Task 1 was not present for Task 2 data. Second, although drift rate was higher for adults
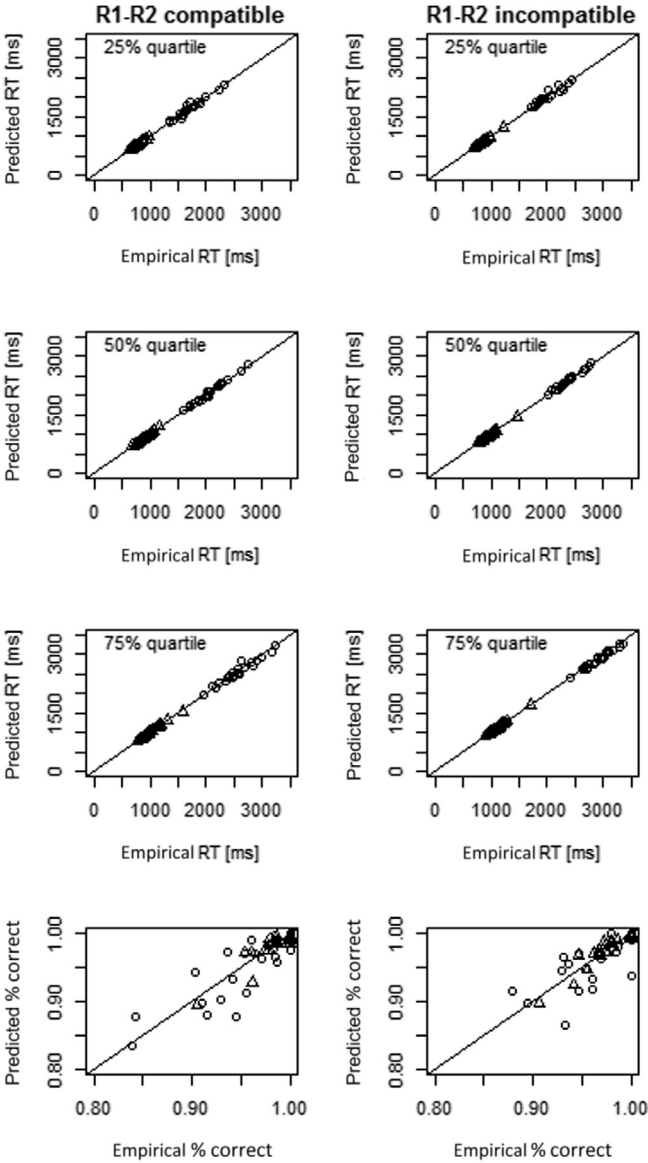
Fig. B2. Observed RTs on the *x* axis and predicted RTs on the *y* axis (top three rows) and observed percentage correct (% correct) on the *x* axis and predicted % correct on the *y* axis (bottom row) of all participants, separately for R1–R2 compatible trials (left column) and incompatible trials (right column) in Task 2. Unfilled circles represent single individuals from the child group, and unfilled triangles represent single individuals from the adult group. Perfect fit would be obtained when all data points lie on the plotted diagonal. Because only small amounts of errors were made in both age groups, RT analyses were restricted to correct trials. (For a similar approach see Voss et al., 2013, or Weeda et al., 2014.)

than for children again, it was not affected by the R1–R2 compatibility. Although it is agreed in the BCE literature that the Task 1 BCE results (at least in adults) from automatic Task 2 response activation, it is not clear whether the actual Task 2 response selection builds on this existing activation or not. Schubert, Fischer, and Stelzel (2008) concluded that it does not, whereas Thomson and Watter

(2013) suggested that is does but only in R1–R2 compatible trials. The similarity of drift rates *v* suggests that no additional S1 categorization occurs during Task 2 response selection, but the shortened non-decision time *t*0 might be taken to suggest that Task 2 response activation facilitates, for example, response execution processes.

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