The influence of stimulus-set size on developmental changes in cognitive control and conflict adaptation

Jutta Kray a,⁎, Julia Karbach a, Agnès Blaye b

a Saarland University, Saarbrücken, Germany
b University of Provence, Marseille, France

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A B S T R A C T

Cognitive control abilities substantially improve from early childhood to adulthood. The primary aim of this study was to examine the influence of stimulus-set size on developmental changes in cognitive control abilities such as task switching, interference control, and conflict adaptation. We assumed that a small stimulus set used in a task-switching paradigm would induce stronger task-stimulus priming that might increase the need for control, thereby amplifying age differences in cognitive control abilities. Therefore, we compared task-switching performance in a group of participants responding to a small stimulus-set (N=4) with a group responding to a large stimulus-set (N=96) in three age groups: kindergarten children (4.1–6.0 years of age), elementary school children (6.1–9.0 years of age), and young adults (21.0–28.0 years of age) on conflicting vs. non-conflicting trials (interference control) and following conflicting vs. non-conflicting trials (conflict adaptation). Results on the basis of error rates support the view that a small stimulus-set size during task switching (i.e., larger task-stimulus priming) increases the need for control as we found (a) worse control between non-switch trials (in mixed-task blocks) and single trials and (b) larger interference costs under small than large set-size condition for elementary school children as compared with young adults. Kindergarten children were less sensitive to the set-size manipulation and showed major problems in interference control while being in a task-switching situation, even if no actual task switch was required, possibly reflecting their inability to represent complex higher-order task rules.

1. Introduction

Cognitive control can generally be seen as an ability to flexibly adapt to continuous changes in the environment. It is conceptualized as a multidimensional construct, including a number of different abilities, such as goal maintenance and selection, switching, and inhibitory control (Huizinga, Dolan, & Van der Molen, 2006; Miyake, Friedman, Emerson, Witzki, & Howerton, 2000). Although these abilities are characterized by different lifespan developmental trajectories (e.g., Bedard et al., 2002; Cepeda, Kramer, & Gonzales De Sather, 2001; Gupta, Bhoomika, & Srinivasan, 2009; Karbach & Kray, 2007; Kray, Eber, & Karbach, 2008; Kray, Kipp, & Karbach, 2009; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), they significantly improve across childhood and mature well into adolescence (e.g., Davidson, Amso, Cruess Anderson, & Diamond, 2006; Huizinga et al., 2006; Reimers & Maylor, 2005).

Evidence for developmental changes in cognitive control is based on a variety of experimental paradigms, among them the task-switching paradigm. In this type of paradigm, participants are instructed to perform two simple classification tasks A and B. For instance, they classify objects according to their shape as a rabbit or a boat (task A) or according to their color as red or blue (task B). The two tasks have either to be performed in separate blocks (single-task blocks) or subjects have to switch between both tasks A and B within the same block (mixed-task blocks). This design allows calculating different types of costs reflecting different components of cognitive control (for a recent review, see Kiesel et al., 2010): Switching costs can be defined as difference in mean performance between switch trials (switching from task A to task B or task B to task A) and non-switch trials (repetition of task A or task B), and are assumed to reflect the ability to flexibly adapt to new task rules on a trial-to-trial basis (e.g., Rogers & Monsell, 1995). Mixing costs are determined as difference in performance between non-switch trials (in mixed-task blocks) and single trials and are assumed to reflect the ability to maintain both tasks A and B and to select between them. In some studies, researchers have applied ambiguous stimuli (e.g., a red and blue rabbit and a red and blue boat; similar to Stroop stimuli) to increase the demands on cognitive control
(e.g., Kray & Lindenberger, 2000; Rogers & Monsell, 1995). Thus, the stimuli included attributes relevant for each one of the tasks. In case only two response keys are used (e.g., a left key to indicate blue and a right key to indicate red and rabbit), task representations of both tasks A and B are partly overlapping. If the attributes of the two tasks are mapped onto different response keys (e.g., when a blue rabbit is presented), the currently irrelevant task attribute has to be ignored during response selection (incompatible trials). In contrast, on compatible trials the attributes of the two tasks are mapped onto the same response key (e.g., a blue boat). Thus, the ability to ignore irrelevant task attributes can be measured as the difference in performance between incompatible and compatible trials (in the following termed as interference costs). The advantage of a task-switching paradigm that includes single-task and mixed-task blocks as well as ambiguous stimuli is that interactions between three control components (switching, maintenance/selection, and interference control) can be measured with the same type of paradigm (cf., Cepeda et al., 2001).

1.1. Developmental changes in task switching

There are only a small number of developmental studies that have applied the task-switching paradigm in middle childhood (elementary school age). Most of them found larger developmental improvements in task maintenance/selection than in task switching (e.g., Crone, Ridderinkhof, Worm, Somsen, & Van Der Molen, 2004; Karbach & Kray, 2007; Kray, Eber, & Lindenberger, 2004; Kray et al., 2008) and developmental improvements in task switching (Huizinga & van der Molen, 2011) especially when irrelevant task attributes have to be ignored, that is, on incompatible trials (Gupta et al., 2009).

Studies focusing on cognitive control development in children younger than 5 years of age have usually applied modified versions of the task-switching paradigm, such as the day–night task (e.g., Diamond & Taylor, 1996; Gerstder, Hong, & Diamond, 1994), the preschool attentional switching task (e.g., Chevalier & Blaye, 2008), or the dimensional change card sort (DCCS; e.g., Kirkham, Cruess, & Diamond, 2003; Zelazo, Frye, & Rapsus, 1996). These studies indicated that even young children are able to maintain a given task rule, but that their switching ability and inhibitory control significantly increased between the ages of 3 and 6 (for reviews, see Garon, Bryson, & Smith, 2008; Zelazo & Jacques, 1996). However, given that the card sorting tasks applied to preschool children were often not computerized and reaction time was not measured, the analysis was mostly restricted to accuracy measures while speed of responding (or trade-offs, for that matter) was not analyzed. Moreover, the number of switch trials in these studies was often quite low which limits the reliability of the measurement of the switching performance. The few studies that have indeed investigated task switching in preschoolers have yielded mixed findings. Comparing preschoolers and elementary school children, some studies found age-related improvements in terms of task maintenance/selection but less in terms of task switching (Dibbets & Jolles, 2006; Karbach & Kray, 2007). In contrast, Davidson et al. (2006) reported worse switching abilities in preschoolers than in middle childhood than in early childhood. In terms of task switching abilities than task maintenance/selection, which is possible associated with the maturation of different sub-regions of the prefrontal cortex (cf., Bunge, Dudukovic, Thomasan, Vaidya, & Gabrieli, 2002; Crone et al., 2004; Stuss, 1992; Van der Molen, 2001; for a review, see Casey, Tottenham, Liston, & Durston, 2005).

1.2. Developmental changes in conflict adaptation

The efficiency of the cognitive control system has been measured not only by costs reflecting the adaptation to a new task (as a task sequence effect) but also by costs varying as a function of adaption to a previous conflict trial (i.e., a previous incompatible trial). The finding that interference costs are smaller following incompatible trials than following compatible trials was first observed by Gratton and colleagues with the flanker task (termed as Gratton effect; Gratton, Coles, & Donchin, 1992). According to cognitive control theories, the Gratton effect occurs because more control is needed to ignore irrelevant information, and as a consequence more attention is directed towards task-relevant information in the following trial, resulting in reduced interference. These theories assume that a control system is monitoring the amount of conflict from trial to trial. If a conflict is detected, attention is biased towards processing relevant and ignoring irrelevant information (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). Other researchers suggested that the Gratton effect could solely be explained by stimulus priming effects, that is, by stimulus-feature binding (Mayr, Awh, & Launey, 2003; Schmidt, Crump, Chessman, & Besner, 2007). Indeed, there is evidence that the Gratton effect is substantially reduced when stimulus priming effects (stimulus and response repetitions) are reduced (Mayr et al., 2003) and it has been shown that the interference effect is sensitive to the proportion of compatible trials (e.g., Tzelgov, Henik, & Berger, 1992). Recently, there were also attempts to integrate both views by Verguts and Notebaert (2008, 2009). In particular, these authors proposed that conflict (e.g., induced by the proportion of incompatible trials) strengthens the bindings between tasks and stimuli, and thereby should facilitate performance on task-repetitions trials but affect performance on task-switching trials. Hence, the Gratton effect should be present for task repetitions but be reduced or reversed on task-switching trials.

To our knowledge, there is so far no study that specifically looked at developmental changes in conflict adaptation as measured with Gratton effect described above. Aside from task switching, there are at least some developmental studies that examined developmental changes in between-trial adjustments. They reported evidence for a developmental decrease from about the age of 6 years (a) in response slowing following errors (post-error slowing; e.g., Gupta et al., 2009), (b) in response slowing on response repetitions on task-repetition trials (e.g., Crone, Bunge, Van Der Molen, & Ridderinkhof, 2006), and (c) in response errors if parts of a stimulus–response mapping are repeated (either the stimulus or the response; Hommel, Kray, & Lindenberger, 2011), but not (d) in behavioral adjustments following stopping trials (Van de Laar, van der Wilderberg, van Bokel, & van der Molen, 2011).

1.3. Study goals and predictions

The main goal of the present study was to investigate developmental changes in task switching and interference control as a function of conflict induced by task-stimulus priming (by variations of stimulus-set size). At a more general level, our aim was to assess methodological as well as theoretical issues that are highly relevant for the study of developmental changes in cognitive control by means of task-switching paradigms.

The methodological issue is related to the fact that quite a number of studies, especially those investigating preschool children, included only a few different stimuli (typically four) in their experimental design to make the task as simple as possible (e.g., for preschool-aged children) and to reduce stimulus-specific variance (e.g., Chevalier & Blaye, 2008; Kirkham et al., 2003; Zelazo & Jacques, 1996; Zelazo et al., 1996). However, in 1995, Rogers and Monsell already argued that a small set of stimuli in task-switching experiments results in stronger associations between task cues, stimulus attributes, and responses than a large set
of stimuli. Importantly, they assumed that these associations might impair the ability to reconfigure task rules on switching trials. Hence, the methodological approach of these task-switching studies, namely to simplify the task and to reduce stimulus-specific variance, also comes at a cost: task-stimulus priming is much larger with only four rather than a larger number of different stimuli, resulting in an increased need for cognitive control (cf., Verguts & Notebaert, 2008, 2009) which directly points to the theoretical implications of this approach.

Evidence for the view that task-stimulus priming (induced by variations of stimulus set size) can indeed influence age differences in task switching and interference control comes from a study by Kray and Eppinger (2006) that examined switching and interference costs in younger and older adults as a function of stimulus-set size and practice. They found reliable age differences in switching costs only for a small stimulus set size (four stimuli) and older adults showed larger switching costs under smaller than under larger set-size conditions. Furthermore, for the smaller set size only younger adults showed a reduction of switch costs on compatible as well as on incompatible trials with practice, while older adults showed this reduction only on compatible trials. This effect was not present for a larger set size.

The focus of this study is on examining the influence of stimulus-set size on developmental changes in cognitive control and conflict adaptation from early childhood to adulthood. To investigate developmental changes, we included three age groups: kindergarten children, elementary school children, and young adults. All participants performed a cue-based switching paradigm including pictures of familiar objects that were presented successively on the computer screen (e.g., a red rabbit or a white boat). The participants had to perform two tasks (an object and a color task) that were indicated by two simple cues (see Procedure and Fig. 1). They performed single-task as well as mixed-task blocks, allowing us to analyze mixing costs and switching costs. Moreover, all stimuli were ambiguous and participants were only to use two different keys to give their manual responses. Half of the trials were incompatible and the other half compatible, allowing us to additionally analyze interference costs. Moreover, to examine developmental changes in conflict adaptation, we analyzed interference costs as a function of conflict (compatible or incompatible trial) on the previous trial (i.e., the Gratton effect). Finally, the experiment included two different stimulus-set sizes that were manipulated between subjects to vary task-stimulus priming. That is, one group only responded to four different stimuli (set-size group 4) throughout the entire experiment, while the other one responded to 96 different stimuli (set-size group 96).

On the basis of previous findings we expected (a) a decrease of mixing costs and switching costs with age that should be more pronounced for mixing than for switching costs (e.g., Karbach & Kray, 2007; Kray et al., 2008), and (b) a decrease of interference costs with increasing age (e.g., Huizinga et al., 2006; Van der Molen, 2001). Furthermore, we also predicted (c) larger interference costs in mixed-task blocks than in single-task blocks as well as (d) larger interference costs on switch than on non-switch trials (e.g., Meiran, 2000), and (e) these effects should be largest for the younger children (cf., Crone et al., 2006; Davidson et al., 2006). Moreover, if greater task-stimulus priming (under conditions with a small stimulus-set size) indeed increases the need for control (cf., Verguts & Notebaert, 2008, 2009), we would expect (f) larger switching costs with a small stimulus-set size, at least for age groups that show less efficient cognitive control processes (i.e., children). Note that we previously only found reliable age differences in switching costs under conditions with a small stimulus-set size when comparing young and older adults (Kray & Eppinger, 2006).

The second set of predictions is related to conflict adaptation. Considering a number of previous findings, we predicted (a) that interference costs will be larger following a compatible trial than following an incompatible trial (Gratton et al., 1992), and (b) this effect should be present in single-task blocks as well as on non-switch trials while it should be reduced or reversed on switch trials (cf., Verguts & Notebaert, 2008, 2009). Again, if task-stimulus priming increases the need for cognitive control, we expected (c) this effect to be more pronounced under a small stimulus-set size than a large stimulus-set size. Given that there is some neurophysiological evidence for developmental changes in conflict monitoring (e.g., Braet et al., 2009, Velanova, Wheeler, & Luna, 2008) one may expect (d) that especially younger children are less efficient in the adjustment to conflict, therefore the Gratton effect should be reduced in this age group. However, at least to our knowledge, there is so far no behavioral study that looked at conflict adaptation as measured with the Gratton effect in early and middle childhood, but one lifespan study that failed to find developmental changes in behavioral adaptations after stopping trials during middle childhood (Van de Laar et al., 2011).

2. Methods

2.1. Participants

Overall 151 participants were recruited for this study: fifty-two kindergarten children aged between 4.1 and 6.0 years, 48 elementary school children between 6.1 and 9.0 years and 48 young adults aged between 21.0 and 28.0 years. Eighteen kindergarten children, six elementary school children as well as two young adults were excluded from data analyses either because they did not finish the experiment or because the performance in the experimental task was more than 2.5 standard deviations above their corresponding group mean. All young adults were students at Saarland University. The children were recruited from a subject pool at Saarland University or in local kindergartens. Young adults and older children were paid 7.50 Euro for a single-session experiment. The younger children were tested in a two-session experiment. They received small presents for their participation and the kindergartens were given money to buy games (total amount per child: 6 Euro).

The effective sample consisted of 36 younger children, 42 older children, and 46 young adults. Table 1 displays the sample characteristics for the three age groups and the two set-size groups. Because the effect of stimulus set-size was tested between subjects, we applied a color-naming test to control for differences in speed of processing (as a marker test of fluid intelligence) between the experimental groups in each age group. In this test, participants saw a sheet with a template in the top row assigning four different colors to four different shapes (yellow circle, blue cross, red triangle, and green square). Subjects

![Fig. 1. The trial procedure of the switching tasks (upper panel: object task, lower panel: color task).](image-url)
were instructed to name the corresponding colors for a series of uncolored shapes displayed below the template as quickly and as accurately as possible. The test score was the number of correctly named colors after 45 s. Analysis of variance (ANOVA) with the between-subjects factors age group (kindergarteners, elementary school children, young adults) and set-size group (4 stimuli, 96 stimuli) showed a reliable main effect of age group, $F(2, 123) = 311.10, p < .001, \eta^2 = .84$, suggesting that the speed of processing increased with age, but we obtained no main effect of set-size group or interactions between age group and set-size group.

### Table 1

Descriptive variables for the three age groups and two set-size groups.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Kindergarten children</th>
<th>Elementary school children</th>
<th>Young adults</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Set size 4</td>
<td>Set size 96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>n</td>
<td>17</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Mean age</td>
<td>4.8</td>
<td>0.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Color naming test score</td>
<td>18.6</td>
<td>8.0</td>
<td>18.8</td>
</tr>
</tbody>
</table>

2.2. Materials and tasks

IBM compatible laptops (Dell™ Latitude™ D820) were used for data collection. The stimuli were presented on a WXGA 15.4-inch color monitor with a white background. We used the software package E-Prime 1.1 to present the stimuli and record reaction times (RT).

In the switching task, the participants were instructed to perform two tasks (task A and task B) either in separate blocks (single tasks) or they had to switch between both tasks (mixed tasks). Pictures of familiar objects (cf., Cannard, Blaye, Scheuner, & Bonthoux, 2005; Snodgrass & Vanderwart, 1980) were presented on successive trials on the screen. In task A, the participants were to classify objects as “animals” or “things” by pressing either right or left response key. In task B, they were to decide whether the color of the pictures was “white” or “colored”, also by pressing right or left response key. The same two response keys were used for both tasks.

As we used only two response keys for four attribute categories, all stimuli were ambiguous. Four attribute combinations were possible: animal/white, animal/colored, thing/white, or thing/colored. In the set-size group 4, only four picture stimuli (i.e., white rabbit, colored rabbit, white boat, colored boat) were presented, meaning that there was only one stimulus per attribute combination. For the set-size group 96, the stimulus-set size consisted of 96 different object pictures; thus, there were 24 different stimuli per attribute combination.

In order to help participants to keep track of the task sequence, we used symbolic cues for each task. The cue for the object task consisted of prototypical pictures of the four possible attribute combinations and the cue for the color task included different colors (including white) (see Fig. 1).

2.3. Procedure

For the older children and the young adults, testing took approximately 45 min. The 5-year-olds were tested in two sessions, each of them lasting of about 35 min. At the beginning of each session, young adults and the parents of the children provided written informed consent and completed a short demographic questionnaire. Afterwards, the color-naming test was administered, followed by the switching task.

The switching task consisted of a short practice phase and an experimental phase. In the practice phase, subjects performed two blocks, each with 12 trials, in which they performed only the object task or the color task. Then, they performed a mixed-task block that consisted of 25 trials. In the experimental phase, each participant worked through 24 blocks, 12 single-task blocks and 12 mixed-task blocks. Two single-task blocks and two mixed-task blocks were always grouped together. This sequence of blocks was constant across subjects and experimental conditions while the sequence of trials within each block was varied across subjects.

Each experimental block consisted of 25 trials, yielding a total of $25 \times 24 = 600$ trials. The first trial in each block was not analyzed. The number of the four attribute combinations (animal/white, animal/colored, thing/white, thing/colored) and the number of compatible and incompatible trials was counterbalanced and equally distributed across blocks. On compatible trials, attributes of both different tasks A and B (e.g., animal and white) were mapped onto the same response key, and on incompatible trials, they were mapped onto different response keys. In addition, mixed-task blocks consisted of an equal number of non-switch and switch trials.

Each trial started with a symbolic cue (see Fig. 1) that was presented on the bottom of the screen. After 600 ms, the object picture appeared in the middle of the screen and was presented until the subject responded. The time interval between the response and the presentation of the next cue was fixed to 800 ms.

At the beginning of each experimental block, an instruction window indicated whether task A, task B, or both tasks had to be performed in the following block. Participants were told to respond as quickly and as accurately as possible. After each experimental block, they were provided feedback regarding their mean response times and percentage of errors.

3. Results

The analyses were based on error rates (%) and on median RTs (ms) for correct responses. Practice trials and the first trial within a block were excluded from all analyses. In order to control for age differences in baseline performance on the level of latencies, we ran the analyses not only on median RTs but also on log-transformed RTs. Unless reported otherwise, results of both analyses were consistent.

The Results section is divided into two parts. In the first part, we report stimulus-set size effects on age differences in cognitive control, and in the second part, we report the effects of stimulus-set size on age differences in conflict adaptation.

3.1. Stimulus-set size effects on age differences in mixing, switching and interference costs

3.1.1. Error rates

The ANOVA included the two between-subjects factors age group (kindergarteners, elementary school children, young adults) and set-size group (4 stimuli, 96 stimuli), and the two within-subjects factors trial type (single, non-switch, switch) and compatibility (compatible, incompatible). To test for age effects we specified two contrasts: the first contrast compared the performances of younger children (kindergarteners) with older children (elementary school children), and the second contrast compared performances of older children with young adults. Similarly, mixing and switching costs were tested by two trial-type contrasts: The first contrast compared the mean performance between single task and non-switch trials
(mixing costs), and the second contrast compared the mean performance between non-switch and switch trials (switching costs).

Means and standard errors of the means based on error rates for all experimental conditions are shown in Table 2 as a function of set-size group, age group, trial type, and compatibility. The corresponding interference costs are illustrated in Fig. 2 as a function of trial type for each age group and set-size group, respectively.

Results on error rates indicated that both age group contrasts were significant, that is, error rates were higher for younger than for older children, \( F(1, 118) = 17.0, p < .001, \eta^2 = .13 \), and also higher for older children than for young adults, \( F(1, 118) = 13.6, p < .001, \eta^2 = .11 \). Participants also made more errors on non-switch trials than on single trials (mixing costs), \( F(1, 123) = 36.26, p < .001, \eta^2 = .23 \), and on switch trials than on non-switch trials (switching costs), \( F(1, 123) = 95.36, p < .001, \eta^2 = .44 \), as well as on incompatible than on compatible trials, \( F(1, 123) = 155.60, p < .001, \eta^2 = .56 \) (interference costs). Furthermore, the factor compatibility interacted with both trial type contrasts, indicating that interference costs were larger on non-switch trials than on single trials, \( F(1, 123) = 53.25, p < .001, \eta^2 = .30 \), as well as larger on switch trials than on non-switch trials, \( F(1, 123) = 112.08, p < .001, \eta^2 = .48 \) (see Fig. 2).

In line with our expectations, we also obtained age differences in the first trial type contrast (mixing costs), indicating more pronounced mixing costs for younger than for older children, \( F(1, 118) = 80.8, p < .001, \eta^2 = .41 \), and also for older children than for young adults, \( F(1, 118) = 5.19, p = .05, \eta^2 = .04 \). Thus, we found a decrease of mixing costs with increasing age. However, we did not obtain reliable age effects on the second trial type contrast (switching costs; \( p = .23 \) and \( p = .84 \); respectively), which is in line with our expectation that developmental changes should be more prominent in mixing than in switching costs. Also in line with our expectation, the factor compatibility interacted with both age group contrasts. Interference costs, that is, higher error rates on incompatible than on compatible trials, were greater for younger children than for older children, \( F(1, 118) = 22.7, p < .001, \eta^2 = .16 \), and also greater for older children than for young adults, \( F(1, 118) = 12.2, p < .001, \eta^2 = .09 \). Hence, interference costs also decreased with increasing age.

Finally, we also obtained age effects in the interaction between compatibility (interference costs) and the first trial-type contrast (mixing costs), suggesting that error rates were higher on incompatible than on compatible trials when subjects performed non-switch trials in mixed-task blocks as compared with single-task trials, and this effect was also larger for younger than for older children, \( F(1, 118) = 61.1, p < .001, \eta^2 = .34 \), and for older children than for young adults, \( F(1, 118) = 7.72, p < .01, \eta^2 = .06 \). Age effects were not significant for interactions between compatibility and switching costs (\( p = .07, p = .50 \), respectively).

Of most interest were interactions with the set size. As can be seen in Table 2, the older children showed larger interference costs than the younger ones when the set size was small compared to when it was large. Indeed, the ANOVA showed reliable interactions between both age group contrasts, compatibility, and set-size group, indicating that interference costs were larger under small than large set-size conditions for the older children compared to the younger ones, \( F(1, 118) = 6.1, p < .05, \eta^2 = .05 \), and also compared to the young adults, \( F(1, 118) = 5.2, p < .05, \eta^2 = .04 \). Separate analyses for each age group revealed that the interaction between set-size group and compatibility was only reliable for the older children, \( F(1, 40) = 6.5, p < .05, \eta^2 = .14 \) (see Fig. 3). However, not in line with our expectation was that we did not find interactions between age group contrasts, set-size group, and switching costs (\( p = .68, p = .78 \), respectively).
3.1.2. Latencies

The ANOVA design and contrasts were identical to the ones in the previous section. The means and standard errors of the means for all experimental conditions are displayed in Table 3 as a function of set-size group, age group, trial type, and compatibility. Interference costs are shown in Fig. 3 as a function of trial type separately for each age group and set-size group.

ANOVA results on latencies indicated reliable age differences in processing speed; the younger children responded much slower than the older children, \(F(1, 118) = 62.7, p < .001, \eta^2 = .35\), and the older children responded much slower than the young adults, \(F(1, 118) = 121.75, p < .001, \eta^2 = .51\). In line with results on error rates, both trial type contrasts were significant, that is, participants responded faster on single trials than on non-switch trials, \(F(1, 123) = 97.97, p < .001, \eta^2 = .44\), and faster on non-switch trials than on switch trials, \(F(1, 123) = 53.72, p < .001, \eta^2 = .30\), indicating reliable mixing and switching costs, respectively. Also in line with the results on error rates, we found a reliable compatibility effect, \(F(1, 123) = 45.48, p < .001, \eta^2 = .27\), suggesting that participants responded faster on compatible than on incompatible trials (interference costs). Moreover, interference costs were larger on switch than on non-switch trials, \(F(1, 123) = 5.73, p < .05, \eta^2 = .05\) (see Fig. 2).

Regarding age differences, we found that mixing costs were greater for younger than for older children, \(F(1, 118) = 8.37, p < .001, \eta^2 = .07\), and also larger for older children than for young adults, \(F(1, 118) = 20.77, p < .001, \eta^2 = .15\). Based on proportional scores (log-transformed RT), the difference in mixing costs between older children and young adults was reliable, \(F(1, 118) = 8.29, p < .01, \eta^2 = .07\), but the difference between younger and older children was not \((p = .93)\). Results are nevertheless in line with the expectation that mixing costs decreased with increasing age. Furthermore, the analysis showed reliable interactions between both age-group contrasts and the second trial-type contrast (switching costs). Based on median RT, switching costs were larger for older children than for young adults, \(F(1, 118) = 13.6, p < .001, \eta^2 = .10\), but smaller for younger than for older children, \(F(1, 118) = 5.01, p < .05, \eta^2 = .04\). However, in line with previous studies (e.g., Karbach & Kray, 2007), age differences in switching costs failed to reach significance on the basis of proportional scores (log-transformed RT) \((p = .14, p = .27, \text{respectively})\). In line with the error analysis, we also obtained interactions between compatibility and both age-group contrasts, that is, interference costs (i.e., longer latencies on incompatible than on compatible trials) were larger for younger than for older children, \(F(1, 118) = 14.3, p < .001, \eta^2 = .11\), and also larger for older children than for young adults, \(F(1, 118) = 5.05, p < .05, \eta^2 = .04\). On the basis of proportional scores, age differences in interference costs were not significant when comparing older children and young adults \((p = .21)\) and were only marginally reliable when comparing younger and older children, \(F(1, 118) = 3.39, p = .07, \eta^2 = .03\). Hence, age-related improvements in interference control seem to occur earlier in childhood than improvements in goal maintenance/selection. Finally, we obtained a three-way interaction between compatibility (interference costs), trial-type contrast 2 (switching costs) and age-group contrast 1 (younger vs. older children) on the basis of proportional scores, \(F(1, 118) = 12.07, p < .01, \eta^2 = .09\), suggesting that especially younger children had problems to control interference when they had to switch between tasks.

Of most interest in the present study was whether set size influenced age differences in task switching and interference control. Results of the ANOVA indicated only a marginally significant interaction between
switching costs and set-size group, \( F(1, 118) = 3.37, p = .07, \eta^2 = .03 \), but this interaction was not qualified by age (ps > .10), and in contrast to the analysis based on error rates, we did not obtain interactions with compatibility.

3.1.3. Controlling for speed–accuracy trade-offs

Given that some of the age effects were only present for the accuracy data but not for the latency data or vice versa, it is reasonable to assume that age differences in speed–accuracy trade-offs may have influenced the results of the present study. To rule out this possibility, we computed correlations between latencies and error rates for all experimental conditions. For the whole sample, all correlations were positive, ranging between \( r = .10 \) and \( r = .42 \), suggesting that longer latencies were generally related to higher error rates. However, separate analyses for each one of the age groups showed that some correlations were negative. For the kindergarten children, all correlations between latencies and error rates on compatible trials were positive (\( r = .13–.44 \)), while correlations between latencies and error rates on incompatible trials were negative (\( r = -.12–-.40 \)). The negative correlations were significant at the 5% level for non-switch trials, \( r = -.37 \), as well as for switch trials, \( r = -.40 \), suggesting that faster responding was associated with higher error rates in switching situations. For the elementary school children, we obtained no significant positive correlations for single-task trials (\( r = .11 \) for compatible and \( r = .09 \) for incompatible trials), while correlations were negative on all mixing trials (\( r = -.11–-.46 \)). Significant negative correlations at the 1%-level were only found for incompatible switch trials, \( r = -.46 \). For young adults, all correlations between latencies and error rates on compatible trials were positive (\( r = .03–.27 \)), while correlations between latencies and error rates on incompatible trials were negative (\( r = -.05–-.34 \)). Negative correlations were significant at the 5% level on incompatible single trials (\( r = -.34 \)).

This pattern of correlations indeed suggests that faster responding is accompanied by higher error rates, at least on interference trials. For adults, this tendency was restricted to single-task trials, while the children in both age groups primarily showed it on mixing trials.

3.2. Stimulus-set size effects on age differences in conflict adaptation

To investigate age differences in conflict adaptation we analyzed interference costs (the amount of conflict in an actual trial \( n \)) as a function of interference in the previous trial (\( n-1 \)), that is, following a compatible or incompatible trial. Means and standard errors of the means based on error rates for all experimental conditions are shown in Fig. 4 as a function of trial type, age group, and set-size group.

3.2.1. Error rates

The ANOVA again included the two-between-subjects factors age group (kindergarteners, elementary school children, young adults) and set-size group (4 stimuli, 96 stimuli), and the two within-subjects factors trial type (single, non-switch, switch) and \( n-1 \) compatibility (compatible, incompatible). We used the same age group contrasts and trial type contrasts for mixing and switching costs as in the previous section.

In line with our predictions, the results revealed a reliable \( n-1 \) compatibility effect, \( F(1, 118) = 13.11, p < .01, \eta^2 = .10 \), indicating that interference costs were larger following a compatible than following an incompatible trial (the Gratton effect). Moreover, this effect interacted with the second trial type contrast (switching costs), \( F(1, 118) = 8.87, p = .05, \eta^2 = .03 \), showing that the Gratton effect was larger on non-switch trials than on switch trials. As expected, the Gratton effect did not interact with the first trial type contrast (mixing costs) (\( p = .30 \)), that is, the Gratton effect was present both on single-task trials and non-switch trials (see Fig. 4).

Again of particular interest were interactions of the Gratton effect with age group and set-size group. Indeed, we found a significant interaction between the \( n-1 \) compatibility effect, the first age group contrast (kindergarten vs. elementary school children), and set-size group: \( F(1, 118) = 3.97, p = .05, \eta^2 = .03 \), separate analyses for both set-size groups revealed that the Gratton effect was reliable only for the small-set-size group, \( F(1, 62) = 10.63, p < .01, \eta^2 = .15 \), and was reduced when subjects had to switch between tasks as compared with task-repetition trials, \( F(1, 62) = 5.25, p < .05, \eta^2 = .08 \). Finally, the Gratton effect was somewhat smaller for younger than for older children, \( F(1, 62) = 2.95, p = .09, \eta^2 = .05 \). For the large-set-size group, the Gratton effect was only marginally significant, \( F(1, 62) = 2.14, p = .08, \eta^2 = .05 \), and did neither interact with trial type nor with the two age-group contrasts.

3.2.2. Latencies

The ANOVA design was identical to the one for the error rates. Results on the basis of latencies also showed a significant \( n-1 \) compatibility effect, \( F(1, 118) = 13.50, p < .01, \eta^2 = .10 \), suggesting that interference costs were reduced following incompatible as compared to compatible trials (Gratton effect). In contrast to the error rates, the Gratton effect did not vary with trial type or set-size group or between younger and older children. We only obtained a larger Gratton effect for older children as compared to young adults, \( F(1, 118) = 5.66, p < .05, \eta^2 = .05 \). This effect was also significant on the basis of log-transformed RTs, \( F(1, 118) = 14.47, p < .01, \eta^2 = .11 \).

4. Discussion

The main goal of this study was to determine the influence of stimulus-set size on developmental changes in cognitive control abilities such as task switching, interference control, and conflict adaptation. To examine this, we included three age groups from early and middle childhood and young adulthood and applied a cue-based task-switching paradigm with ambiguous stimuli. The purpose of this study was twofold: first, to determine whether age differences in cognitive control components reflected by mixing, switching, and interference costs were larger when the need for control was increased by task-stimulus priming that was induced by manipulations of stimulus-set size. Second, we investigated age differences in between-trial adjustments (the Gratton effect), that is, adjustments to the presence of a previous conflict (incompatible trial).

First of all, the results on developmental changes in cognitive control are fully in line with empirical evidence from previous studies (e.g., Bunge et al., 2002; Cepeda et al., 2001; Crone et al., 2004; Crone et al., 2006; Davidson et al., 2006; Dibbets & Jolles, 2006; Huizinga et al., 2006; Karbach & Kray, 2007; Kray et al., 2004; Kray et al., 2008; Reimers & Maylor, 2005). Both the results based on latencies and error rates showed that mixing costs as well as interference costs decreased with increasing age, suggesting that the ability to select and maintain task-set representations as well as the ability to suppress irrelevant task information improved from early childhood to young adulthood. The latency results further suggest that improvements in interference control occur somewhat earlier during childhood development than improvements in maintaining and selecting relevant task-set instructions.

Also in line with our predictions was the finding that developmental changes were less pronounced in switching costs than in mixing costs. We found no reliable age differences in switching costs, based neither on accuracy nor on latencies (not even when age differences in baseline performance were taken into account). Note that so far only a few studies examined task switching in children aged between 4 and 6 years with a modified task-switching paradigm (Davidson et al., 2006; Dibbets & Jolles, 2006; Karbach & Kray, 2007). The results of these studies were quite mixed. Dibbets and Jolles (2006) found age differences neither in RT mixing and switching costs nor in switching costs on the level of accuracy. Only mixing costs based on errors decreased from early to middle childhood. Davidson et al.
(2006) also found no age differences in RT switching costs but found an increase in switching costs on the level of error rates from early to middle childhood. In contrast, mixing costs decreased from early to middle childhood based on error rates but increased with age based on latencies, a pattern that is likely due to age differences in speed–accuracy trade-offs. However, none of these studies is directly comparable to the present one because they only used univalent stimuli while the present study exclusively relied on bivalent stimuli (cf., Karbach & Kray, 2007).

A few other developmental studies also analyzed interactions between interference control and task switching and found that the ability to ignore currently irrelevant task information in the context of task switching develops substantially with increasing age (Crone et al., 2006; Davidson et al., 2006). Our results indicated larger task-switching costs on incompatible than on compatible trials (e.g., Meiran, 2000). For mixing costs, this effect was more pronounced for elementary school children than for young adults (cf., Cepeda et al., 2001) and also more pronounced for kindergarteners than for elementary school children. However, in the present study these interactions were restricted to the error data (see Fig. 3). This is consistent with Crone et al. (2006) who reported the interactions between switching costs and interference costs on the level of accuracy to be larger for elementary school children than for young adults. Note that some developmental researchers found that age changes in the accuracy of responding were more sensitive to age differences in performance than age changes in latencies (e.g., Diamond & Kirkham, 2005; Hommel et al., 2011; Karbach, Kray, & Hommel, 2011), given that latencies are often highly variable in younger children as in the present study (see also Fig. 3; for a further discussion see below).

The specific goal of this study was to determine whether the number of stimuli included in a task-switching paradigm influences developmental changes in cognitive control. We argued that paradigms with only a small stimulus set size (often used in developmental studies to reduce complexity) may induce stronger task-stimulus priming, thereby increasing the need for control on as well as across conflicting trials. Along this line, we found effects of stimulus set size in the expected direction for the error rates. As displayed in Fig. 2, the results showed a differential developmental pattern in interference control for the two set-size groups (see Fig. 3). The kindergarten children showed large impairments in interference control, that is, they made much more errors on incompatible than on compatible trials, independently of task-stimulus priming. One possible explanation for this finding is that younger children are generally more stimulus-driven and less able to represent and to maintain task rules on a higher-order level (cf., Zelazo & Jacques, 1996; Zelazo et al., 1996). There is indeed evidence that the ability to develop higher-order task representations and to translate cues into a verbal format improves during childhood development (Blaye & Chevalier, 2011; Chevalier & Blaye, 2009). Thus,
young children may be less sensitive to task-stimulus priming, because they are less efficient in representing higher-order task goals. In contrast, the elementary school children were more sensitive to task-stimulus priming, as interference costs were substantially larger for a smaller than for larger stimulus-set size, whereas this effect was less pronounced for young adults. Hence, with the improved ability to represent task goals, task-stimulus priming increases the demands on cognitive control processing, resulting in higher error rates on incompatible as compared with compatible trials.

Consistent with these theoretical interpretations are the results for developmental changes in conflict adaptation. First of all, we were able to replicate the well-known Gratton effect in our study, that is, interference costs (RTs as well as error rates) were reduced following incompatible trials. The idea here is that on incompatible trials, the current conflict signals the need for control and therefore relevant task representations are strengthened, so that less interference occurs on the following trial. This adaptation process should facilitate performance on task-repetition trials (here for single and non-switch trials) but not on switch trials because the strengthening of the currently irrelevant task makes switching to the other one more difficult. Results on the basis of error rates indeed provide evidence for this hypothesis. The Gratton effect was reduced on switch trials, and, as shown in Fig. 4, sometimes even reversed as compared to non-switch trials, while there was no difference between single and non-switch trials.

A second noteworthy finding is that the Gratton effect was also susceptible to task-stimulus priming, that is, it varied with stimulus-set size. The Gratton effect was larger under small than large set-size conditions. This is in line with a number of studies demonstrating that the Gratton effect is influenced by stimulus-specific priming, as it is largely reduced when stimulus and response repetitions are excluded (cf., Mayr et al., 2003). Moreover, the larger Gratton effect under small stimulus set-size conditions was more pronounced for older children than for younger children, while no difference was obtained between older children and young adults. Hence, elementary school children were more susceptible to bindings between task representations and stimuli.

According to conflict monitoring theories (e.g., Botvinick et al., 2001), at least two brain regions are critically involved in cognitive control. The anterior cingulate cortex seems to be required for conflict detection. The need for control is then signaled to the dorsolateral prefrontal cortex (DLPFC) that is mainly responsible for maintaining and biasing currently appropriate task-set representations (Miller & Cohen, 2001). Since the prefrontal brain regions mature relatively late during childhood development (Casey et al., 2005; Gogtay et al., 2004), results of the present study suggest that the ability to detect conflict develops earlier during childhood development, while the flexible adaptation to conflict or new task requirements is strongly dependent on the appropriate maintenance of task representation. Recently, Bunge and Zelazo (2006) proposed that improvements in using more complex task rules (as switching between ambiguous stimuli) during early childhood development (between 2 and 5 years) depend on the maturation of an increasingly complex hierarchical network of the PFC regions. In particular, the dorsolateral and rostral lateral PFC are involved when switching between ambiguous tasks is required, and these regions mature latest during childhood development (Gogtay et al., 2004; O’Donnell, Noseworthy, Levine, & Dennis, 2005). Therefore, it is reasonable to assume that the kindergarten children in the present study had problems in representing higher-order rules and were therefore less sensitive to manipulations of the task context (stimulus-set size).

4.1. Limitations of this study

Some limitations of the present study have to be acknowledged. First of all, our young children’s group may be positively selected given that a number of 4-to-6 year-old children were not able and/or not willing to finish the experiment (n = 18). Although we made the switching task as easy as possible, for instance by providing simple task cues (pictures indicating the object and the color task, see Fig. 1), it still was quite difficult for them to perform the switching task. This difficulty may have been strengthened by the fact that, in contrast to previous studies (Davidson et al., 2006; Dibbets & Jolles, 2006), we only included bivalent stimuli. Given that these studies reported similar exclusion rates (e.g., Dibbets & Jolles, 2006), a likely reason for this relatively high drop out rate is that the brain regions involved in representing higher-order task rules are still maturing (Bunge & Zelazo, 2006).

Second, we used a between-subjects design to manipulate stimulus-set size because of the limited testing time for 4-to-6-year-old children. However, to control for individual differences in perceptual speed of processing across groups, we applied a modified version of the Digit-Symbol Substitution test that was adapted for testing with children (the color naming test) in this study. This test measures fluid intelligence and is known to be highly correlated with reasoning tests (e.g., Kray & Lindenberger, 2000). Importantly, we found no significant differences between the two set-size groups in any age group, indicating that individual differences in fluid intelligence most likely cannot account for the present findings.

Third, although we were able to replicate a number of findings in the literature on the basis of latencies and error rates, some effects (primarily age differences in the control of interference during task switching and following conflict trials as well as effects of task-stimulus priming) were only reliable for the accuracy of responding. Note that also other developmental studies have reported this phenomenon (e.g., Diamond & Kirkham, 2005; Hommel et al., 2011; Karbach et al., 2011). One obvious reason that has already been mentioned, is the high variability in speed of responding in early and middle childhood although children in this study performed about 600 experimental trials. However, to rule out that age differences in speed–accuracy trade-offs limit the interpretation of our findings, we also looked at correlations between the accuracy and speed of responding across experimental conditions. Interestingly, we obtained a pattern of positive correlations for compatible trials and mostly negative correlations on incompatible trials across all age groups. For the older children, negative correlations were reliable only for switch trials while for the youngest children significant correlations were found for non-switch and switch trials. We consider this pattern as evidence for age-related impairments in adjusting performance across trials, particularly for the ability to reduce speed in order to avoid errors on conflicting trials (cf., Huizinga & van der Molen, 2011). Given that the general correlational pattern was similar across age groups, it seems unlikely that age differences in trade-offs can account for our findings.

4.2. Implications and conclusions

The results of this study reveal that associative effects occurring between tasks, stimuli, and responses, induced by the stimulus set size, can influence cognitive control processing during childhood development. This finding yields important implications for developmental research in general, particularly because a number of developmental studies, for instance those applying traditional card-sort tasks (e.g., Zelazo & Jacques, 1996; Zelazo et al., 1996), have used rather few stimuli for experimental testing. Interestingly, the kindergarten children in our study were not sensitive to task-stimulus priming, probably because the general demands on cognitive control processing were so high. It seems that this sensitivity develops during childhood along with the increased ability to represent more complex higher-order task rules, which is thought to be related to the maturation of the lateral prefrontal cortex (Bunge & Zelazo, 2006). Task-stimulus priming indeed induced greater needs for control as reflected in larger interference costs in elementary school children as compared with young adults.
References


