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What Visual Information Do Children and Adults Consider While Switching Between Tasks? Eye-Tracking Investigation of Cognitive Flexibility Development

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This study investigated the visual information that children and adults consider while switching or maintaining object-matching rules. Eye movements of 5- and 6-year-old children and adults were collected with two versions of the Advanced Dimensional Change Card Sort, which requires switching between shape- and color-matching rules. In addition to a traditional *integrated* version with bidimensional objects (e.g., a blue bear), participants were tested on a *dissociated* version with pairs of unidimensional objects as stimuli (e.g., a noncolored bear beside a blue patch) so that fixations on the relevant and irrelevant dimensions of the stimuli could be distinguished. The fixation times were differentially distributed depending on whether children had to switch or maintain matching rules. Trial type differences in fixation times were primarily observed for the cues and the relevant and irrelevant dimensions of the stimuli, whereas responses options were seldom fixated even by the youngest children. In addition, the shape modality of the stimulus was more fixated than the color modality whether or not shape was relevant. Finally, the fixation patterns were modulated by age. These results suggest that switch costs are more related to selection of the relevant dimension on the stimulus than to response selection and point to age-related differences in strategies underlying flexible behavior.

Keywords: cognitive flexibility, executive control, eye tracking, task switching, preschool children

Children often have to respond flexibly to instructions that they receive or to changing environmental information. For instance, in the classroom, they may be asked to circle particular pictures and color others and then to cut them off and glue them on a sheet. Such behaviors require *cognitive flexibility* (also termed *set shifting* or *task switching*) to switch between successive tasks that must be performed on the same materials. Cognitive flexibility involves the ability to adaptively select—among multiple representations of an object, multiple strategies, or multiple task sets—the one that best fits the features of a given situation and the ability to switch among them as a function of relevant environmental changes (e.g., Jacques & Zelazo, 2005). Cognitive flexibility has been shown to develop dramatically over the preschool period (e.g., Carlson,

2005; Garon, Bryson, & Smith, 2008; Zelazo, Müller, Frye, & Marcovitch, 2003) and to be closely involved in cognitive acquisitions occurring at that age in domains such as theory of mind (e.g., U. Müller, Zelazo, & Imrisek, 2005) and language (e.g., Deák, 2003). The present study used, for the very first time, an eye-tracking methodology to further document cognitive flexibility development during the preschool years by investigating what information children consider in situations requiring flexible behaviors and comparing it with information considered by adults.

Evidence for the development of flexibility in preschoolers has been found with a set of different paradigms (e.g., Chevalier & Blaye, 2008; Deák, 2003; Espy, 1997; Espy & Cwik, 2004; Jacques & Zelazo, 2001). The Dimensional Change Card Sort (DCCS; Frye, Zelazo, & Palfai, 1995; Zelazo, 2006) is one of these paradigms. It requires children to sort test cards (stimuli) depicting bidimensional objects (e.g., red rabbits and blue boats) into two trays on which incongruent target cards (response pictures) are affixed (e.g., a blue rabbit or a red boat). After a series of successful trials in which one dimension was relevant across all trials (first simple block or preswitch block), children are then explicitly instructed to switch to sorting by the other dimension (e.g., from color to shape) for the next series of trials (second simple block or postswitch block). Traditionally, most 3-year-old children do not switch dimensions, whereas the majority of 4-year-olds succeed in switching dimensions (e.g., Zelazo, Frye, & Rapus, 1996; Zelazo et al., 2003). Although children obtain ceiling performance by age 4 on the standard version of the DCCS, performance continues to improve at least up to age 7 on the Advanced DCCS in which a third block (mixed block) is added. In this mixed block, color and

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shape alternate unpredictably, and children must switch back and forth between dimensions as a function of a visual cue (e.g., the presence of a star beside the bidimensional object on the test card means color is relevant, whereas no star means shape is relevant; Carlson, 2005; Chevalier & Blaye, 2009; Hongwanishkul, Happanye, Lee, & Zelazo, 2005).

The requirement to switch back and forth in a third phase makes the Advanced DCCS similar to the cued task-switching paradigm that is traditionally used to study cognitive flexibility (most commonly under the rubric *set-shifting* or *task-switching*) in adults (e.g., Meiran, 1996). In this paradigm, participants are instructed to perform the same task across a series of trials in the single blocks (also called *pure blocks*) and then to switch between two or more tasks as a function of cues in the mixed blocks. Cognitive flexibility is indexed through two measures: (a) mixing costs (also termed *global* or *general costs*) that compare performance on the single blocks and no-switch trials (i.e., trials on which the relevant task repeats) of the mixed blocks and (b) local switch costs (also called *specific* or, simply, *switch costs*) that compare performance on switch trials (i.e., trials on which the relevant task changes) and no-switch trials within the mixed blocks. Both mixing and local costs have been found to decrease until late adolescence (but they remain significant even in adults), though mixing costs are often found to be more developmentally sensitive than local costs (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Karbach & Kray, 2007; Reimers & Maylor, 2005).

Different theoretical frameworks have been proposed to account for flexibility development at preschool age and for flexible behavior during adulthood. In preschoolers, theoretical proposals have mainly emphasized the increase in cognitive flexibility between 3 and 4 years of age, as observed on the standard DCCS. This increase has been hypothesized to relate to different processes, such as if-then reasoning (Zelazo et al., 1996, 2003), inhibition (Bialystok & Martin, 2004; Kirkham, Cruess, & Diamond, 2003), active-memory representations (Cepeda & Munakata, 2007; Morton & Munakata, 2002), stimulus redescription (Kloo & Perner, 2003, 2005), and representation maintenance (Chevalier & Blaye, 2008). Moreover, these proposals commonly assume that young preschoolers' difficulty on the DCCS arises from the visual conflict between test and target cards (Garon et al., 2008), although this assumption does not rely on any direct measure of eye fixations on target and test cards.

Similarly, studies that have used the task-switching paradigm with adults have highlighted different processes believed to be responsible for switch costs (for reviews, see Meiran, 2008; Monsell, 2003, 2005). These processes are thought to relate to two main components: task goal setting and switch implementation (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Gruber & Goschke, 2004; Miyake, Emerson, Padilla, & Ahn, 2004; Rubinstein, Meyer, & Evans, 2001). Goal setting is used to determine which task is relevant (i.e., which goal must be reached). Once the relevant task goal is set and if it differs from the previous one, a switch in task set (i.e., bunch of task-relevant perceptual, mnemonic, attentional, and motor processes, including stimuli encoding, action rules, and response selection) must be implemented by reorienting attention to the relevant information and selecting the correct response. It is argued that goal setting is primarily captured by mixing costs because no-switch trials within mixed blocks necessitate goal setting, whereas single-block trials do not (but neither of them has switching demands). Local costs

are thought to mainly reflect switching per se because they contrast switch trials (goal-setting and switching demands) to no-switch trials (goal-setting demands only; Rubin & Meiran, 2005). In the cued task-switching paradigm (and the Advanced DCCS), task goal setting is achieved by translating task cues into verbal representations of tasks goals. The difficulty of cue-goal translation depends on the availability of inner speech and the degree of cue transparency (i.e., the strength of cue-goal associations) as shown by the detrimental effect of concomitant articulatory suppression and poorly transparent cues on adults' switch costs (Miyake et al., 2004). Even without concomitant articulatory suppression, preschoolers encounter goal-setting difficulties in the Advanced DCCS, especially when cues are poorly transparent, most likely because preschoolers do not spontaneously and efficiently recruit inner speech. Such difficulties progressively disappear with age and inner-speech development (Chevalier & Blaye, 2009), hence suggesting that goal setting contributes to cognitive flexibility development occurring over this period of age (see also Marcovitch, Boseovski, & Knapp, 2007, and Towse, Lewis, & Knowles, 2007, for evidence for goal neglect in the standard DCCS).

In adults, two types of theoretical accounts for switch implementation have been proposed. First, some authors have proposed that switch implementation requires executive processes responsible for active task-set reconfiguration (Rogers & Monsell, 1995). These accounts highlight activation and inhibition processes that specifically occur on switch trials (e.g., Rubinstein et al., 2001). Second, other authors have instead argued in favor of automatic phenomena that make task-set activation more difficult on switch trials than no-switch trials (e.g., Allport, Styles, & Hsieh, 1994; Altmann, 2004; Logan & Schneider, 2006). For instance, when a task has just been performed, its task set remains active in working memory and only progressively decays with time. This task-set inertia then facilitates repetition of the task on no-switch trials but makes activation of other task sets more difficult on switch trials (Allport et al., 1994). These two types of account differ in their prediction of switch costs between tasks of unequal difficulty. Task-set reconfiguration proponents argue that it should be harder to switch to a more difficult (weaker) task because it takes longer to activate on switch trials, and in the meantime, it is harder to inhibit the more interfering task set related to the easier (stronger) task set. In contrast, task-set inertia proponents argue that when one engages in the more difficult (weaker) task, the alternative easier (stronger) task is negatively primed, making it especially difficult to reactivate, whereas no such negative priming phenomenon occurs while engaging in the easy (stronger) task because the more difficult task is mildly interfering. Mixed findings have previously been reported, with higher switch costs sometimes observed for the weaker task (Mayr & Kliegl, 2000; Monsell, Yeung, & Azuma, 2000; Rubinstein et al., 2001) and other times observed for the stronger task—in which case they are termed *asymmetrical switch* (Allport et al., 1994; Allport & Wylie, 2000; Cragg & Nation, 2009; Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Ellefson, Shapiro, & Chater, 2006; Meuter & Allport, 1999; Yeung & Monsell, 2003). Proponents of task-set reconfiguration now acknowledge that switch costs can be greater for the stronger task, but they argue that the carryover effect of inhibition is related to active inhibition processes occurring as part of task-set reconfiguration (Yeung & Monsell, 2003).

The theoretical debate regarding the processes underlying flexibility development could greatly benefit from the study of what visual information children consider while behaving flexibly and whether this information changes over age. Eye-tracking methodology could offer an interesting window on such visual information because it is well established that eye movements are, in part, endogenously controlled (e.g., Deubel, 2008; Eenshuistra, Ridderinkhof, Weidema, & van der Molen, 2007; Karatekin, 2007; Peterson, Beck, & Wong, 2008; Schall & Boucher, 2007) and attention is given to information contained in fixated areas (McCarley & Kramer, 2006; Miller, 2000). To our knowledge, Li and Feng (2007) have conducted the only existing study that has used eye-tracking methods to examine 3- and 5-year-olds' performance on the standard DCCS. They observed that overall proportions of fixation times (on successful trials) did not differ between the two phases of the standard DCCS. However, the first trial after the switch in dimensions presented a specific pattern of fixations, resulting in more fixations than the other trials. Although this study illustrates the potential of eye movements to further the understanding of cognitive-flexibility development, it presented two main limitations. First, it used traditional spatially integrated pictures (e.g., a yellow duck) as stimuli and response pictures. Thus, it did not allow distinction between visual information gathering related to the relevant and irrelevant dimensions, and it precluded assessment of interference created by the irrelevant dimension on the relevant one. Second, because the features of the standard DCCS (explicit announcement of the switch and the relevant task before each trial) minimize goal-setting demands, this study did not capture visual information that children use to set task goals.

To move beyond these limitations, the present study explored the eye movements of preschool children and adults while they performed the Advanced DCCS. Because this paradigm requires switching back and forth between color and shape, it involves several switch trials, that is, trials for which visual information gathering mostly varies (Li & Feng, 2007). Each participant was tested with two versions of the Advanced DCCS: a traditional version with spatially integrated dimensions on stimuli and response pictures (e.g., a blue car was used as a stimulus) and a version in which dimensions were spatially dissociated (e.g., a noncolored car beside a blue patch). The latter version allowed distinguishing between fixations related to the relevant and irrelevant dimensions. Moreover, the use of the Advanced DCCS in the present study offered two main advantages. First, because it is more developmentally sensitive than the standard DCCS, it allowed examination of changes in visual information gathering over a wider age span. Second, the comparison of fixations across simple blocks and no-switch trials of mixed block allowed inferences about goal-setting processes. Efficient goal setting should result in an increase in fixation time on the task cues in the mixed block as compared with simple blocks. The comparison of switch and no-switch trials within the mixed block should provide information about interference of the irrelevant dimension while participants are implementing a switch. This dimension should be differentially fixated as a function of interference level and, thus, should be more fixated on switch than no-switch trials. Finally, given that color matching has been shown to be easier than shape matching (Cragg & Nation, 2009; Ellefson et al., 2006), we examined whether an asymmetry in fixation time would be observed between color and shape. On the basis of the task-set reconfigu-

ration account, shape should be harder to activate, and color should be harder to inhibit. Therefore, longer fixation times should be observed for both shape and color on switch than no-switch trials when shape is the relevant dimension (high difficulties of shape activation and color inhibition), whereas no such pattern should be observed when color is the relevant dimension (low difficulties of color activation and shape inhibition). In contrast, on the basis of the task-set inertia account, color should be especially difficult to activate and, therefore, should be longer fixated on switch trials than on no-switch trials when color is relevant, whereas no such pattern should be observed on trials where shape is relevant.

Methods

Participants

Ninety-five children and adults participated in this study. They were split into three age groups: 32 were 5-year-olds ($M = 66.3$ months, $SD = 3.9$ months, age range = 60–71 months; 17 girls, 15 boys), 31 were 6-year-olds ($M = 80.9$ months, $SD = 5.8$ months, age range = 73–90 months; 19 girls, 12 boys), and 32 were adults ($M = 23$ years, $SD = 4.2$ years, age range = 18–33 years; 22 women, 10 men). Children were recruited from a preschool (5-year-olds) and a primary school (6-year-olds) located in a small town in the south of France. Adults were psychology students from the same geographical area, and they received course credit for participating. Most participants were Caucasian and came from middle-class backgrounds, although race and socioeconomic status data were not collected. All participants consented to take part in the study. In addition, parental consent was received for all children. Children were tested individually in a quiet room in their school, and adults were tested individually at the laboratory. Because of experimenter error, data from 2 additional children (one 5-year-old and one 6-year-old) were eliminated.

Recording Setup

Bilateral eye movements were recorded with a Tobii T120 Eye Tracker (Tobii Technology AB, Danderyd, Sweden) using a 120 Hz data-sampling rate and an automatic 5-point calibration procedure performed on each participant before administering the tasks. This equipment ensured an eye-position accuracy of 0.5 degrees. The eye tracker was integrated in a 17-in. monitor (1280×1024 pixels) that was used to present stimuli through a Dell Latitude ATG D620 laptop running ClearView 2.7.1 software (Tobii Technology AB, Danderyd, Sweden). The eye tracker was particularly appropriate for preschoolers because it was transportable, necessitated neither a headrest nor a helmet, and tolerated head motions within a $30 \times 22 \times 30$ cm window. Participants were seated 60 cm away from the eye tracker. They entered their responses with the *Q* and *Home* keys of a QWERTY keyboard. The remaining keys were masked. The recording setup was the same in all three groups.

Materials

The Advanced DCCS required participants to match bidimensional stimuli to one of two response pictures as a function of cues that signaled whether color or shape was the relevant dimension (task). In each version, there were two different stimuli (e.g., blue car or red teddy bear) displayed in a $10\text{-cm} \times 6.5\text{-cm}$ frame (delineated by a

black line). The lower side of the stimulus frame was located 4 mm above the center of the screen. All stimuli were incongruent with the two response pictures, meaning that each response picture partially matched each stimulus in either shape or color (e.g., red car and blue teddy bear). The response pictures were presented in frames (similar to the frame for the stimulus) located in the left and right bottom corners of the screen (1.5 cm away from the screen borders) and corresponding to the *Q* and *Home* keys, respectively. Response pictures remained constantly visible to reduce the working memory demand related to retention of response button meanings. In the integrated condition, pictures were bidimensional (e.g., a blue car) and were displayed at the center of their respective frames. In the dissociated condition, pictures were pairs of unidimensional objects (e.g., a noncolored car beside a blue patch) separated by 1.5 cm (1.4°) and displayed side by side in their respective frames. The side of presentation of the dimensions was counterbalanced across participants. All presented objects were contained into a virtual 4-cm × 4-cm square. The shape cue was a 2.3-cm × 2.3-cm noncolored square containing geometric shapes. The color cue was a 2.3-cm × 2.3-cm square containing multiple patches of color. Task cues were presented at the top of the screen (1.5 cm up from the top border of the stimulus frame). Participants saw different pairs of shapes and colors in the two conditions (either teddy bear/car in red/blue or castle/turtle in yellow/green). Presentation side and picture pairs were counterbalanced across conditions and participants (eight different versions).

Each trial started with a fixation screen, that is, a fixation point appearing at the top of the screen (300 ms). It was followed by the cue screen, during which the cue was displayed for 500 ms (cue–target interval; CTI). Then the stimulus appeared. The cue and stimulus remained visible until a response was entered (stimulus screen). The response triggered a final screen where only the response pictures remained visible (200 ms; Figure 1). Contrary to the card version of the Advanced DCCS in which cues and stimuli are simultaneously displayed (i.e., CTI = 0 ms), we fixed the CTI to 500 ms to examine whether participants would use this period to set task goals before stimulus onset (i.e., whether they would gaze longer at the cue when goal setting was more demanding) and because reliable costs have been observed on the Advanced DCCS with such a CTI length even in adults (Diamond & Kirkham, 2005).

Procedure

Each participant was tested on both the integrated and dissociated conditions in a single session lasting approximately 25 min for children and 15 min for adults. Condition order was counterbalanced across participants. Each condition comprised two simple blocks and one mixed block. There were 11 test trials preceded by 4 warm-up trials in each simple block. In such blocks, the same dimension was constantly relevant across all trials, but it changed as the participant moved from the first to the second simple block (e.g., color was relevant in the first simple block, and shape was relevant in the second one). Dimension order was counterbalanced across conditions and participants. If one dimension came first for the first version a participant took, then the second version started with the other dimension. Simple blocks were followed by a mixed block that contained 6 warm-up trials and 46 test trials (three short breaks were interspersed with test trials). Mixed-block test trials fell into 14 switch trials (i.e., the relevant dimension changes), 28 no-switch trials (i.e., the relevant dimension repeats), and 4 start trials (the very first trial of the block plus the first trial after each break). The mixed block in each condition contained equal numbers of each stimulus and each correct response, as well as equal numbers of color and shape trials. Color and shape alternated unpredictably. There could be 0 to 2 successive switch trials and 0 to 2 successive no-switch trials too.

In the beginning of each condition, children were told that they would see pictures and would have to play either the Color Game or the Shape Game on the basis of cues. In the Color Game, they were instructed to press the key under the bottom picture of the same color as the top picture. In the Shape Game, they were instructed to press the key under the bottom picture of the same shape as the top picture. Children were asked to respond as quickly and accurately as possible and to remain as still as they could. The experimenter helped children and provided feedback on warm-up trials if necessary but not on test trials. After completion of the two simple blocks, children were told that they would now play the two games at the same time, and they proceeded to the mixed block. The mixed block started with a warm-up phase of six trials. Children were guided by the experimenter on these trials (*Which cue is it? Which game does it mean? So which color/shape is it [stimulus]? Which one [response pictures] is of*

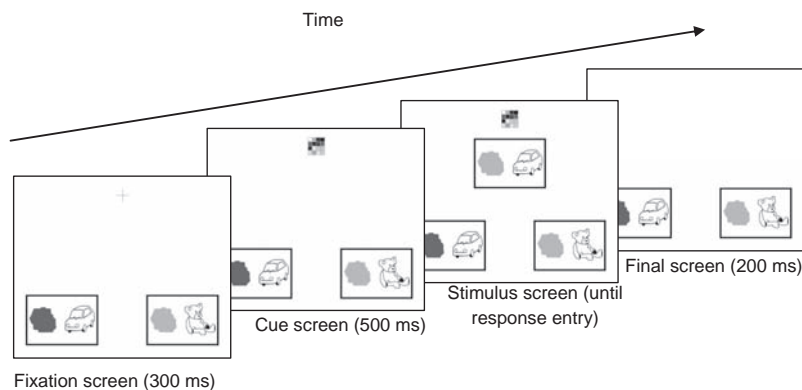


Figure 1. Trial procedure. The response pictures at the bottom of each screen show a patch (which was red in the experiment) beside a noncolored car (left) and a patch (which was blue in the experiment) beside a noncolored teddy bear (right). The cue and stimulus screens additionally show a rectangular color palette (used as a task cue; top). The stimulus (center) on the stimulus screen shows a patch (which was blue in the experiment) beside a noncolored car.

the same color/shape?). The test trials were then administered with no help from the experimenter. Children were encouraged to take a short break between blocks and during the three pauses in the mixed block.

Data Analysis

All analyses were run after discarding the first trial of each block and the first trial following a break, because these were neither switch nor no-switch trials. Outliers ($>10,000$ ms or <200 ms; reaction times [RTs] beyond or over the mean RT plus or minus two standard deviations for each participant and for each trial type) were also excluded (5.3%). In addition, for RT analyses we included only successful trials immediately preceded by a successful trial after we applied a natural logarithmic transformation to the data to control for age-related baseline differences (Meiran, 1996). For the sake of clarity, the reported values were back-transformed. Children with missing data for some slots of the experimental design (e.g., switch trials for shape in the integrated version) were excluded from RT (and fixation time) analyses: 16 participants in the integrated version (eleven 5-year-olds and five 6-year-olds) and 12 participants in the dissociated version (seven 5-year-olds and five 6-year-olds), resulting in a total of 21 children excluded from RT analyses (fourteen 5-year-olds and seven 6-year-olds). As the number of excluded participants decreased with age, it may have resulted in overselected samples of children, which in turn may have led to underestimated effects of age. However, previous analyses, in which the factor dimension was not entered and in which only 10 children were excluded, resulted in the exact same pattern of results, hinting at the robustness of the effects. Data were analyzed with mixed analyses of variance (ANOVAs), planned contrasts, and Tukey's post hoc tests. When appropriate (as evidenced by Mauchly's tests; Mauchly, 1940), the Greenhouse–Geisser (Greenhouse & Geisser, 1959) correction was applied for violation of the assumption of sphericity. Mixing costs were examined, contrasting simple-block trials and no-switch trials in the mixed block. Local costs were examined, contrasting switch and no-switch trials within the mixed block.

Eye fixations were calculated with the ClearView 2.7.1 software, with a fixation radius of 30 pixels and a minimum fixation duration of 50 ms. Eye fixations were categorized according to where they landed on spatial areas related to the cue, stimulus, and response pictures displayed on the screen. Two sets spanning different areas of interest (AOIs) were defined, one set for the integrated version and another set for the dissociated version (Figure 2). Each AOI covered a specific object displayed on the screen. AOI borders were located 0.5° (0.5 mm) away from the most extreme limits of the objects on each side. This criterion corresponds to the spatial error margin of the device used in the present study. There were four AOIs in the integrated version: the cue (Cue), the stimulus (Stim), the relevant response (RResp), and the irrelevant response (IResp). There were seven AOIs in the dissociated version: the cue (Cue), the relevant dimension of the stimulus (RStim), the irrelevant dimension of the stimulus (IStim), the relevant dimension of the relevant response (R-RResp), the irrelevant dimension of the relevant response (I-RResp), the relevant dimension of the irrelevant response (R-IResp), and the irrelevant dimension of the irrelevant response (I-IResp). Pairs of AOIs related to the stimulus or the response pictures were separated by a buffer zone of 0.5° (corresponding to the eye-tracker error margin) where fixations were

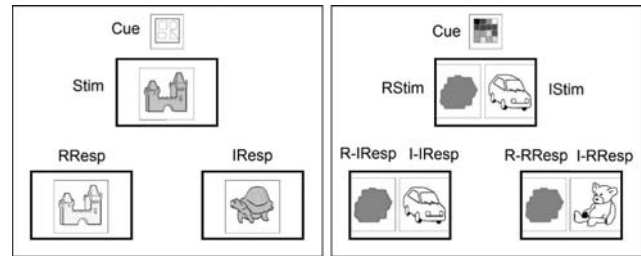


Figure 2. Illustration of the areas of interest in the integrated version (left) and the dissociated version (right). Area-of-interest names correspond to gray squares. The left panel shows a rectangular shape palette (shape cue, top), a castle (green in the experiment; stimulus, center), and a castle (yellow in the experiment) and a turtle (green in the experiment; response pictures, bottom). The right panel shows a rectangular color palette (color cue, top), a patch (blue in the experiment) beside a noncolored car (stimulus, center), and a patch (red in the experiment) beside a noncolored car and a patch (blue in the experiment) beside a noncolored teddy bear (response pictures, bottom). Stim = stimulus; RResp = relevant response; IResp = irrelevant response; RStim = relevant dimension of the stimulus; IStim = irrelevant dimension of the stimulus; R-IResp = relevant dimension of the irrelevant response; I-IResp = irrelevant dimension of the irrelevant response; R-RResp = relevant dimension of the relevant response; I-RResp = irrelevant dimension of the relevant response.

not taken into account because they could not be clearly defined in relation to any of the two AOIs.

Eye-tracking analyses were performed after discarding trials in which no fixations were recorded (6.7% of cue screens and 1.2% of stimulus screens). The analyses reported here were performed on total fixation times (i.e., cumulative duration of all fixations) for each AOI because this index more straightforwardly reflects attention allotted to AOIs than mean fixation times. More important, analyses of total fixation times can be directly related to traditional analyses of RTs. They provide a direct indication of the time spent on each piece of visual information on the screen and, therefore, are informative regarding which visual information is responsible for variations in RTs across trial types. Furthermore, these analyses are easier to interpret than analyses of proportions of fixation times on each AOI because variations in proportion of fixation times may result from different actual behaviors and are thus ambiguous.¹ The analyses were run on raw fixation times because a logarithm transformation would have distorted the data, given that some AOIs were infrequently visited and thus often obtained 0-ms values that could not be transformed.² Analyses of raw fixation times do not control for age-related baseline differences. However, our primary goal was to assess the change in

¹ For instance, a decrease across trial types in the proportion of fixation time for Area A and an increase for Area B may result from four different patterns: (a) total fixation time for A remains constant, whereas that for B increases; (b) total fixation time for A decreases, and total fixation time for B increases; (c) total fixation time for A decreases, and total fixation time for B remains constant; and (d) both increase, but the increase is stronger for B than for A.

² A short average fixation time for a given AOI might either reflect skipping this AOI (i.e., 0-ms values) on most trials or reflect a consistent short fixation time on each trial. This issue especially applies to the response pictures AOI. For clarification, the proportions of trials on which each AOI was skipped are provided in the Appendix. As shown in the Appendix, these AOIs were skipped on substantial proportions of trials.

fixation-time *patterns* over age rather than in fixation times per se. Post hoc comparisons were run on values for different AOIs within each age group but not between age groups, hence suppressing the issue of baseline differences. Analyses performed on total numbers of fixations led to similar results but are not reported here.

For the sake of clarity, we report fixations for only the most informative phases of the trial, that is, for the cue screens corresponding to fixations occurring between cue onset and stimulus onset and for stimulus screens corresponding to fixations occurring between stimulus onset and response entry. Fixations from both fixation screens and final screens were not analyzed. During cue screens, only fixations related to the cue were analyzed because they inform on task preparation, whereas AOIs related to response pictures were not directly interpretable at that stage of the task (preliminary analyses showed they were almost not fixated: all mean values < 17 ms). During stimulus screens, all AOIs were included in the analyses. ANOVAs with age as a between-subjects variable and all other variables (AOL, trial type, and dimension) as within-subject variables were run. Significant effects were further explored with Tukey post hoc tests. All analyses on fixation times (as well as accuracy and RTs) were rerun with adults excluded to make sure that the main effects of age or interactions with age were not exclusively driven by differences between adults and children only. These analyses yielded the exact same effects involving age, except when planned comparisons or Tukey post hoc tests showed that the two groups of preschoolers did not differ from each other as indicated in the Results section. Analyses for the integrated version, which corresponds to the traditional format of the Advanced DCCS, are reported first. The study of visual information gathering in the Advanced DCCS was further examined in the dissociated version, which allowed the distinction of fixations related to the relevant and irrelevant dimensions.

Results

Accuracy and Latency Analyses

Two mixed-design ANOVAs were computed with age (5-year-olds, 6-year-olds, adults) as the between-subjects variable and with version (integrated, dissociated), trial type (simple block, no switch, switch), and dimension (color, shape) as within-subjects variables. These ANOVAs performed on accuracy rates and RTs, respectively, are presented in Table 1. Accuracy rates and RTs are shown in Figures 3 and 4, respectively. Both analyses yielded significant main effects of age, trial type, and dimension as well as significant Trial Type \times Age interactions (all $ps < .001$). There was also a significant Trial Type \times Dimension interaction for accuracy ($p < .001$). For RTs, we additionally observed a significant main effect of version and significant Version \times Age, Version \times Dimension, and Trial Type \times Dimension \times Age interactions (all $ps < .05$). Main effects of trial type and interactions involving this variable are further explored later. Overall, accuracy significantly increased across all age groups ($M_5 = 75\%$, $M_6 = 82\%$, $M_{adults} = 95\%$; $ps < .01$), and adults responded faster than children ($M_5 = 1,877$ ms, $M_6 = 1,634$ ms, $M_{adults} = 675$ ms; $ps < .001$), whereas the RTs for the two groups of children did not differ significantly ($p = .18$). Performance was overall more accurate and faster on color trials ($M = 89\%$ and $M = 1,366$ ms, respectively) than on shape trials ($M = 80\%$ and $M = 1,424$ ms, respectively). Version (integrated, dissociated) was entered as an independent variable in the ANOVAs because previous studies showed that spatial dissociation of dimensions had a facilitative effect on 3-year-olds' performance on the standard DCCS (Diamond, Carlson, & Beck, 2005; Kloof & Permer, 2005). It is noteworthy that we did not find any effect of version on accuracy. In contrast, the ANOVA on RTs showed a significant main effect of version related to longer RTs in the dissociated version ($M = 1,462$ ms) than in the integrated one ($M = 1,329$ ms). It also

Table 1

Analyses of Variance Computed on Accuracy and Reaction Times With Age as a Between-Subjects Variable and Version, Trial Type, and Dimension as Within-Subjects Variables

Effect	Accuracy					Reaction time				
	<i>df</i>	<i>MSE</i>	<i>F</i>	<i>p</i>	η_p^2	<i>df</i>	<i>MSE</i>	<i>F</i>	<i>p</i>	η_p^2
Age	2, 92	1,233	31.49	<.001	0.41	2, 70	0.51	152.11	<.001	0.81
Version	1, 92	285	0.34	.562	<0.01	1, 70	0.09	8.11	.006	0.10
Version \times Age	2, 92	285	0.70	.499	0.01	2, 70	0.09	4.07	.021	0.10
Trial Type	2, 184	305	99.98	<.001	0.52	2, 140	0.10	246.60	<.001	0.78
Trial Type \times Age	4, 184	305	15.65	<.001	0.25	4, 140	0.10	19.66	<.001	0.36
Dimension	1, 92	1,074	21.52	<.001	0.19	1, 70	0.04	11.02	.001	0.14
Dimension \times Age	2, 92	1,074	2.16	.121	0.04	2, 70	0.04	2.40	.098	0.06
Version \times Trial Type	2, 184	151	1.73	.184	0.02	2, 140	0.04	2.50	.091	0.03
Version \times Trial Type \times Age	4, 184	151	0.16	.945	<0.01	4, 140	0.04	0.96	.427	0.03
Version \times Dimension	1, 92	755	0.56	.458	0.01	1, 70	0.02	5.37	.023	0.07
Version \times Dimension \times Age	2, 92	755	0.34	.711	0.01	2, 70	0.02	0.09	.912	<0.01
Trial Type \times Dimension	2, 184	214	8.02	.001	0.08	2, 140	0.02	2.06	.131	0.03
Trial Type \times Dimension \times Age	4, 184	214	0.51	.671	0.01	4, 140	0.02	3.98	.004	0.10
Version \times Trial Type \times Dimension	2, 184	237	0.28	.677	<0.01	2, 140	0.03	1.85	.168	0.03
Version \times Trial Type \times Dimension \times Age	4, 184	237	0.61	.599	0.01	4, 140	0.03	0.04	.993	<0.01

Note. Significant effects appear in bold. η_p^2 = partial eta squared.

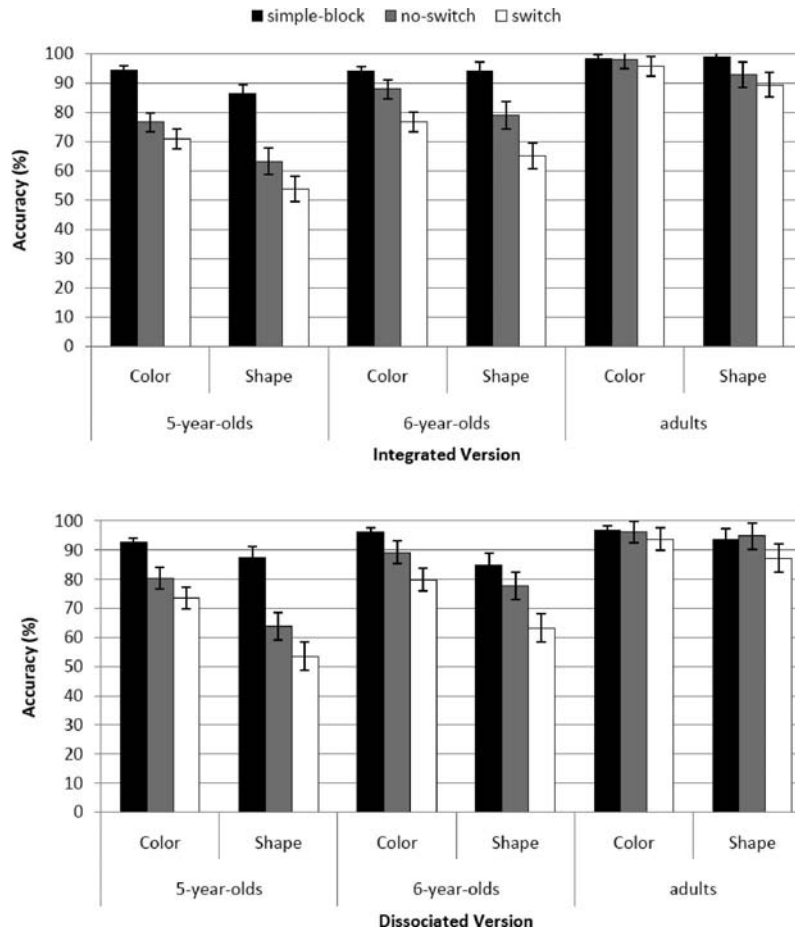


Figure 3. Accuracy (%) as a function of age, trial type, and dimension in the integrated version (top) and dissociated version (bottom). Vertical bars indicate standard errors.

yielded significant Version \times Age and Version \times Dimension interactions. Post hoc tests showed that version significantly affected only 5-year-olds' performance ($p < .05$; all other $ps > .36$). There was no simple effect of version for color ($ps < .33$), whereas RTs to shape were significantly longer in the dissociated version ($M = 1,506$ ms) than in the integrated version ($M = 1,342$ ms, $p < .001$).

Mixing costs. Planned contrasts for accuracy showed significant mixing costs at ages 5 and 6, $M = 19.1\%$, $F(1, 92) = 56.35$, $MSE = 415.57$, $p < .0001$, $\eta_p^2 = .38$, and $M = 8.9\%$, $F(1, 92) = 11.72$, $MSE = 415.57$, $p < .001$, $\eta_p^2 = .11$, respectively, but not for adults ($M = 1.4\%$, $F < 1$). In addition, mixing costs significantly decreased between ages 5 and 6, $F(1, 92) = 7.98$, $MSE = 415.57$, $p < .01$, $\eta_p^2 = .08$, and between age 6 and adulthood, $F(1, 92) = 4.23$, $MSE = 415.7$, $p < .05$, $\eta_p^2 = .04$. Mixing costs were significantly higher for shape ($M = 12.29\%$) than for color ($M = 7.32\%$), $F(1, 92) = 4.74$, $MSE = 247.88$, $p < .05$, $\eta_p^2 = .05$.

Significant mixing costs for latencies were observed for all age groups: $M = 943$ ms for 5-year-olds, $F(1, 70) = 92.87$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .57$; $M = 724$ ms for 6-year-olds, $F(1, 70) = 104.47$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .60$; $M = 119$ ms for adults, $F(1, 70) = 14.26$, $MSE = 0.11$, $p < .001$, $\eta_p^2 = .17$. Mixing costs for adults were significantly lower than those for 5- and 6-year-old

children, $F(1, 70) = 28.91$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .29$, and $F(1, 70) = 26.82$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .28$, respectively. Mixing costs did not significantly differ between ages 5 and 6 ($F < 1$). Mixing costs were significantly higher for shape ($M = 642$ ms) than color ($M = 548$ ms) at age 5, $F(1, 70) = 8.62$, $MSE = 0.02$, $p < .01$, $\eta_p^2 = .11$, whereas they were unaffected by dimension in older participants ($ps < .47$).

Local costs. All age groups showed significant local costs for accuracy rates: $M = 8.1\%$ at age 5, $F(1, 92) = 28.81$, $MSE = 145.08$, $p < .0001$, $\eta_p^2 = .27$; $M = 12.2\%$ at age 6, $F(1, 92) = 64.01$, $MSE = 145.08$, $p < .0001$, $\eta_p^2 = .43$; $M = 3.9\%$ for adults, $F(1, 92) = 6.86$, $MSE = 145.08$, $p < .05$, $\eta_p^2 = .07$. Local costs marginally increased from age 5 to age 6, $F(1, 92) = 3.75$, $MSE = 145.08$, $p < .06$, $\eta_p^2 = .04$, and they significantly decreased from age 6 to adulthood, $F(1, 92) = 14.94$, $MSE = 145.08$, $p < .0001$, $\eta_p^2 = .15$. Local costs for accuracy were higher for shape ($M = 9.84\%$) than for color ($M = 6.34\%$), $F(1, 92) = 6.37$, $MSE = 90.91$, $p < .05$, $\eta_p^2 = .07$.

Significant local costs for latencies were observed for all age groups: $M = 432$ ms at age 5, $F(1, 70) = 22.90$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .25$; $M = 402$ ms at age 6, $F(1, 70) = 40.41$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .37$; $M = 93$ ms for adults, $F(1, 70) = 15.36$, $MSE = 0.11$, $p < .0001$, $\eta_p^2 = .18$. Local costs significantly

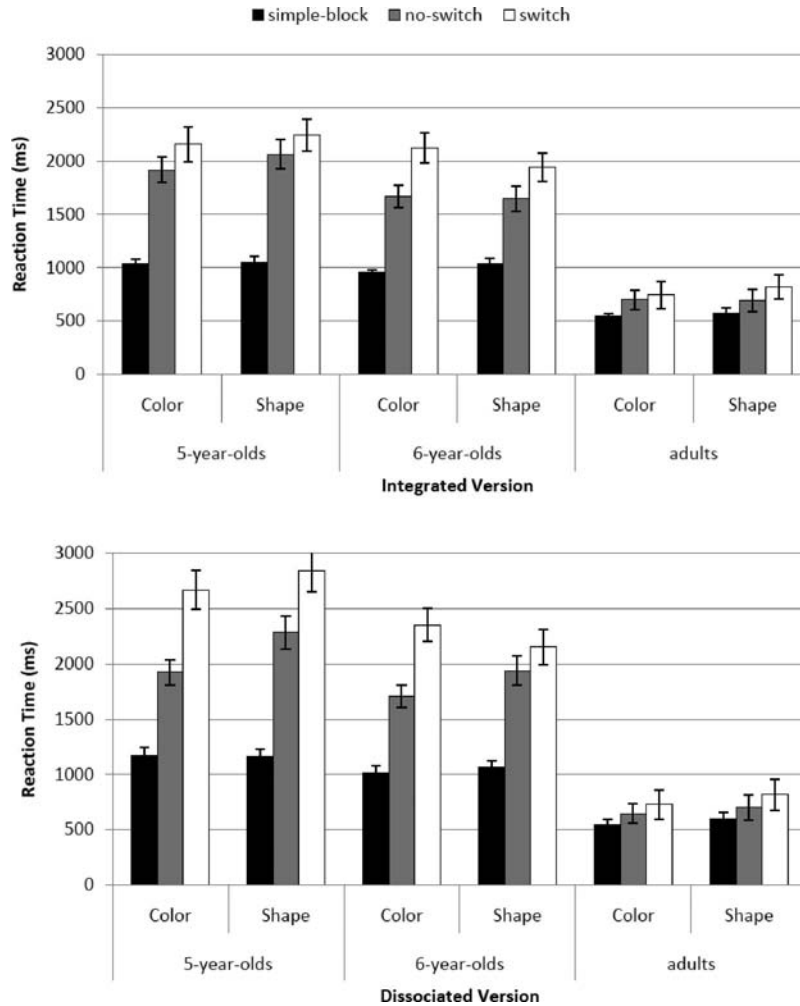


Figure 4. Reaction times (ms) as a function of age, trial type, and dimension in the integrated version (top) and dissociated version (bottom). Vertical bars indicate standard errors.

differed between age 6 and adulthood, $F(1, 82) = 4.78$, $MSE = 0.04$, $p < .05$, $\eta_p^2 = .06$, but not between ages 5 and 6, $p > .58$. Finally, local costs were significantly higher for color than for shape at age 5, $M = 493$ ms and $M = 370$ ms, respectively, $F(1, 70) = 3.98$, $MSE = 0.02$, $p < .05$, $\eta_p^2 = .05$, and at age 6, $M = 552$ ms and $M = 253$ ms, respectively, $F(1, 70) = 5.06$, $MSE = 0.02$, $p < .07$, but they were unaffected by dimension in adults ($p > .21$).

Eye-Tracking Analyses

Integrated version. We then compared fixation times across simple-block, no-switch, and switch trials (including only successful trials) to determine what visual information was associated with the just reported variations in RTs.³ Fixation times appear in Table 2. The 3 (age: 5, 6, adults) \times 3 (trial type: simple block, no switch, switch) \times 2 (dimension: color, shape) mixed ANOVA performed for cue screens showed only a significant main effect of trial type and a significant Trial Type \times Dimension interaction ($ps < .05$; Table 3). Across all age groups combined, we observed

a significant increase in the time spent on the cue between simple-block trials (74 ms) and no-switch trials (224 ms, $p < .0001$) and a marginal increase between no-switch and switch trials (254 ms, $p = .09$). The difference between no-switch and switch trials was significant for color ($p < .001$) but not for shape ($p > .97$).

Stimulus screens were analyzed with a 3 (age: 5, 6, adults) \times 4 (AOI: Cue, Stim, RResp, IResp) \times 3 (trial type: simple block, no switch, switch) \times 2 (dimension: color, shape) mixed ANOVA. All main effects and interactions, except those involving dimension, turned out to be significant ($ps < .001$). In addition, there was a significant AOI \times Dimension \times Age interaction ($p < .001$; Table 3). Exploring further the AOI \times Trial Type \times Age interaction ($p < .001$; Figure 5), it appeared that trial types mainly affected the fixation time on the cue. For all age groups, the cue was fixated for a significantly longer time in switch and no-switch trials than in simple-block trials ($ps < .001$). The effect of trial type on

³ Low error rates (especially in adults: $<5\%$) precluded entering the success/failure variable into the analysis.

Table 2

Mean Fixation Times (and Standard Deviations) in Milliseconds for Each Area of Interest as a Function of Age, Trial Type, and Relevant Dimension in the Integrated Version

Age group, trial type, and relevant dimension	Area of interest				
	Cue (CS)	Cue	Stim	RResp	IResp
5-year-olds					
Simple block					
Color	65 (91)	66 (204)	687 (189)	134 (98)	15 (27)
Shape	102 (126)	67 (85)	749 (188)	79 (94)	18 (39)
No switch					
Color	172 (99)	405 (312)	819 (348)	197 (153)	32 (37)
Shape	210 (126)	401 (272)	988 (443)	223 (196)	60 (74)
Switch					
Color	247 (175)	527 (385)	903 (396)	257 (213)	74 (86)
Shape	212 (174)	460 (350)	988 (386)	242 (194)	155 (155)
6-year-olds					
Simple block					
Color	68 (72)	39 (44)	632 (179)	60 (66)	15 (32)
Shape	66 (86)	38 (43)	683 (146)	47 (46)	18 (30)
No switch					
Color	234 (129)	380 (217)	663 (259)	139 (94)	17 (31)
Shape	249 (116)	381 (222)	636 (207)	134 (94)	33 (38)
Switch					
Color	281 (137)	418 (259)	842 (418)	166 (150)	69 (70)
Shape	284 (138)	511 (293)	716 (324)	135 (129)	67 (82)
Adults					
Simple block					
Color	61 (118)	34 (93)	390 (140)	10 (28)	0 (2)
Shape	84 (145)	25 (58)	422 (142)	9 (17)	1 (2)
No switch					
Color	223 (150)	139 (109)	340 (142)	6 (16)	0 (1)
Shape	241 (160)	145 (108)	335 (130)	8 (13)	1 (5)
Switch					
Color	258 (163)	103 (89)	398 (148)	11 (24)	1 (5)
Shape	233 (175)	172 (178)	395 (159)	15 (26)	4 (11)

Note. CS = cue screens; Stim = stimulus; RResp = relevant response; IResp = irrelevant response.

fixation time for the stimulus was modulated by age. At age 5, fixation time on the stimulus increased from simple-block to no-switch trials ($p < .001$), whereas the increase between no-switch and switch trials was not significant ($p > .99$). At age 6, children spent significantly more time on the stimulus in switch trials than in the other two trial types ($ps < .01$), which did not differ from each other ($p > .99$). By contrast, no significant differences pertaining to fixation times on the stimulus were observed in adults ($ps > .53$). At age 5, the relevant response picture was more fixated in switch trials than in simple-block trials ($p < .001$). No other significant pairwise comparisons were found. Finally, the AOI \times Dimension \times Age interaction ($p < .001$) was driven by a significantly longer fixation time on the stimulus when shape was relevant relative to color at age 5 ($p < .0001$). No other effects of dimension were observed.

Dissociated version. Two mixed ANOVAs (one for cue screens and one for stimulus screens) were run on successful trials (Tables 2 and 4). The 3 (age: 5, 6, adults) \times 3 (trial type: simple block, no switch, switch) \times 2 (dimension: color, shape) ANOVA performed for cue screens revealed a significant main effect of trial type ($p < .001$). All other effects were not significant. Fixation time on the cue increased from simple-block trials to no-switch trials ($p < .0001$) and from no-switch trials to switch trials ($p < .05$).

For stimulus screens, the 3 (age: 5, 6, adults) \times 7 (AOI: Cue, RStim, IStim, R-RRsp, I-RRsp, R-IResp, I-IResp) \times 3 (trial type: simple block, no switch, switch) \times 2 (dimension: color, shape) mixed ANOVA revealed that all main effects and interactions were significant (all $ps < .05$), with the notable exceptions of Dimension \times Age, Trial Type \times Dimension, and a nearly significant AOI \times Trial Type \times Dimension \times Age interaction ($p = .08$; Table 4). Exploring further the AOI \times Trial Type \times Age interaction ($p < .001$; Figure 6), we observed that the time spent on the cue increased between simple-block trials and both no-switch and switch trials for all age groups ($ps < .0001$). The relevant dimension of the stimulus (RStim) was the most fixated area for all age groups. At age 5, the time spent on the RStim progressively increased across simple-block trials, no-switch trials, and switch trials, but only simple-block and switch trials significantly differed ($p < .0001$). At age 6, the time spent on the RStim did not significantly vary across trial types ($ps > .99$). In adults, fixation times on the RStim even decreased from simple-block trials to mixed-block trials ($ps < .0001$). In addition, the interference created by the irrelevant dimension of the stimulus (IStim) varied across age groups. In the simple-block trials, IStim was almost not fixated by adults (39 ms), whereas children spent a substantial amount of time on it (288 and 163 ms at ages 5 and 6, respectively). At age 5, the increase in fixation times on IStim across trial

Table 3

Analyses of Variance Computed on Fixation Times With Age as a Between-Subjects Variable and Area of Interest, Trial Type, and Dimension as Within-Subjects Variables in the Integrated and Dissociated Versions

Effect	Integrated version					Dissociated version				
	df	MSE	F	p	η_p^2	df	MSE	F	p	η_p^2
Cue screens										
Age	2, 76	62,512	0.48	.621	0.01	2, 80	60,222	0.51	.602	0.01
Trial Type	2, 152	15,849	87.60	<.001	0.54	2, 160	12,301	150.19	<.001	0.65
Trial Type × Age	4, 152	15,849	1.35	.259	0.03	4, 160	12,301	2.02	.121	0.05
Dimension	1, 76	6,450	1.20	.277	0.02	1, 80	5,438	0.44	.507	0.01
Dimension × Age	2, 76	6,450	0.10	.901	0.00	2, 80	5,438	0.97	.383	0.02
Trial Type × Dimension	2, 152	6,015	3.50	.036	0.04	2, 160	6,451	1.24	.291	0.02
Trial Type × Dimension × Age	4, 152	6,015	0.87	.474	0.02	4, 160	6,451	1.27	.284	0.03
Stimulus screens										
Age	2, 77	151,706	61.08	<.001	0.61	2, 80	111,812	56.44	<.001	0.59
AOI	3, 231	74,321	467.45	<.001	0.86	6, 480	42,958	255.77	<.001	0.76
AOI × Age	6, 231	74,321	18.02	<.001	0.32	12, 480	42,958	12.33	<.001	0.24
Trial Type	2, 154	36,761	87.16	<.001	0.53	2, 160	31,231	75.33	<.001	0.48
Trial Type × Age	4, 154	36,761	17.23	<.001	0.31	4, 160	31,231	16.43	<.001	0.29
Dimension	1, 77	12,334	3.96	.050	0.05	1, 80	10,683	16.72	<.001	0.17
Dimension × Age	2, 77	12,334	2.54	.085	0.06	2, 80	10,683	1.18	.313	0.03
AOI × Trial Type	6, 462	17,780	41.90	<.001	0.35	12, 960	13,774	48.68	<.001	0.38
AOI × Trial Type × Age	12, 462	17,780	5.14	<.001	0.12	24, 960	13,774	5.26	<.001	0.12
AOI × Dimension	3, 231	10,179	2.68	.072	0.03	6, 480	25,606	84.10	<.001	0.51
AOI × Dimension × Age	62, 231	10,179	6.31	<.001	0.14	12, 480	25,606	7.93	<.001	0.17
Trial Type × Dimension	2, 154	18,737	0.31	.647	0.00	2, 160	8,099	4.20	.020	0.05
Trial Type × Dimension × Age	4, 154	18,737	1.10	.348	0.03	4, 160	8,099	1.03	.391	0.03
AOI × Trial Type × Dimension	6, 462	11,384	2.15	.098	0.03	12, 960	8,139	3.54	.004	0.04
AOI × Trial Type × Dimension × Age	12, 462	11,384	2.01	.069	0.05	24, 960	8,139	1.70	.083	0.04

Note. Significant effects appear in bold. AOI = area of interest; η_p^2 = partial eta squared.

types was significant from simple-block trials to no-switch trials and switch trials ($ps < .05$) but not between no-switch and switch trials ($p > .90$). At age 6, it increased significantly from simple-block trials to no-switch trials ($p < .05$), and from no-switch to switch trials ($p < .0001$). In adults, it significantly increased from

simple-block trials to switch trials only ($p < .001$). Fixation time on the relevant dimension of the relevant response (i.e., the one that matches the relevant dimension of the stimulus) also increased from simple-block trials to switch trials at age 5 ($p < .001$). No other differences were significant for response pictures.

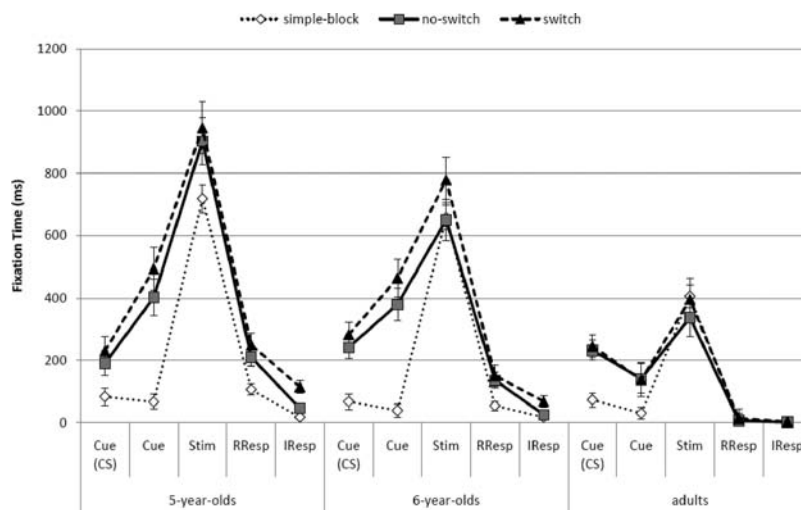


Figure 5. Fixation times for each area of interest as a function of trial type, dimension, and age for successful trials in the integrated version. Vertical bars indicate standard errors. CS = cue screens; Stim = stimulus; RResp = relevant response; IResp = irrelevant response. All measures relate to stimulus screens, except Cue (CS), which relates to cue screen. Curves are only visual help for readers.

Table 4

Mean Fixation Times (and Standard Deviation) in Milliseconds for Each Area of Interest as a Function of Age, Trial Type, and Relevant Dimension in the Dissociated Version

Age group, trial type, and relevant dimension	Area of interest							
	Cue (CS)	Cue	RStim	IStim	R-RResp	I-RResp	R-IResp	I-IResp
5-year-olds								
Simple block								
Color	74 (99)	48 (60)	289 (211)	429 (194)	54 (60)	43 (69)	9 (25)	9 (21)
Shape	55 (68)	49 (66)	620 (198)	147 (178)	77 (91)	23 (28)	12 (19)	3 (11)
No switch								
Color	187 (150)	324 (258)	329 (288)	510 (242)	108 (90)	94 (81)	12 (23)	27 (41)
Shape	218 (127)	463 (325)	687 (370)	258 (239)	189 (136)	59 (48)	29 (45)	14 (22)
Switch								
Color	255 (149)	499 (332)	413 (357)	606 (297)	121 (124)	89 (108)	47 (63)	101 (104)
Shape	216 (186)	466 (305)	783 (509)	291 (256)	261 (271)	63 (83)	63 (110)	44 (64)
6-year-olds								
Simple block								
Color	58 (76)	46 (83)	323 (161)	256 (162)	47 (47)	34 (48)	8 (15)	4 (10)
Shape	68 (86)	41 (54)	569 (193)	69 (84)	66 (77)	29 (58)	15 (20)	8 (16)
No switch								
Color	218 (97)	336 (212)	248 (137)	372 (182)	74 (43)	66 (60)	12 (21)	21 (41)
Shape	219 (115)	411 (272)	577 (320)	145 (98)	117 (80)	37 (40)	22 (33)	20 (26)
Switch								
Color	273 (137)	400 (221)	320 (417)	564 (280)	95 (87)	83 (85)	34 (48)	42 (50)
Shape	298 (143)	495 (264)	563 (276)	227 (126)	140 (86)	48 (59)	62 (93)	25 (35)
Adults								
Simple block								
Color	52 (106)	19 (50)	327 (136)	59 (70)	6 (17)	1 (3)	0 (0)	1 (4)
Shape	69 (127)	36 (102)	401 (149)	18 (76)	17 (39)	0 (0)	4 (15)	0 (0)
No switch								
Color	247 (152)	139 (123)	137 (98)	144 (116)	3 (10)	1 (3)	0 (0)	0 (0)
Shape	272 (158)	157 (142)	282 (120)	36 (58)	14 (25)	1 (3)	2 (5)	1 (3)
Switch								
Color	266 (148)	144 (153)	147 (128)	203 (126)	6 (18)	1 (5)	1 (4)	2 (9)
Shape	255 (157)	161 (139)	252 (113)	96 (113)	25 (49)	0 (2)	1 (4)	0 (0)

Note. CS = cue screens; RStim = relevant dimension of the stimulus; IStim = irrelevant dimension of the stimulus; R-RResp = relevant dimension of the relevant response; I-RResp = irrelevant dimension of the relevant response; R-IResp = relevant dimension of the irrelevant response; I-IResp = irrelevant dimension of the irrelevant response.

Of interest, the significant AOI \times Trial Type \times Dimension interaction ($p = .004$; Figure 7) showed that the shape modality of the stimulus was significantly more fixated than the color modality whatever the relevant dimension. Furthermore, the interaction mainly concerned the stimulus AOIs (RStim and IStim). When shape was relevant, fixation times were higher on RStim (i.e., here shape modality of the stimulus) than on IStim (i.e., here color modality of the stimulus) on all trial types ($ps < .0001$). When color was relevant, the reverse pattern was observed on switch and no-switch trials; that is, fixation times were higher for IStim (i.e., here shape modality of the stimulus) than RStim (i.e., here color modality of the stimulus; $ps < .0001$). On simple-block trials where color was relevant, RStim was gazed at longer than IStim ($p < .001$). Whatever the relevant dimension, time spent on IStim increased across simple-block trials, no-switch trials, and shift trials ($ps < .05$). In contrast, increase in the time spent on RStim varied as a function of the relevant dimension. When color was relevant, the time spent on RStim decreased from simple-block trials to no-switch trials ($p < .0001$) and tended to increase from no-switch to switch trials ($p = .08$), whereas no significant variation was observed when shape was relevant ($ps > .99$). In addition to effects on RStim and IStim, there was also a signifi-

cantly higher fixation time on the cue for shape than for color on no-shift trials ($p < .001$) and a similarly higher fixation time on R-RResp for shape than for color on switch trials ($p < .01$). Finally, although the AOI \times Trial Type \times Dimension \times Age interaction only neared significance after the Greenhouse–Geisser correction ($p = .08$), it showed that dimension-related differences tended to lessen with participants' age, especially for simple-block trials where there were absolutely no differences between color and shape in adults.

Discussion

The present study explored the visual information that preschoolers and adults consider while performing the Advanced DCCS. Despite a common high level of accuracy from 5 years on, a decrease in mixing and local costs was observed. The decrease was more conspicuous for mixing costs than for local costs, which is consistent with prior evidence showing that mixing costs are more developmentally sensitive (e.g., Cepeda et al., 2001; Reimers & Maylor, 2005). Mixing and local costs did not vary across versions, but the dissociated version yielded longer RTs than the integrated one, although they both led to similar accuracy perfor-

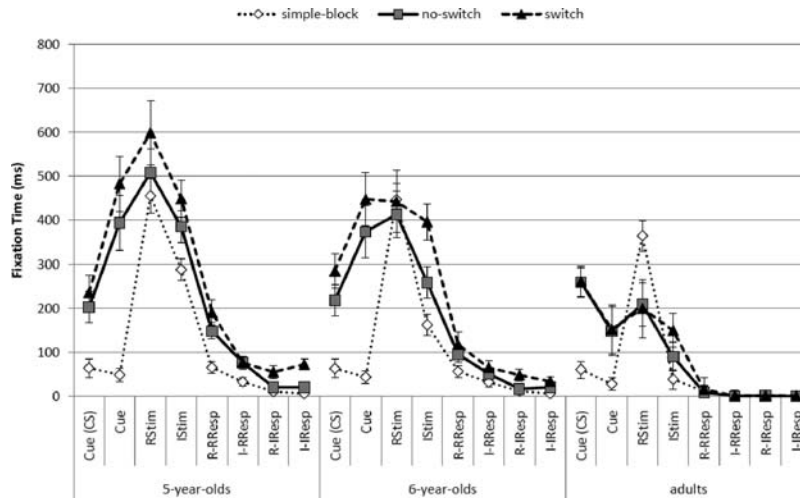


Figure 6. Fixation times for each area of interest as a function of trial type, dimension, and age for successful trials in the dissociated version. Vertical bars indicate standard errors. CS = cue screens; RStim = relevant dimension of the stimulus; IStim = irrelevant dimension of the stimulus; R-RResp = relevant dimension of the relevant response; I-RResp = irrelevant dimension of the relevant response; R-IResp = relevant dimension of the irrelevant response; I-IResp = irrelevant dimension of the irrelevant response. All measures relate to stimulus screens, except Cue (CS), which relates to cue screen. Curves are only visual help for readers.

mance (see Kloo et al., 2008, for similar results in adults; longer RTs with dissociated stimuli have also been observed in school age children on the task-switching paradigm; Cragg & Nation, 2009). Accuracy and RTs confirmed that shape matching was more difficult than color matching (Ellefsen et al., 2006). This asym-

metry resulted in higher mixing costs for the weaker shape task than the stronger color task, which is consistent with some prior findings with preschoolers (e.g., Davidson, Amso, Anderson, & Diamond, 2006). Of interest, local costs were higher for the weaker task (shape) in terms of accuracy but higher for the

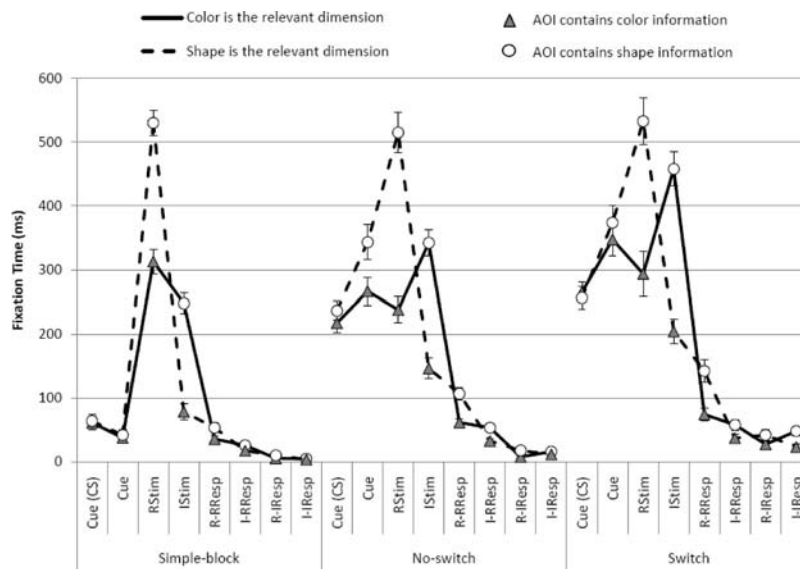


Figure 7. Fixation times for each area of interest as a function of trial type and dimension for successful trials in the dissociated version. Vertical bars indicate standard errors. AOI = area of interest; CS = cue screens; RStim = relevant dimension of the stimulus; IStim = irrelevant dimension of the stimulus; R-RResp = relevant dimension of the relevant response; I-RResp = irrelevant dimension of the relevant response; R-IResp = relevant dimension of the irrelevant response; I-IResp = irrelevant dimension of the irrelevant response. All measures relate to stimulus screens, except Cue (CS), which relates to cue screen. Curves are only visual help for readers.

stronger task (color) pertaining to RTs, bringing further evidence for speed–accuracy trade-offs in task-switching settings (Davidson et al., 2006; Samavatyan & Leth-Steensen, 2009). Therefore, the effects of dimension were different for mixing and local costs, whereas previous results showed both higher mixing costs and local costs for the stronger task in preschoolers (Ellefsen et al., 2006). Our study used random switches that necessitated setting goals on the basis of task cues only. In contrast, Ellefsen et al.'s (2006) study involved switching on the basis of a predictable sequence (either on every trial or every second trial, depending on the block) that necessitates setting goals by updating this internal sequence in working memory. Because goal setting is primarily captured by mixing costs, this difference in goal-setting demands may account for the discrepancy in findings across studies for mixing costs (and not local costs), although future research is needed to clarify this issue.

Accuracy and RT performance suggest that processes underlying flexible behavior might be different or differently applied across age groups. Eye-tracking data provided interesting insight on this issue. The analyses of fixation times showed that participants mostly fixated the stimulus, regardless of trial type, and to a lesser extent fixated the cue in the mixed block, but they almost did not attend to the response pictures. Participants spent more time on the cue and children also fixated the stimulus longer, in the mixed-block than the simple blocks. Fixation times for the relevant and irrelevant dimensions of the stimulus changed differently across trial types and age groups. In particular, fixation times on the irrelevant dimension in the simple-block trials were relatively high for children but were very low for adults. In addition, they increased across simple-block, no-switch, and switch trials in all age groups. At age 5, a similar increase across the three trial types was found for the relevant dimension of the stimulus. In contrast, these fixation times did not significantly vary across trials at age 6 and even significantly decreased from the simple blocks to the mixed block in adults. Finally, fixation times were found to be higher for the shape modality of stimuli than for the color modality whatever the relevant dimension.

Participants spent more time fixating the cue in the mixed-block trials than in the simple-block trials, which is consistent with the claim that goal setting is especially demanding in the mixed block and suggests that participants efficiently used the cue to set goals in the mixed block. The increase in fixation time on the cue occurred both before and after stimulus onset, suggesting that a 500-ms cue–stimulus interval is not sufficient, even for adults, to set the relevant goal and/or that task-set maintenance or switching requires reconsidering the cue after stimulus onset, which speaks to Rogers and Monsell's (1995) claim that, even with a large amount of time between cue and stimulus, part of intentional task-set reconfiguration has to be done after stimulus onset. These results also confirm that at least from age 5, children can successfully use cue–stimulus interval for advance preparation, which is in line with previous reports of significant effect of CTI variation on preschoolers' and older children's performance (Cepeda et al., 2001; Karbach & Kray, 2007).

Between stimulus onset and response entry (stimulus screens), participants mainly fixated on the stimulus. In contrast, response options, especially the irrelevant one, were almost not fixated in the Advanced DCCS, even by the youngest children. This result suggests that the main difficulty in this paradigm consists in

extracting the relevant information from the stimulus rather than selecting the correct response. In addition, it is generally assumed that 3-year-olds' difficulty in the standard DCCS partially results from the visual conflict arising between test cards (stimuli) and target cards (response pictures; e.g., Garon et al., 2008), as suggested by 3-year-olds' improved switching performance when the visual conflict is suppressed by replacing target cards with puppets (Perner & Lang, 2002). The very short fixation times on response pictures in the Advanced DCCS suggest that, in this paradigm, conflict does not lie at the visual level but is related to the reversed contingency of responses between tasks per se (i.e., color and shape lead to divergent responses). Consistently, significant switch costs are observed in adults even when the response pictures are not visually materialized in the task-switching paradigm (e.g., Koch & Allport, 2006). The divergent results regarding the importance of visual conflict on the standard and Advanced DCCS suggest that the difficulties at age 3 and later on at least partially differ in nature.

While performing the Advanced DCCS, participants mostly fixated the stimulus area, hence pointing out the difficulty of attention reorientation to the relevant dimension while implementing a switch in task set and, to a lesser extent, while maintaining a given task set under high task uncertainty. The patterns of fixations on the stimulus across trial types greatly differed with age. Fixation times on the stimulus increased from simple-block to no-switch trials at age 5; it increased significantly only from simple-block trials to switch trials at age 6, and it did not vary significantly across trials for adults. Therefore, the youngest children encountered difficulty in orienting attention in the mixed block even when they did not have to implement a switch, suggesting that when task uncertainty is high, they have more difficulty than older participants in setting relevant task goals and/or resisting the interference created by the other dimension. This is consistent with findings that mixing costs are very developmentally sensitive (e.g., Cepeda et al., 2001; Reimers & Maylor, 2005).

The analyses run on the dissociated version highlighted that fixation time on the stimulus not only differed as a function of trial type but also differed as a function of the relevant/irrelevant status of the dimensions at stake. In particular, fixation times on the irrelevant dimension of the stimulus progressively increased across simple-block, no-switch, and switch trials for all age groups. This suggests that the interference of the irrelevant dimension increases as executive demands and task uncertainty increase. The significant increase between simple-block trials and no-switch trials indicates that task-set maintenance is especially difficult on no-switch trials, possibly because of the high goal-setting demand that generates task uncertainty and/or a difficulty resisting interference related to the presence of the irrelevant dimension. In addition, it may be more resource consuming to maintain activation of a task set that was previously inhibited (as is the case in the mixed block) rather than maintain it across a whole series of trials (simple blocks; see Diamond, 2009, for a similar argument). The irrelevant dimension caused even more interference in the switch trials where participants had to disengage from this dimension (and related task set) and reorient attention to the newly relevant dimension, that is, implement a switch in task set.

Trial type also influenced the amount of time the participants spent on the relevant dimension of the stimulus. Contrary to the irrelevant dimension of the stimulus, the effect of trial type on

fixation time on the relevant dimension differed across age groups. At age 5, fixation time on the relevant dimension progressively increased across simple-block, no-switch, and switch trials (although only simple-block and switch trials significantly differed), whereas no significant differences were found at age 6. Surprisingly, adults spent significantly less time on the relevant dimension in mixed-block trials than in simple-block trials. This phenomenon may relate to the small stimulus sample size used in the present study. With only two different stimuli, participants could easily realize that a given value of one dimension was always associated with the same value of the other dimension on the stimuli (e.g., the teddy bear always appeared beside the color red). With age, participants might be increasingly sensitive to bindings between dimension values and increasingly inclined to infer the value on one dimension on the basis of what they know of the other dimension value. Such a strategy would help participants save time (and thus compensate for the additional time spent on the irrelevant dimension) by not fixating (or spending less time) on the relevant dimension when it happened that the irrelevant dimension was fixated first. Complementarily, when the irrelevant dimension was fixated first, participants may have adopted a strategy of pressing the key opposite to the key related to the relevant dimension. The use of such a strategy seems all the more probable because *silly-game strategies* (i.e., reverse matching on a given dimension, e.g., teddy bear with car and car with teddy bear) have been shown to facilitate switching performance, at least in the standard DCCS (Kloo, Perner, Kerschhuber, Dabernig, & Aichhorn, 2008; Perner & Lang, 2002).

Alternatively, the decrease in fixation time on the relevant dimension of the stimulus between simple-block trials and mixed-block trials in adults may reflect the time necessary for motor response entry. Given that the adults hardly fixated on response pictures at all, they might have continued to gaze at the stimulus (although they no longer processed it) while entering the motor response. Because adults almost exclusively fixated the relevant dimension in the simple blocks, they may have continued to gaze at this dimension during response entry. In the mixed block, the time related to response entry would have been more equally split between the relevant and irrelevant dimensions of the stimulus, hence leading to a decrease in fixation time on the relevant dimension from simple-block trials to mixed-block trials. Because children spent more time on the correct response, time for response entry may not have been spent (or was spent to a lesser extent) on the stimulus. However, this does not account for why fixation time on the relevant dimension increased even from the simple blocks to the mixed blocks in preschoolers or why the drop in fixation time for the relevant dimension was not fully compensated by an increase in the time spent on the other dimension in adults, at least on no-switch trials. Researchers could confront the information-strategy hypothesis and motor-response time hypothesis, using a paradigm in which participants would not have to manually respond but would instead respond by fixating the correct response picture on the screen. If the decrease in fixation time on the relevant dimension observed in adults is related to a strategic utilization of information related to the irrelevant dimension, then the same phenomenon should be observed with such a design. By contrast, if it is related to motor-response entry, then this phenomenon should disappear because this design would require participants to stop fixating the stimulus while responding.

Eye-tracking analyses revealed that the effect of trial type on fixation times was modulated by the dimension. The color/shape asymmetry was underpinned by longer fixation times for the shape modality of stimuli relative to the color modality. Of interest, in switch and no-switch trials, shape yielded longer fixation times even when it was irrelevant. It might be argued that longer gazes for shape reflect the higher perceptual saliency of this dimension. Consistent with this idea, global properties, such as shape, are conveyed by low spatial frequency components of stimuli that are extracted faster than high spatial frequency components that convey color (Bonnet, 1989; Chelazzi, Miller, Duncan, & Desimone, 1993), hence giving attentional priority to shape information over color information (Robertson, Egly, Lamb, & Kerth, 1993). However, if shape is more perceptually salient than color, why was performance better when color was the relevant dimension (higher accuracy and lower RTs)? It may be argued that perceptual saliency and cognitive-processing difficulty are conceptually separated. Shape could thus be more perceptually salient (i.e., it catches attention) but more difficult to process, probably because shape information is more visually complex and/or activates semantic processing to a greater extent than color (Boucart, Humphreys, & Lorceau, 1995). Shorter fixation times on color would thus suffice to yield better RT and accuracy performance when color is relevant.

The results did not confirm any of the predictions we derived from either the task-set inertia or the task-set reconfiguration accounts. On the basis of the task-set inertia account, we expected that a switch to the stronger, color task set would lead to a higher increase in fixation time for the relevant stimulus dimension (color) relative to a switch to shape, because the stronger task is supposedly harder to reactivate. However, fixations on the color modality of stimuli were only marginally longer on switch than no-switch trials when color was relevant, hence providing only weak support to this hypothesis. Contrary to what we expected on the basis of the task-set reconfiguration account, the shape modality of stimuli was not fixated longer on switch than no-switch trials when shape was relevant, suggesting that activating the shape task set was not particularly difficult on switch trials. In addition, when shape was relevant, the time spent on the color modality of the stimulus increased by 59 ms on switch trials relative to no-switch trials, whereas when color was relevant, the time spent on the shape modality increased by 113 ms, hence suggesting that color was indeed easier to inhibit than shape. Although predictions directly derived from the task-set reconfiguration account were not supported, other results speak to this account. Switches to color mainly differed from no-switch trials by an increase in the time spent on the irrelevant shape dimension. Although participants may have spent more time on shape because they struggled to activate color, such a finding can be more straightforwardly interpreted as reflecting a higher difficulty for inhibiting shape. Because shape needs more processing, it probably results in a higher activation level, which may in turn lead to a need for extra inhibition on trials that switch to color. This means that the weaker shape dimension probably also undergoes a carryover effect but, contrary to the carryover effect for the stronger task that is hypothesized to result from automatic phenomena, this effect may stem from an active executive process related to task-set reconfiguration (Mayr & Keele, 2000; Yeung & Monsell, 2003). The present findings thus complement previous studies by showing that

asymmetrical local costs result from carryover effects related not only to the stronger task but also to the weaker task, and this latter carryover effect may be due to executive processes. Furthermore, the tendency of the shape/color asymmetry to decrease with age is consistent with previous evidence for lessening sensitivity to carryover effects with age (Cepeda et al., 2001; Crone et al., 2006) and increasing efficiency of inhibition over the preschool period (Gerstadt, Hong, & Diamond, 1994; Kirkham et al., 2003).

Eye-tracking data surprisingly showed that one of the main differences between children and adults related to simple-block trials, that is, the trials in which executive demands were the lowest. Whereas adults almost exclusively fixated the relevant dimension of the stimulus in the simple-block trials, 5- and 6-year-old children spent a substantial amount of time on the irrelevant dimension of the stimulus, hence suggesting that children struggled to ignore the irrelevant dimension of the stimulus even when executive demands were supposedly low. The difference between children and adults may hint at adults' ability to exert a higher degree of executive control than children in these poorly demanding trials. Alternatively, it may reflect adults' reduced need to resort to executive control in such trials, relative to children, because of a higher automaticity of color/shape matching processes. For instance, adults could be more prone than children to fixate only the relevant side of the stimulus in the simple-block trials of the dissociated version, as further suggested by adults' especially low fixation times on shape when color was relevant on such trials. Such a strategy would become automatic across trials. A lack of automaticity in children would suggest that flexibility development does not exclusively consist of an increasingly efficient ability to exert executive control in situations with a high degree of interference but also consists of automaticity (i.e., reduction of the level of executive control required to succeed) of some behaviors in situations with a low degree of interference. This idea largely converges with Case's (1987) claim that cognitive development is partly dependant on automaticity of cognitive processes, which liberates cognitive resources for more complex processing.

Finally, the present study relied on the assumption that the pattern of fixation times observed on the dissociated version was also informative of the integrated version. In contrast to results obtained on the standard DCCS at age 3 (Carlson, 2005; Kloo & Perner, 2005; Kloo et al., 2008), both versions led to similar accuracy performance, hence suggesting they were of equivalent difficulty. However, the longer RTs observed on the dissociated version (see Kloo et al., 2008, and Cragg & Nation, 2009, for similar results in adults and children, respectively) hint at some different and/or additional attentional processes occurring when dimensions are spatially dissociated. This finding is consistent with previous studies showing that it is easier to switch attention within one object than across objects (e.g., H. J. Müller & O'Grady, 2000). In addition, the dissociated version may have required both analytic attention (for color and shape information) and spatial attention (to switch between the two stimulus objects), which have been found separable (Chajut, Schupak, & Algom, 2009), whereas the integrated version may involve only analytic attention. Future research will have to determine to what extent these types of attentional mechanisms interact with executive control to produce different patterns of fixations.

In conclusion, the present study examined the visual information that children and adults consider while performing the Advanced DCCS and led to new insightful findings regarding the processes involved in cognitive flexibility. First, preschoolers and adults looked longer at the cue when goal-setting demands were high, suggesting that goal setting is an essential component of flexible behavior. Second, switch costs seemed to relate to selection of the relevant information on the stimulus to a greater extent than response selection. Third, the switch cost asymmetry between color and shape was driven by longer fixation times on shape modality of the stimulus than on the color modality. Finally, the present study strikingly showed that the patterns of visual information that participants considered differed over age, suggesting that differences in latency did not merely reflect age differences in the time required to apply identical processes. Instead, flexible responses seemed underpinned by qualitatively different strategies over age, although this will have to be confirmed in future studies.

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(Appendix follows)

Appendix

Mean Percentages (and Standard Deviations) of Trials With No Fixations (0-ms Fixation Time) for Each Area of Interest and as a Function of Trial Type, Relevant Dimension, Age, and Version

Age group, trial type, and relevant dimension	Integrated version					Dissociated version							
	Cue (CS)	Cue	Stim	RResp	IResp	Cue (CS)	Cue	RStim	IStim	R-RResp	I-RResp	R-IResp	I-IResp
5-year-olds													
Simple block													
Color	78 (25)	82 (24)	1 (4)	55 (27)	88 (16)	76 (26)	77 (23)	32 (31)	14 (16)	77 (23)	85 (22)	94 (10)	96 (8)
Shape	69 (32)	71 (33)	0 (0)	69 (27)	89 (15)	78 (27)	79 (24)	7 (13)	56 (31)	74 (24)	88 (11)	91 (11)	97 (8)
No switch													
Color	47 (24)	28 (25)	1 (2)	46 (26)	78 (15)	52 (35)	40 (37)	31 (27)	17 (18)	63 (26)	70 (22)	92 (8)	86 (20)
Shape	47 (29)	28 (28)	1 (3)	48 (29)	69 (17)	49 (29)	36 (33)	12 (21)	35 (28)	55 (30)	78 (16)	81 (16)	85 (17)
Switch													
Color	39 (30)	29 (31)	1 (5)	43 (24)	64 (24)	50 (31)	31 (34)	24 (26)	13 (21)	67 (23)	72 (20)	82 (19)	72 (24)
Shape	57 (31)	34 (34)	1 (3)	55 (30)	55 (24)	55 (35)	39 (32)	13 (23)	40 (31)	63 (27)	82 (16)	71 (25)	74 (23)
6-year-olds													
Simple block													
Color	75 (22)	76 (24)	1 (4)	68 (29)	89 (18)	78 (23)	79 (25)	23 (22)	40 (29)	76 (19)	84 (15)	96 (6)	97 (7)
Shape	74 (26)	74 (21)	0 (2)	73 (26)	89 (15)	76 (22)	76 (22)	3 (6)	72 (27)	73 (27)	87 (18)	92 (9)	95 (8)
No switch													
Color	38 (28)	22 (20)	2 (5)	48 (26)	87 (13)	37 (22)	32 (19)	31 (19)	20 (19)	65 (17)	72 (21)	93 (10)	89 (10)
Shape	34 (24)	20 (20)	3 (6)	51 (26)	79 (18)	41 (25)	23 (21)	8 (16)	47 (22)	54 (20)	80 (15)	85 (14)	86 (11)
Switch													
Color	31 (24)	24 (23)	1 (3)	51 (28)	67 (25)	36 (30)	27 (21)	34 (26)	7 (13)	66 (21)	65 (21)	83 (18)	76 (14)
Shape	37 (27)	25 (22)	1 (4)	61 (23)	68 (25)	40 (30)	33 (26)	8 (16)	34 (24)	57 (23)	83 (14)	80 (18)	81 (19)
Adults													
Simple block													
Color	81 (30)	88 (23)	5 (18)	91 (22)	99 (8)	86 (28)	91 (17)	16 (22)	78 (23)	95 (13)	99 (4)	100 (0)	100 (2)
Shape	77 (37)	87 (26)	3 (8)	92 (16)	99 (2)	78 (36)	86 (29)	3 (13)	93 (20)	88 (25)	100 (0)	97 (10)	100 (0)
No switch													
Color	39 (34)	47 (30)	9 (18)	94 (13)	100 (1)	34 (36)	52 (31)	47 (26)	49 (30)	98 (7)	99 (3)	100 (0)	100 (1)
Shape	34 (36)	43 (35)	7 (12)	93 (12)	98 (4)	31 (36)	46 (34)	16 (18)	81 (20)	90 (15)	99 (3)	97 (4)	99 (2)
Switch													
Color	33 (37)	54 (35)	4 (11)	91 (17)	99 (4)	29 (33)	52 (35)	49 (30)	33 (30)	95 (11)	99 (5)	99 (3)	98 (9)
Shape	40 (39)	44 (35)	5 (10)	89 (17)	96 (7)	35 (34)	49 (34)	23 (20)	65 (25)	86 (25)	99 (3)	99 (4)	100 (0)

Note. CS = cue screens; Stim = stimulus; RResp = relevant response; IResp = irrelevant response; RStim = relevant dimension of the stimulus; IStim = irrelevant dimension of the stimulus; R-RResp = relevant dimension of the relevant response; I-RResp = irrelevant dimension of the relevant response; R-IResp = relevant dimension of the irrelevant response; I-IResp = irrelevant dimension of the irrelevant response.