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PAPER

How useful is executive control training? Age differences in near and far transfer of task-switching training

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Abstract

Although executive functions can be improved by training, little is known about the extent to which these training-related benefits can be transferred to other tasks, or whether this transfer can be modulated by the type of training. This study investigated lifespan changes in near transfer of task-switching training to structurally similar tasks and its modulation by verbal self-instructions and variable training, as well as far transfer to structurally dissimilar 'executive' tasks and fluid intelligence. Three age groups (8–10; 18–26; 62–76 years of age) were examined in a pretest-training-posttest design. We found near transfer of task-switching training in all age groups, especially in children and older adults. Near transfer was enhanced in adults and impaired in children when training tasks were variable. We also found substantial far transfer to other executive tasks and fluid intelligence in all age groups, pointing to the transfer of relatively general executive control abilities after training.

Introduction

Recently, much research has focused on executive control, that is, on the ability to plan, guide, and monitor complex goal-directed actions, considered to be a fundamental ability of human intelligent behavior. Today, it is widely accepted that executive control consists of separate control components, such as switching, updating, and inhibition (e.g. Fisk & Sharp, 2004; Miyake, Friedman, Emerson, Witzki & Howerter, 2000). For some of these components, substantial age-related changes have been observed across the lifespan (e.g. Bedard, Nichols, Schachar, Schachar, Logan & Tannock, 2002; Cepeda, Kramer & Gonzales De Sather, 2001; Kray, Eber & Karbach, 2008; Kray, Eber & Lindenberger, 2004; Williams, Ponesse, Schachar, Logan & Tannock, 1999). Evidence for these differential age-related changes in executive control comes from a variety of experimental paradigms, among them the task-switching paradigm. In task-switching studies, participants are instructed to perform two simple tasks A and B, either in single-task blocks (only A or B) or in mixed-task blocks (switching between both tasks). This design allows calculating two types of task-switching costs: Mixing costs, defined as the difference in mean performance between mixed-task and single-task blocks, refer to the ability to maintain and select two tasks. Switching costs, defined as the difference in mean performance between switch and nonswitch trials within mixed-task blocks, measure the ability to flexibly switch between tasks. Young adults usually show smaller mixing costs than children (e.g. Crone, Ridderinkhof, Worm, Somsen & Van der Molen, 2004; Kray *et al*., 2008; Kray *et al*., 2004) and older adults (e.g. Mayr, 2001; Meiran, Gotler & Perlman, 2001), while age differences on the level of switching costs seem to be less pronounced (e.g. Kray & Lindenberger, 2000; Mayr, 2001; Verhaeghen & Cerella, 2002). Consistently, lifespan studies showed U-shaped developmental functions for mixing costs, but not for switching costs (cf. Kray *et al*., 2008; Kray *et al*., 2004; Reimers & Maylor, 2005).

Based on these findings, developmental researchers have investigated the potential range of cognitive plasticity in task-switching abilities. So far, a number of previous studies have indicated that training can reduce age-related differences in both types of switching costs (e.g. Cepeda *et al*., 2001; Kray *et al*., 2008; Kray & Lindenberger, 2000). Cepeda and colleagues (2001), for instance, found that mixing costs were reduced after two sessions of task-switching training, especially in children (10–12 years of age) and in older adults. Similarly, Kray and Lindenberger (2000) showed a reduction of mixing as well as switching costs after six sessions of training in young and older adults. The primary aim of our study was to examine whether these training-related improvements in task-switching abilities can be transferred to new switching tasks, and whether training strategies and the type of task-switching training can modulate this transfer in different age groups.

Evidence for the transfer of executive control training is rather scarce and comes from a wide variety of

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experimental paradigms and training tasks. Regarding childhood, a number of developmental studies showed that different types of executive control training could be transferred to structurally similar (near transfer) and dissimilar (far transfer) tasks after training. Kloo and Perner (2003), for instance, trained 3- to 4-year-olds by means of the Dimensional Change Card Sort (DCCS) and the false-belief task. They found that DCCS training improved performance on the false-belief task and vice versa (for transfer in autistic children, see Fisher & Happé, 2005). Also, Rueda, Rothbart, McCandliss, Saccomanno and Posner (2005) showed that training including a battery of executive control tasks generalized to similar new tasks as well as to aspects of intelligence quite remote from the training tasks (cf. Dowsett & Livesey, 2000; Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlström, Gillberg, Forssberg & Westerberg, 2005). Evidence for the near transfer of executive control training in older age mostly comes from dual-task studies (cf. Kramer & Kray, 2006): Recently, Bherer and colleagues (Bherer, Kramer, Peterson, Colcombe, Erickson & Becic, 2005) showed that dual-task training benefits in young and older adults generalized to new tasks and stimuli (cf. Kramer, Larish, Weber & Bardell, 1999; Kramer, Larish & Strayer, 1995). Similarly, Minear, Shah and Park (2002) found that task-switching training transferred to similar tasks after training in young and older adults. However, this near transfer was found only for mixing costs, not for switching costs. Thus, existing evidence for the transferability of task-switching training seems to be restricted to near transfer in younger and older adults.

In sum, there are a number of studies indicating that children, young adults, and older adults can transfer executive control training to untrained tasks. However, these effects are highly variable and based on rather different types of training, such as working memory training (e.g. Klingberg *et al*., 2005), dual-task training (e.g. Bherer *et al*., 2005; Kramer *et al*., 1999; Kramer *et al*., 1995), task-switching training (Minear *et al*., 2002) or even a battery of several executive control tasks (e.g. Rueda *et al*., 2005). Also, the range of transfer distance (i.e. different types of near and far transfer) as well as the age range of the participants was very diverse in these studies. Hence, the comparability of previous studies focusing on the transfer of training seems to be very limited. Although most of these findings suggest that at least near transfer is possible in different age groups, conditions supporting the occurrence of far transfer, differences between diverse types of training, and the lifespan development of these effects are still not clear. Therefore, the aim of the present study was to systematically investigate age-related changes in the near and far transfer of training and the influence of different types of training within one study and across a wide range of ages.

In order to investigate transfer of cognitive training, we applied the task-switching paradigm, tapping at least two aspects of executive control, namely task-set maintenance and selection as well as task-set switching. Similar to Minear *et al*. (2002), we compared transfer after task-switching training to transfer after training on the same two single tasks performed separately. To examine whether specific training strategies or the type of training can modulate transfer, this study included two additional training conditions. In one of these conditions, we investigated whether verbal self-instruction strategies can be transferred to new, untrained tasks. Prior research indicated that verbal processes could support the retrieval of the phonological representation of currently relevant task goals (e.g. Baddeley, Chinchotta & Adlam, 2001). This effect is particularly pronounced when external task cues are missing and the need for endogenous control is increased (e.g. Emerson & Miyake, 2003). Consistently, a recent study showed that verbal self-instructions (i.e. naming the next task goal during task preparation) facilitate the maintenance and selection of task sets, especially in childhood and older age. That is, they serve as effective means to reduce age-related differences in task-switching abilities (Kray *et al*., 2008). To examine whether these verbal self-instruction benefits can be transferred to a new task, we trained one group of participants not only in task switching, but also in the use of verbal self-instructions.

In the other condition, we also tested the influence of the type of task-switching training on the amount of transfer in different age groups. Previous studies have provided considerable evidence indicating that conditions facilitating performance during training are not always most effective in supporting the acquisition of a generalizable skill. In contrast, manipulations decreasing the speed of skill acquisition during training, such as variable training tasks, can support its transfer to a new, untrained task (for reviews, see Rosenbaum, Carlson & Gilmore, 2001; Schmidt & Bjork, 1992). For instance, Sanders, Gonzalez, Murphy, Pesta and Bucur (2002) showed that high variability training in mental calculation supported transfer to non-trained tasks in young adults (for similar results after dual-task training, see Kramer *et al*., 1999). Thus, for another group in the present study, training was variable, meaning that the stimuli and the type of tasks in each task-switching training session were different.

In sum, the first goal of this study was to examine age differences in the transfer of task-switching training to a similar switching task (near transfer) and its modulation by a training strategy and by the type of training. Since prior evidence indicated that verbal self-instructions could support task switching (Kray *et al*., 2008), we investigated whether these verbal self-instructions performed during training influence the amount of transfer. Also, because variable training tasks can foster transfer in adults (cf. Kramer *et al*., 1999; Sanders *et al*., 2002), we expected more near transfer after variable training, at least in adults.

Table 1 *Outline of the training and transfer procedure*

Pretest Sessions 1 + 2	Training Sessions 3–6	Posttest Sessions 7 + 8
All groups: Single tasks (tasks A and B) Task switching (tasks A and B) Cognitive battery: Stroop task Verbal working memory Spatial working memory Fluid intelligence	*Group 1:* Single-task training (tasks C and D) *Group 2:* Task-switching training (tasks C and D) *Group 3:* Task-switching (tasks C and D) + verbal self-instruction training *Group 4:* Task-switching + verbal self-instruction training + training variability (tasks C/D, E/F, G/H, I/J)	*All groups:* Single tasks (tasks A and B) Task switching (tasks A and B) Cognitive battery: Stroop task Verbal working memory Spatial working memory Fluid intelligence

Note: Subjects within each age group were matched to one of the four training groups based on their pretest performance in task switching (mixing costs), single-task reaction time, and Raven score to prevent differences in baseline performance between the training groups. Pretest 1/Posttest 1 included the measurement of verbal and spatial working memory as well as fluid intelligence abilities, and Pretest 2/Posttest 2 single tasks, task-switching, and the Stroop task.

The second goal was to investigate the range of transfer. Therefore, we examined age-related changes in the far transfer of task-switching training to other ‘executive control tasks’, that is, the Stroop test and working memory tasks. Given that these tasks require executive control abilities that are also needed for task switching, such as the online maintenance of relevant task goals and the inhibition of currently irrelevant information, far transfer to these tasks may be expected. Finally, we also included measures of fluid intelligence to investigate far transfer to another task domain. While we expected near transfer of task-switching training in all age groups (cf. Bherer *et al*., 2005; Minear *et al*., 2002; Kramer *et al*., 1999; Kramer *et al*., 1995; Rueda *et al*., 2005), age differences in the amount of far transfer and its modulation by the type of training were an open question. Since there is usually less transfer when the training and transfer tasks are less similar (for a review, see Klauer, 2001), we expected more transfer of training to structurally similar tasks than to structurally dissimilar tasks.

Method

Participants

Fifty-six children (mean age = 9.2, *SD* = 0.6, range = 8.1–10.1 years, 43% female), 56 young adults (mean age = 22.4, *SD* = 2.2, range = 18.0–26.3 years, 51% female), and 56 older adults (mean age = 68.7, *SD* = 3.0, range = 62.3–76.8 years, 59% female) participated in this study. They were recruited from the subject pool at Saarland University, tested individually by one of the eight experimenters and were paid 60 Euros (~95 USD) for participating in the eight sessions of the study.

Materials and procedure

We used IBM-compatible computers for data collection. Stimuli were presented on a 17-inch CRT color monitor and an external keypad registered manual responses.

Transfer of training was assessed by means of a pretest-training-posttest design (see Table 1) and was defined as performance improvement at posttest relative to the baseline performance at pretest. The two pretest sessions included baseline measurements of task switching and single-task performance as well as a battery of cognitive tasks. They were followed by four training sessions. The two posttest sessions were identical to pretest sessions, each of them taking 60–70 minutes. For each participant, testing took 6–8 weeks, that is, they performed approximately one session per week.

Pretest and posttest assessment

Task switching

We used a modified version of the task-switching paradigm, including performance in single-task (task A or B only) and mixed-task blocks (switching between both tasks). In mixed-task blocks, subjects were instructed to switch tasks on every second trial. Task A required participants to decide whether a picture showed a fruit or a vegetable (‘food’ task), and task B whether a picture was small or large (‘size’ task). The same two response keys were used for both task sets. Stimuli consisted of 16 fruit and 16 vegetable pictures, each one presented in a large and a small version. Mixing and switching costs were defined as two orthogonal contrasts for the factor trial type (single, nonswitch, switch trials): Mixing costs were measured as the difference in mean performance between single-task and mixed-task blocks (contrast: -2 1 1), and switching costs as the difference between nonswitch and switch trials within mixed-task blocks (contrast: 0 1 -1). Participants performed two single-task practice blocks (17 trials) followed by 20 experimental blocks[1] (eight single and 12 mixed blocks; 17 trials). Trials started with a fixation-cross (1400 ms), followed by the target until the subject responded. After

[1] Block sequence: 2 single – 2 mixed – 2 single – 2 mixed – single – 2 mixed – single – 2 mixed – single – 2 mixed – single – 2 mixed.

25 ms, the next fixation-cross appeared. Subjects were instructed to respond as fast and as accurately as possible, and they were offered a short break after half of the blocks had been completed.

Cognitive test battery

To examine whether task-switching training also transfers to structurally dissimilar 'executive' tasks and fluid intelligence, the cognitive battery included tests for four constructs (each measured with two or three indicators to increase the reliability of the measurement):

1. Inhibitory control: Color-Stroop/Number-Stroop (cf. Salthouse & Meinz, 1995). In the Color-Stroop task, subjects saw words (e.g. 'red', 'tree') presented in red, blue, green, or yellow letters. Participants indicated the letter color as quickly as possible by pressing one of four response buttons. In the Number-Stroop task, participants saw characters (e.g. 2, HHH) presented one-, two-, three-, or fourfold and decided how many stimuli were presented. Stroop interference was defined as the difference in performance between 'neutral' (e.g. 'tree' in red ink, 'HH') and incongruent (e.g. 'blue' in red ink, '44') trials. Participants performed two practice blocks (12 trials) and four experimental blocks (24 trials) for each of the tasks. Stimuli were presented for 2000 ms or until the subject responded, followed by a response–stimulus interval of 700 ms.
2. Verbal WM: Reading span/counting span (see Kane, Hambrick, Tuholski, Wilhelm, Payne & Engle, 2004). In the reading span task, participants recalled letters against a background reading task; in the counting span task, they recalled digits against a background counting task (for details, see Kane *et al*., 2004).
3. Spatial WM: Symmetry span/navigation span (adapted from Kane *et al*., 2004). In the symmetry span task, subjects recalled sequences of locations in a 4×4 matrix against a background symmetry-judgment task. In the navigation span task, they recalled the paths of moving balls across the screen against a background rotation task (for details, see Kane *et al*., 2004).[2]

   Set sizes for all WM tasks ranged from two to five items, with a total of eight sets (i.e. two items per set size). The test score refers to the number of sets correctly recalled.
4. Fluid intelligence: Figural reasoning/letter series (cf. Lindenberger, Mayr & Kliegl, 1993) and Raven's Standard Progressive Matrices (Raven, 1988). In the figural reasoning task, items followed the format, 'A is to B as C is to ?' In the letter series task, subjects saw items consisting of five letters followed by a questions mark (e.g. a c e g i ?), and named the letter that would logically fill the position of the question mark. In both tasks, five response alternatives were presented along with the items. The experimenter terminated the task when subjects committed three consecutive errors or after they answered all 16 items (for details, see Lindenberger *et al*., 1993). In the Raven's task, subjects completed 30 trials in which they selected one of eight figures that best completed a pattern (for details, see Raven, 1988). Test scores refer to the number of correctly solved items.

Training sessions

For the four training sessions, participants within each age group were assigned to one of the following four training groups (see Table 1): During *single-task training* (group 1), subjects practiced only the two single tasks, so that executive control demands during training were relatively low (control condition). During *task-switching training* they practiced only mixed-task blocks, so that executive control demands during training were high (group 2). In the *task-switching + verbal self-instruction training* group, participants also trained on mixed-task blocks. In addition, they verbalized the upcoming task goal (e.g. 'transportation' or 'number', see below) to the onset of the fixation-cross in each trial (group 3). Finally, the *task switching + verbal self-instruction + training variability* group received the same training as the third group, but the tasks and stimuli were different in each training session (group 4).

In the single-task training group, participants performed alternating blocks including tasks A or B. The task-switching procedure during training was structurally similar to the one applied at pretest and posttest except that subjects performed different tasks. In task C ('transportation' task), subjects had to decide whether the pictures showed planes or cars, and in task D ('number' task) whether one or two planes/cars were presented. The design of the additional tasks applied to group 4 (tasks E–J) was similar to tasks C and D, but included different stimuli and response categories. That is, while participants in this fourth group also performed tasks C and D in the first training session, they were instructed to classifying pictures according to task E ('hobby' task: Sport [e.g. a football] or music

[2] The adaptation of the tasks from Kane *et al*. (2004) included the following details: In the original version of the symmetry span task, the symmetry judgment required participants to decide whether two complex geometric matrices were symmetrical along a vertical axis. Since pilot testing indicated that this task was too difficult for children, subjects were shown two letters instead of the complex matrices and they were instructed to decide whether these letters were symmetrical along a vertical axis. Similarly, the navigation span task from Kane *et al*. (2004) included a distraction task requiring participants to count the corners of bold uppercase letters from a certain starting point in a designated direction. Given that children in particular had problems performing this task, we substituted the letters with polygons (including the same number of to-be-counted corners).

[e.g. a piano]?) and F ('stoplight' task: Red or green?) in the second training session, task G ('animal' task: Fish or bird?) and H ('direction' task: Normal or rotated?) in the third training session, and task I ('plant' task: Tree or flower?) and J ('color' task: Black-and-white or colored?) in the fourth training session. Training sessions for all groups took about 30–40 minutes. They started with two practice blocks followed by 24 experimental blocks (17 trials), so that all groups performed 1768 training trials.

Subjects were matched to these training groups based on their pretest performance in task switching (RT mixing costs), single-task RT, and Raven score to prevent baseline differences between the training groups. In order to test whether this matching procedure was successful, pretest data for the three matching criteria were subjected to a two-way analysis of variance (ANOVA) with the between-subjects factors Age (children/young adults/older adults) and Training (group 1/2/3/4). Neither the main effect for training nor its interaction with age reached significance for any of the matching criteria (all *p*s > .31), indicating that there were no baseline differences between the training groups (see Table A1 in Appendix).

Data analysis

Analyses for task switching and the Stroop task were restricted to mean RT for correct responses.[3] Practice blocks and the first trial in each block were not analyzed. To control for age differences in baseline performance, we ran ANOVAs based on log-transformed RT (cf. Kray & Lindenberger, 2000). Unless reported otherwise, these results were consistent with those based on mean RT. We also analyzed error rates, but there were no significant interactions with the factor Training on the level of accuracy; therefore, the presentation of results focuses on RT. Data were corrected for multiple comparisons using a Bonferroni correction at $p < .05$. For the remaining tasks (WM, fluid intelligence), the analyses were based on accuracy (% correct) relative to baseline performance at pretest.

To examine the range of transfer effects across training conditions of near and far transfer tasks, we also calculated Cohen's (1977) *d*, or the standardized mean difference in performance between pretest and posttest (cf. Verhaeghen, Marcoen & Goossens, 1992). That is, the pretest–posttest difference (for each training and age group) was divided by the pooled standard deviation for both test occasions. We then corrected all *d*-values for small sample bias using the Hedges and Olkin (1985) correction factor (d'). A pretest-posttest effect size $d' = 1$, for instance, indicates that the mean difference between pretest and posttest corresponds to one standard deviation.

[3] For task switching, latencies > 4000 ms were excluded from the analyses (Training: children: 1.43%; young adults: 0.01%; older adults: 0.15%. Pretest and posttest: children: 2.35%; young adults: 0.09%; older adults: 0.81%).

Results

Training data

To investigate training-related benefits (i.e. a reduction of switching costs from the beginning to the end of training) in the three task-switching training groups, data[4] were subjected to a four-way ANOVA with the between-subjects factors Age (children/young adults/older adults) and Training (group 2/3/4), and the within-subjects factors Session (training 1/training 4) and Trial Type (nonswitch/switch).

We found a quadratic age effect, indicating that young adults responded faster than children and older adults, age^2: $F(1, 116) = 144.33$, $p < .0001$, $\eta^2 = .46$, and a main effect for session, showing a speeding of RT from the first to the last training session, $F(1, 116) = 205.01$, $p < .0001$, $\eta^2 = .63$, that was more pronounced for children than for adults and also larger for the groups performing verbal self-instructions (groups 3 and 4) than for group 2 (both *p*s = .01). We found significant switching costs, that were larger for children and older adults than for young adults, $F(1, 116) = 311.63$, $p < .0001$, $\eta^2 = .67$, and age^2: $F(1, 116) = 22.80$, $p < .0001$, $\eta^2 = .05$. Switching costs were smaller in the groups performing verbal self-instructions (groups 3 and 4) than in the group without verbalizations (group 2), $F(1, 116) = 7.48$, $p < .01$, $\eta^2 = .01$. Switching costs were reduced from the first to the last training session, $F(1, 116) = 113.48$, $p < .0001$, $\eta^2 = .46$, but this reduction was less pronounced in the variability group (group 4) than in the remaining groups, $F(1, 116) = 11.33$, $p = .001$, $\eta^2 = .04$. This interaction was not modulated by age ($p = .78$).

Near transfer, verbal processes and training variability

Next, we examined near transfer of task-switching training to a structurally similar switching task (i.e. a reduction of mixing and switching costs from pretest to posttest) and its modulation by verbal processes and training variability. Data were subjected to a four-way ANOVA with the between-subjects factors Age (children/young adults/older adults) and Training (group 1/2/3/4), and the within-subjects factors Session (pretest/posttest) and Trial Type (single/nonswitch/switch). Young adults responded faster than children and older adults, age^2: $F(1, 156) = 195.39$, $p < .0001$, $\eta^2 = .53$, and a main effect for session pointed to faster RTs at posttest, $F(1, 156) = 363.40$, $p < .0001$, $\eta^2 = .67$. There were

[4] Data for one child in the variability group were lost, so the analysis of training data was restricted to 125 instead of 126 subjects.

reliable mixing and switching costs, $F(1, 156) = 666.65$, $p < .0001$, $\eta^2 = .78$, and $F(1, 156) = 658.66$, $p < .0001$, $\eta^2 = .80$. Mixing costs were generally larger for children and older adults than for young adults, age^2: $F(1, 156) = 22.52$, $p < .0001$, $\eta^2 = .03$, but there were no age differences for switching costs[5] ($p = .19$). Both types of costs were reduced from pretest to posttest (both ps < .0001). However, the outcome of greatest interest in this study was whether training modulated these interactions. Indeed, we found interactions between session and training, $F(3, 156) = 6.11$, $p < .001$, $\eta^2 = .03$, session, trial type, and training, $F(6, 312) = 10.61$, $p < .0001$, $\eta^2 = .08$, as well as between session, trial type, training, and age, $F(12, 312) = 3.07$, $p < .001$, $\eta^2 = .04$. To disentangle these interactions, we specified three contrasts for the factor Training: Comparing groups 1 and 2 showed that the reduction of mixing and switching costs from pretest to posttest was larger after task-switching training (group 2) than after single-task training (group 1), $F(1, 156) = 32.05$, $p < .0001$, $\eta^2 = .07$, and $F(1, 156) = 14.10$, $p < .001$, $\eta^2 = .04$, respectively. For mixing costs, this transfer effect was more pronounced in children and older adults than in young adults, age^2: $F(1, 39) = 4.57$, $p < .05$, $\eta^2 = .03$ (see Figure 1). A comparison of groups 2 and 3 indicated that near transfer was not modulated by verbal self-instructions performed during task-switching training ($p = .64$). Finally, a comparison between groups 2/3[6] and 4 revealed that transfer on the level of mixing costs was reduced in children and increased in adults when training tasks were variable, $F(1, 52) = 11.89$, $p = .001$, $\eta^2 = .10$, and $F(1, 104) = 10.95$, $p = .001$, $\eta^2 = .07$, but there was no such effect for switching costs ($p = .90$).

These results were supported by the pretest-posttest effect sizes (ES). For both types of costs, ES were larger after task-switching ($d' = .88$–2.12) than after single-task training ($d' = .11$–$.60$), particularly for children (see Figure 2). ES for mixing costs in adults increased again when the switching training was combined with verbalizations ($d' = 1.44$–1.46) and variability ($d' = 1.28$–1.66), while we found the reverse effect for children: The verbalizations ($d' = 1.55$) performed during training, and even more the variable training ($d' = .65$) resulted in substantially smaller ES (see Figure 2). Results for switching costs were similar, with maximized ES in young adults in the variability group ($d' = 1.59$) and decreased ES in children ($d' = .68$).

Far transfer to other executive tasks and other task domains

Second, we investigated far transfer to a structurally dissimilar 'executive' task, namely the Stroop task.[7] Since the modulation of far transfer by verbal self-instructions and training variability was an open question, we first examined whether the task-switching training groups (2–4) showed different amounts of transfer (see Table A2). We found no interactions of training with age, session, or trial type (all ps > .10), so we collapsed data across groups 2–4 to increase the statistical power. Data were then subjected to a four-way ANOVA with the factors Age (children/young adults/older adults), Training (single-task/task-switching), Session (pretest/posttest), and Trial Type (neutral/incongruent). We found a main effect for session, indicating that participants responded faster at posttest than at pretest, $F(1, 162) = 65.15$, $p < .0001$, $\eta^2 = .25$, as well as a reliable interference effect,[8] $F(1, 162) = 254.20$, $p < .0001$, $\eta^2 = .60$, showing longer latencies on incongruent than on neutral trials, but the main effect of training was not significant ($p = .35$). Again, of greatest interest in this study were interactions with the factors Session and Training. Indeed, there was a session × training × trial type interaction, $F(1, 162) = 9.25$, $p < .01$, $\eta^2 = .05$, indicating that interference was reduced from pretest to posttest after task-switching training, $F(1, 123) = 13.11$, $p < .001$, $\eta^2 = .09$ (but not after single-task training, $p = .14$), pointing to far transfer of task-switching training to interference control in the Stroop task (see Table 2). However, this far transfer was not modulated by age ($p = .18$). Although the reduction of interference effects from pretest to posttest after task-switching training was consistent with the initial expectations, there also was an unexpected deterioration of performance (i.e. increased interference effects) in adults after the single-task training (see Table 2). Control analyses for younger and older adults indicted that the increased interference effects were due to a larger pretest–posttest improvement in the baseline condition (i.e. neutral trials), $F(1, 26) = 16.01$, $p < .001$, $\eta^2 = .59$, and not to impairments in high-interference conditions (i.e. incongruent trials), $F(1, 26) = 7.52$, $p < .05$, $\eta^2 = .29$, resulting in larger interference effects for the single-task training group at posttest.

Finally, we investigated two additional executive domains (verbal and visuospatial WM) and another

[5] Based on mean RT, switching costs were larger for children and older adults than for young adults, age^2: $F(1, 156) = 25.67$, $p < .0001$, $\eta^2 = .04$.

[6] Since we found no difference between groups 2 and 3, data were collapsed across both groups to increase statistical power. We found the same pattern when we compared groups 2 and 3 separately to group 4 (all ps < .05).

[7] Correlations between task versions were high (neutral trials: $r = .82$*** incongruent trials: $r = .76$***) and the pattern of results was similar, so the data were collapsed across the color and the number version.

[8] Analyses based on mean RT showed larger interference in children and older adults than in young adults, age^2: $F(1, 162) = 6.08$, $p = .01$, $\eta^2 = .02$.

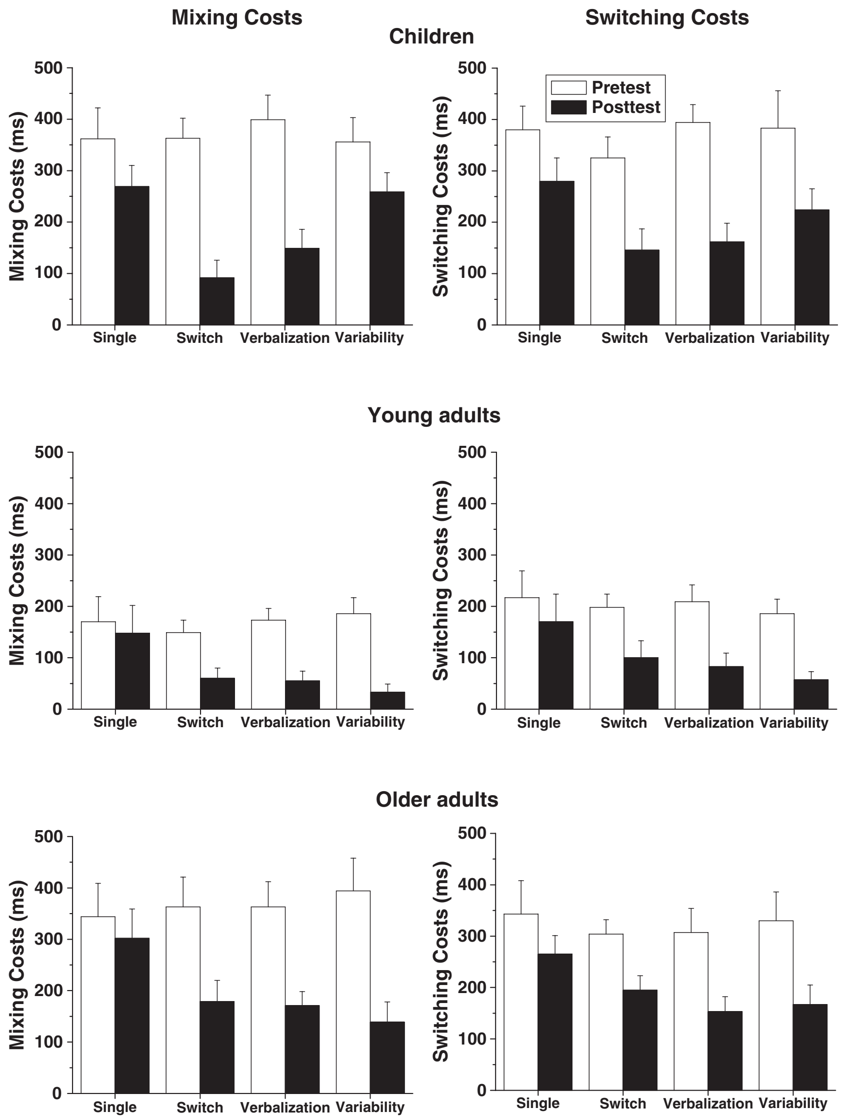

Figure 1 *Mixing costs (left panel) and switching costs (right panel) as a function of session (pretest, posttest), training (single = single-task training; switch = task-switching training; verbalization = task-switching + verbal self-instruction training; variability = task-switching + verbal self-instructions + training variability), and age (children, young adults, older adults). Error bars refer to standard errors of the mean.*

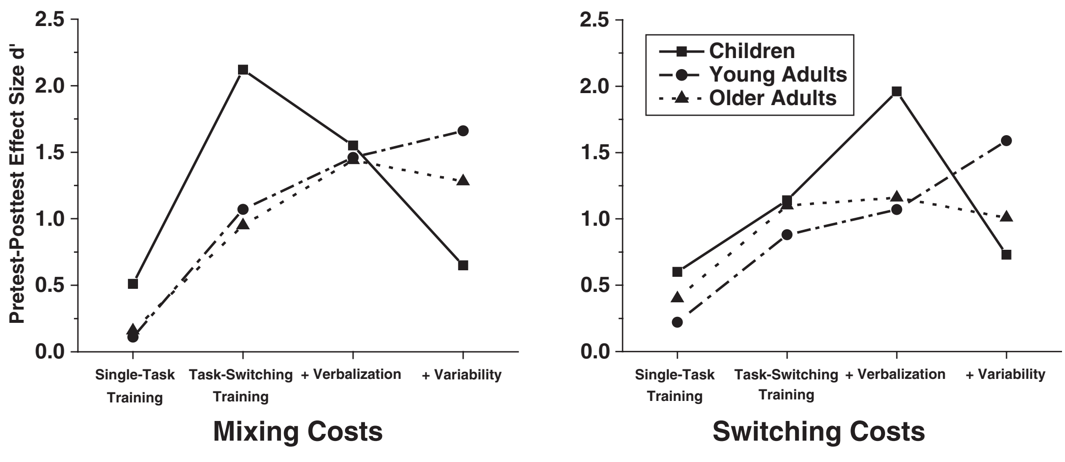

Figure 2 *Effect size d′ for near transfer of task-switching training based on mixing costs (left panel) and switching costs (right panel) as a function of training (single-task training, task-switching training, task-switching + verbal self-instruction training, task-switching + verbal self-instructions + training variability) and age (children, young adults, older adults).*

Table 2 *Mean performance (SD) for far transfer tasks (Stroop, verbal WM, spatial WM, and fluid Intelligence) as a function of session (pretest/posttest), training (single-task training/task-switching training), and age (children/young adults/older adults)*

	Children				Young adults				Older adults			
	Pretest		Posttest		Pretest		Posttest		Pretest		Posttest	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Stroop interference (ms)												
STT	70	(42)	72	(49)	30	(31)	48	(41)	57	(57)	72	(55)
TST	48	(61)	24	(53)	57	(41)	27	(34)	77	(81)	56	(46)
Verbal working memory (% correct)												
STT	47.3	(14.4)	47.8	(24.0)	66.1	(12.7)	68.3	(16.3)	56.3	(16.8)	58.0	(15.8)
TST	45.8	(13.4)	56.0	(17.2)	71.6	(16.1)	81.3	(15.3)	55.1	(15.9)	62.4	(18.6)
Spatial working memory (% correct)												
STT	20.1	(10.7)	23.7	(12.8)	44.2	(14.0)	46.4	(17.1)	25.9	(18.0)	26.3	(21.4)
TST	17.7	(11.6)	27.2	(16.4)	46.0	(17.6)	56.1	(17.4)	21.7	(16.6)	26.3	(16.8)
Fluid intelligence (% correct)												
STT	75.2	(12.0)	76.8	(16.0)	92.7	(5.0)	93.7	(4.1)	78.6	(10.2)	79.5	(17.2)
TST	73.3	(10.5)	79.8	(9.8)	89.8	(6.3)	93.4	(6.2)	75.1	(10.9)	79.7	(12.5)

Note: STT = Single-task training, TST = Task-switching training.

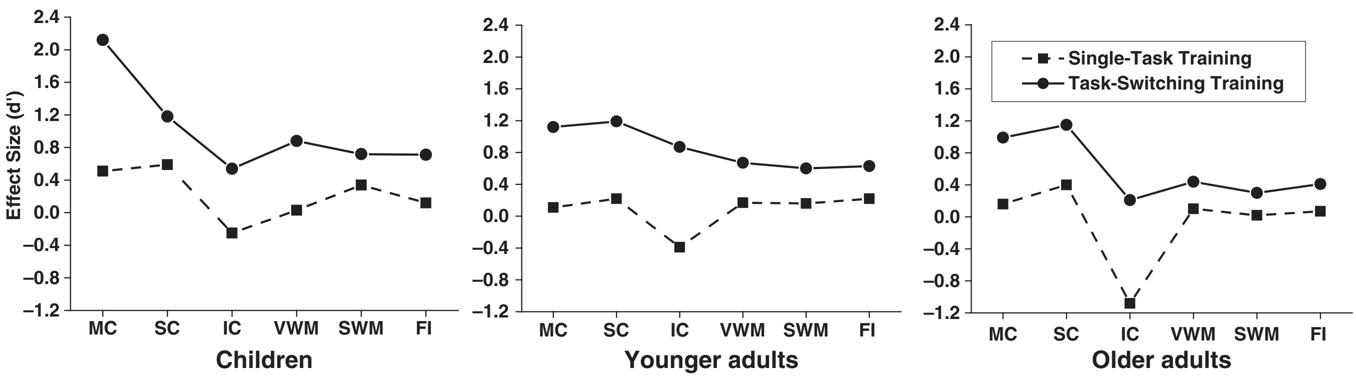

Figure 3 *Effect size d′ for near and far transfer of training as a function of training (single-task training, task-switching training), transfer measure (MC = mixing costs; SC = switching costs; IC = interference control; VWM = verbal working memory; SWM = spatial working memory; FI = fluid intelligence), and age (children, young adults, older adults).*

task domain (fluid intelligence). For each domain,[9] we again tested whether the task-switching training groups (2–4) showed different amounts of transfer (see Table A3). Since we found no effect of training for any domain (all *p*s > .13), data were collapsed across groups 2–4 and subjected to a two-way ANOVA with the between-subjects factors Age (children/young adults/older adults) and Training (single-task/task-switching). The results indicated that the task-switching training groups showed more far transfer than the single-task groups for both verbal and spatial WM, $F(1, 162) = 4.94$, $p < .05$, $\eta^2 = .02$, and $F(1, 162) = 4.60$, $p < .05$, $\eta^2 = .02$, and also for fluid intelligence, $F(1, 162) = 5.37$, $p < .05$, $\eta^2 = .03$ (see Table 2). Thus, the performance improvements from pretest to posttest were larger after task-switching training than after single-task training, and were not modulated by age (all *p*s > .61).

In order to investigate the range of far transfer, we calculated the pretest-posttest ES (see Figure 3). Consistent with previous findings (cf. Klauer, 2001), ES were smaller for far transfer to other executive tasks and fluid intelligence than for near transfer. However, ES after task-switching training were still relatively large even for far transfer, with most values > .70 for children, > .60 for adults, and > .40 for older adults, and were quite consistent across the far transfer tasks. In contrast, ES for the single-task training were generally small or even negative, and substantially smaller than for task-switching training under all experimental conditions.

[9] Correlations between the tasks were high (Verbal WM: counting span–reading span, $r = .50^{**}$; spatial WM: symmetry span–navigation span, $r = .56^{**}$; fluid intelligence: letter series–figural reasoning, $r = .45^{**}$; letter series–Raven, $r = .59^{**}$; figural reasoning–Raven, $r = .52^{**}$) and the results were similar across tasks for the respective constructs.

Discussion

The primary aim of this study was to investigate the usefulness of task-switching training. To answer this question, we examined the amount of near and far transfer of task-switching training in children, young adults, and older adults under different training conditions. Our results identified several important new findings. First, we found evidence for substantial transfer of task-switching training to a structurally similar new switching task after training. Consistent with a prior study (Minear *et al*., 2002), the reduction of mixing costs from pretest to posttest was much larger after task-switching training (mean $d' = 1.44$) than after single-task training (mean $d' = .26$). From a theoretical point of view, this finding is particularly important because it shows that the trainability and transferability of executive control processes is not merely mediated by automatization of single-task components (cf. Kramer *et al*., 1999). In contrast to the Minear *et al*. study, we also found near transfer of task-switching training on the level of switching costs (mean $d' = 1.17$).

Second, and particularly interesting from a developmental perspective, the near transfer on the level of mixing costs was most pronounced in children and older adults. Thus, in particular the age groups usually characterized by marked deficits in task-set selection and maintenance were able to transfer training-related benefits to a new task. This finding has important implications for the application of training programs to individuals with executive deficits in the clinical and educational contexts.

A third result was that the type of training modulated the amount of near transfer. On the one hand, verbal self-instructions did not promote transfer of task-switching training. There are at least two possible explanations for this finding. First, the groups trained in task switching without verbal self-instructions used an internal verbal strategy similar to the overt self-instructions anyway so that we found no difference in the amount of transfer between these groups. Second, if training and transfer tasks were more similar for the verbal self-instruction group, that is, if participants were allowed to verbalize at posttest (and not only during training), then transfer may occur. This idea is in line with results from Healy, Wohldmann, Parker and Bourne (2005), showing that participants performing a secondary verbal task during training in a prospective paradigm performed worse during transfer when the secondary task was not required during transfer. The authors suggested that the training task and the verbal task are integrated into a single, more complex task during practice, and that transfer only occurs when the cognitive operations acquired during training can be applied at transfer.

On the other hand, training variability resulted in differential age effects. Specifically, the requirement for adapting to new task demands in each training session supported the acquisition of a generalizable switching skill in adults, but hindered it in children. Regarding adults, this finding is consistent with the literature, suggesting that variable training can promote transfer (cf. Schmidt & Bjork, 1992), although the training-related benefits (i.e. the reduction of switching costs from training session 1 to 4) were smaller than in the remaining two task-switching training groups. However, regarding children, it seems that the increased cognitive load associated with variable training tasks did not leave enough processing capacity to implement the abilities improved during training and to develop cognitive representations of the task structure (cf. van Merriënboer, Kester & Paas, 2006). This interpretation is consistent with theoretical accounts (e.g. Sweller, 1999) emphasizing that complex tasks and stimuli result in higher working memory demands while performing a given task. Since working memory capacity is more limited in children than in adults (for a review, see Hitch, 2006), the increased cognitive load associated with the variable training would be more likely to affect children's performance. Hence, the implementation of the trained abilities and the representation of the task structure are impaired, especially on the level of mixing costs, which include a substantial working memory component (i.e. the ability to maintain two task sets). Future studies may test this hypothesis by including a cognitively less demanding variable training condition.

A potentially critical point for the interpretation of this finding is the fact that the variable training was combined with verbal self-instruction training. Although a comparison of training groups 2 and 3 indicated that verbal self-instructions did not influence the amount of transfer, it may be argued that the decreased transfer after variable training found in children is the result of an interaction between the variable training and the verbalizations performed during training, which makes the training even more complex. However, in order to ultimately disprove this point, a variable training condition without verbal self-instructions would have been necessary.

The fourth and most striking result concerns far transfer of task-switching training. Our data clearly show that in contrast to single-task training, task-switching training resulted in improved performance in an interference control task, in verbal and spatial WM tasks, and even in fluid intelligence tasks. Although there is some evidence for far transfer of executive control training in children (Fisher & Happé, 2005; Klingberg *et al*., 2005; Kloo & Perner, 2003; Rueda *et al*., 2005), most training programs in previous studies focusing on adults resulted in large improvements on the training task itself while transfer to other tasks was very limited, suggesting that transfer was quite domain and process specific (e.g. Ball, Berch, Helmers, Jobe, Leveck, Marsiske, Morris, Rebok, Smith, Tennstedt, Unverzagt & Willis, 2002; Jennings, Webster, Kleykamp &

Dagenbach, 2005). Also, in previous studies reporting far transfer, the transfer distance and the type of training were not systematically varied. In contrast, the present study shows broad transfer that was stable even for different measures of far transfer and to domains quite remote from the training tasks. It also provides the first evidence that the near and far transfer of executive control training can indeed be achieved across a wide range of ages. Still, it may seem surprising that far transfer was neither modulated by age nor by the type of task-switching training. Given that there is no prior evidence with respect to these aspects, our expectations were relatively unspecific. Based on the present results, one may assume that the different types of task-switching training were equally efficient, and that the training was equally beneficial for all age groups. However, this conclusion should be drawn cautiously. In line with previous results (cf. Klauer, 2001; Salomon & Perkins, 1989), effects sizes were generally smaller for far transfer than for near transfer in this study. The smaller effects are, the harder they are to verify in small samples (for a meta-analysis, see Lipsey & Wilson, 1993), indicating why it may have been hard to find a modulation of far transfer by age group or training type. In order for the age group or training type differences to reach statistical significance, the sample would have to be relatively large, which is usually hard to realize in training studies.

Considering the findings of the present study, the obvious question is what kinds of processes were actually transferred after task-switching training? Our data suggest that subjects transferred more than the mere ability to switch between tasks. However, the task-switching version we used in this study required a number of different executive control processes. First, demands on goal maintenance were high because subjects received no external task cues. Second, stimuli were highly ambiguous; that is, they always represented features relevant to both tasks, and the currently irrelevant feature had to be suppressed. Consequently, interference control was constantly required. Finally, because subjects had to perform two rather than only one task during task-switching training, task-set selection demands were high. Thus, assuming that all these executive processes were trained, it seems less surprising that our task-switching training showed broad transfer to other executive and cognitive task domains. Nevertheless, since the transfer distance is an important aspect for evaluating training programs, it seems that this type of task-switching training is suitable for promoting not only one, but several executive control abilities; therefore, it is probably useful for a number of clinical and educational applications. It should also be noted that compared with other studies investigating the transfer of training (cf. Klauer, 2001), the ES were relatively large for near transfer, particularly for children, and consistently remained on a high level even across far transfer tasks.

Determining the relative training potential regarding different executive control components and the long-term effects of task-switching training is a matter for future research. Also, it may be important to consider individual differences regarding transfer benefits to clarify how the training improves performance, so that it can be optimized when applied to those who need it most (cf. Bissig & Lustig, 2007; van Merriënboer *et al.*, 2006).

Appendix

Table A1 *Means* (M) *and standard deviations* (SD) *for the training group matching criteria (single-task RT, mixing costs, Raven score) as a function of age (children, young adults, older adults) and training group (single-task training, task-switching training, task-switching + verbal self-instruction training, task-switching + verbal self-instruction + variability training) at pretest*

	Matching variables					
	Single-task RT		Mixing costs		Raven score	
Training group	*M*	*SD*	*M*	*SD*	*M*	*SD*
Children						
Single-task training	1000	184	363	227	23.6	3.5
Task-switching training	1040	194	363	148	23.6	2.1
+ verbalization	973	148	400	182	23.1	2.3
+ + variability	996	297	357	179	22.6	2.3
Young adults						
Single-task training	570	118	170	184	27.8	1.6
Task-switching training	545	67	149	91	26.8	1.9
+ verbalization	525	105	174	88	26.6	1.9
+ + variability	604	91	186	118	27.8	1.8
Older adults						
Single-task training	758	175	345	243	23.9	3.9
Task-switching training	818	262	363	217	22.1	2.7
+ verbalization	705	121	364	184	23.2	3.3
+ + variability	765	215	394	243	23.9	1.9

Table A2 *Stroop task mean RT* (M) *and standard deviation* (SD) *as a function of age (children, young adults, older adults), training (single-task training, task-switching training, task-switching + verbal self-instruction training, task-switching + verbal self-instruction + variability training), session (pretest, posttest), and trial type (neutral, incongruent)*

	Pretest				Posttest			
	Neutral		Incongruent		Neutral		Incongruent	
Training group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Children								
Single-task training	904	91	974	98	927	170	999	192
Task-switching training	992	156	1017	146	933	123	954	154
+ verbalization	960	88	1029	103	889	103	929	111
+ + variability	952	187	1004	182	876	145	889	144
Young adults								
Single-task training	631	92	661	99	573	71	621	93
Task-switching training	582	76	634	95	542	62	572	85
+ verbalization	628	115	680	129	554	92	586	119
+ + variability	569	95	636	116	509	65	528	79
Older adults								
Single-task training	821	172	878	206	754	149	832	209
Task-switching training	863	113	954	161	828	128	897	149
+ verbalization	791	107	853	114	733	104	787	97
+ + variability	736	127	802	159	678	112	725	124

Table A3 *Mean performance* (M) *and standard deviation* (SD) *for verbal WM, visuospatial WM, and fluid intelligence (% correct) as a function of age (children, young adults, older adults), training (single-task training, task-switching training, task-switching + verbal self-instruction training, task-switching + verbal self-instruction + variability training), and session (pretest, posttest)*

	Verbal WM				Visuospatial WM				Fluid intelligence			
	Pretest		Posttest		Pretest		Posttest		Pretest		Posttest	
Training group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Children												
Single	47.3	14.4	47.8	24.0	20.1	10.7	23.7	12.8	75.2	12.0	76.8	16.0
Switch	43.3	15.6	56.3	23.8	16.1	13.4	26.3	17.9	74.3	11.4	81.4	7.3
+ verbalization	47.8	14.8	58.0	16.3	17.9	8.4	28.1	16.0	73.2	8.9	78.9	11.8
+ + variability	46.4	9.4	53.6	11.7	19.2	13.1	27.2	16.4	72.3	11.6	78.9	10.3
Young adults												
Single	66.1	12.7	68.3	16.3	44.2	14.0	46.4	17.1	92.6	5.0	93.6	4.1
Switch	73.7	11.5	81.3	12.3	43.8	20.9	55.8	17.9	88.1	7.1	93.1	7.2
+ verbalization	69.2	20.4	79.0	17.9	51.3	16.7	55.8	21.9	90.4	4.4	92.9	6.4
+ + variability	71.9	15.3	83.5	16.0	42.9	14.7	56.7	12.6	90.9	7.2	94.3	5.1
Older adults												
Single	56.3	16.8	58.0	15.8	25.9	18.0	26.3	21.4	78.6	10.2	79.5	17.2
Switch	52.7	16.4	59.4	17.1	14.3	13.7	21.4	15.1	68.9	10.0	74.3	14.1
+ verbalization	55.8	18.4	64.7	21.1	25.4	20.1	29.9	17.7	75.4	12.7	81.1	13.3
+ + variability	56.7	13.3	62.9	18.3	25.4	13.8	27.7	17.4	81.0	6.1	83.7	8.3

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