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Plasticity of executive control through task switching training in adolescents

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Research has shown that cognitive training can enhance performance in executive control tasks. The current study was designed to explore if executive control, specifically task switching, can be trained in adolescents, what particular aspects of executive control may underlie training and transfer effects, and if acute bouts of exercise directly prior to cognitive training enhance training effects. For that purpose, a task switching training was employed that has been shown to be effective in other age groups. A group of adolescents (10–14 years, $n = 20$) that received a three-session task switching training was compared to a group ($n = 20$) that received the same task switching training but who exercised on a stationary bike before each training session. Additionally, a no-contact and an exercise only control group were included (both $ns = 20$). Analyses indicated that both training groups significantly reduced their switching costs over the course of the training sessions for reaction times and error rates, respectively. Analyses indicated transfer to mixing costs in a task switching task that was similar to the one used in training. Far transfer was limited to a choice reaction time task and a tendency for faster reaction times in an updating task. Analyses revealed no additional effects of the exercise intervention. Findings thus indicate that executive control can be enhanced in adolescents through training and that updating may be of particular relevance for the effects of task switching training.

Keywords: executive control, task switching, training, plasticity, transfer, sport, physical exercise, updating

INTRODUCTION

Executive control is the ability to plan, execute, and monitor goal-directed behavior (Norman and Shallice, 1986). It is a central neurocognitive process that is involved in a range of cognitive functions that are of everyday relevance, like problem solving or reasoning (Engle et al., 1999; Baddeley, 2003; van der Sluis et al., 2007). According to a model by Miyake et al. (2000) that has been derived empirically in adult and child populations (Lehto et al., 2003), executive control consists of different distinguishable components: maintaining and monitoring working memory representations (updating), deliberately suppressing prepotent responses (inhibition), and shifting between different tasks, or mental sets (set-shifting or switching).

There is a small, but growing body of promising research showing that executive control functions can be enhanced by systematic cognitive training with tasks requiring updating (Dahlin et al., 2008; Jaeggi et al., 2008), working memory (Klingberg et al., 2005; Holmes et al., 2009; Klingberg, 2010), task switching (Karbach and Kray, 2009), or dual task performance (Bherer et al., 2005; Liepelt et al., 2011). In addition to increases in performance on trained tasks, some of these studies were able to show transfer effects to non-trained tasks within the trained domain (e.g., working memory training transferred to complex working memory span tasks, Holmes et al., 2009) as well as to other executive control domains (e.g., inhibition tasks, Olesen et al., 2004; Klingberg et al., 2005; Karbach and Kray, 2009) or measures of non-verbal reasoning (Klingberg et al., 2005; Jaeggi et al., 2008). However, other studies have failed to find any transfer to similar tasks or suggest that transfer may be restricted to the trained domain (e.g., Dowsett and Livesey, 2000; Li et al., 2008; Strobach et al., in press). All of these studies have used a process-based training approach, where repeated performance on tasks, feedback, and often gradual adjustment of difficulty (Klingberg, 2010) implicitly leads to improvements.

Executive control training studies have targeted young (Jaeggi et al., 2008; Karbach and Kray, 2009) and older adults (Buschkuehl et al., 2008; Dahlin et al., 2008; Li et al., 2008; Zinke et al., 2012), as well as clinical populations of children, for example children with ADHD (Klingberg et al., 2005) or with low working memory abilities (Holmes et al., 2009). Evidence for training and transfer effects in typically developing children has only recently been accumulated (Karbach and Kray, 2009; Jaeggi et al., 2011; Loosli et al., 2012), whereas studies with older children and adolescents (especially above 12 years) are surprisingly very rare. This fact is rather remarkable because executive control processes are on the one hand highly relevant in the adolescents' daily life and school-related academic activities, e.g., reading or arithmetic (van der Sluis et al., 2007). Besides their ubiquitous relevance, executive control functions are on the other hand among the few functions that show development trajectories well into adolescence (Anderson, 2002; Huizinga et al., 2006) corresponding to relatively late maturation of prefrontal brain regions (Bunge et al., 2002; Luna et al., 2010). Recent studies suggest an ongoing development of different executive control functions across adolescence and even into young adulthood (Luna et al., 2004; Huizinga et al., 2006; Rubia et al., 2006). Taking these findings into account it appears straightforward to predict that the potential for plasticity through executive control training may be especially large in this age group. For that reason, it was the first aim of the current study to explore if an executive control training can also benefit cognitive functions in a population of adolescents.

With regard to executive control training, currently, one conceptual issue is especially under debate: does it matter what domain of executive control is being trained? The most consistent findings for executive control trainings have, so far, been achieved in a range of studies that train tasks requiring updating (e.g., Dahlin et al., 2008; Jaeggi et al., 2008, 2011) or working memory (Klingberg et al., 2005; Holmes et al., 2009; Loosli et al., 2012; see Klingberg, 2010 for a review). These studies have mostly found robust transfer to other working memory tasks and even some (but limited) far transfer to other executive control domains or reasoning (Klingberg et al., 2005; Jaeggi et al., 2011), and mathematical or reading performance (Holmes et al., 2009; Loosli et al., 2012). Much less consistent findings come from the few training studies employing inhibition tasks. One study was able to show transfer of an inhibitory control training to a non-trained inhibition task (Go/No Go, Dowsett and Livesey, 2000), whereas another study did not find any transfer to other executive control tasks (Thorell et al., 2009). With respect to the third facet of executive control, switching, the available literature is also scarce: although there are a range of studies showing practice-related improvements in task switching paradigms (Kramer et al., 1999; Buchler et al., 2008; Kray et al., 2008), fewer have explored transfer to other tasks. Those that have, report transfer to other switching tasks (Minear and Shah, 2008) or to other domains of executive control like working memory, inhibition, and reasoning (Karbach and Kray, 2009; Kray et al., 2010). Summarizing research on the different domains of executive functions, a broad range of findings in the updating domain suggest consistent training and transfer effects, whereas the very few findings for the inhibition domain are inconclusive and do not seem to be very promising. In contrast, the few findings from the task switching domain seem to be promising concerning the range of transfer effects, especially the study by Karbach and Kray (2009). For that reason, the current study aimed at training task switching abilities and closely modeled the training regime after the study by Karbach and Kray (2009). Extending that study which had targeted primary school children, young adults, and older adults, the current study aimed at exploring if similar effects of this particular task switching training can also be achieved in adolescents.

Task switching requires participants to switch from performing one (mostly) simple task (e.g., deciding whether a picture shows a vegetable or a fruit) to performing a second simple task (e.g., deciding whether an object is small or large) from trial to trial. Task switching paradigms usually involve single-task blocks where only one task has to be performed the whole time and mixed-task blocks where the participant has to switch between tasks. Switching to a new task is usually accompanied by costs (slower and more error-prone task execution). The literature distinguishes between mixing costs as the difference in mean performance between mixed-task and single-task blocks and switching costs as the difference in mean performance between switch and non-switch trials within mixed-task blocks (see, e.g., Karbach and Kray, 2009). These costs are thought to reflect different executive control processes. Mixing costs are thought to reflect a more global ability to maintain and select two different task sets, whereas switching costs reflect more specifically the actual act of switching from one task to the other (Kray and Lindenberger, 2000; Braver et al., 2003). With regard to task switching training, studies mostly report practice-related reductions in both types of costs during training (Cepeda et al., 2001; Kray et al., 2008). Studies comparing both types of costs suggest larger decreases (or even elimination) with training in mixing costs as compared to switching costs (Berryhill and Hughes, 2009; Strobach et al., 2012). Transfer has been found for mixing costs only (Minear and Shah, 2008) or both types of costs (Karbach and Kray, 2009).

What aspects of task switching are actually trained and may underlie the transfer to other switching or executive control tasks is not well understood. It has been suggested that different executive control processes are involved in switching from one task to the other. These include maintaining several task sets in working memory, selecting, and configuring the appropriate task set (as is thought to be indicated by mixing costs), or focusing attention on relevant aspects and inhibiting now irrelevant aspects of the stimulus or task set (as is thought to be indicated by switching costs, Kramer et al., 1999; Mayr, 2003; Minear and Shah, 2008). Thus, it is reasonable to assume that changes in some or all of the three facets of executive control may be of importance for the possible effects of task switching training. In line with this assumption, (Karbach and Kray, 2009) suggest that task switching training may not only improve task set selection, but also improve maintenance of goals (updating) and/or improve inhibitory control to suppress currently irrelevant features. Findings of transfer to mixing costs (Minear and Shah, 2008; Karbach and Kray, 2009) may point to the relevance of updating processes in mediating training and transfer effects, because mixing costs are thought to reflect the more global ability to maintain different task sets (Kray and Lindenberger, 2000; Braver et al., 2003). The involvement of inhibitory processes in task switching training effects may be inferred from transfer that has been found for an inhibition task (i.e., Stroop task, Karbach and Kray, 2009). However, the transfer tasks used in Karbach and Kray's study were not specifically chosen to tap all different domains of executive control – therefore, one cannot directly infer from their data which of the executive control domains may be specifically associated with the training and transfer effects. Following up on this issue, as a second aim, the current study was set up to systematically explore transfer to all three executive control domains, namely shifting (e.g., with a number switch task), updating (e.g., with an *n*-back task), and inhibition (e.g., with a Stroop task). Because effects may be different for speed and accuracy of responses (as may be inferred from differing developmental trajectories for reaction time, RT, and accuracy measures for executive control tasks, e.g., (Davidson et al., 2006), measures for both RTs and error rates were included.

A third open question addressed by the current study concerns the specific conditions under which executive control training is most effective. Besides the conceptual question of pathways leading to training and transfer effects, this question was also motivated by the applied aspect of how to implement training regimes best for adolescents. One possible contributing factor in this regard concerns the interplay of cognitive and physical activation as it can be found in school settings. Here, another line of research is relevant to consider that is concerned with the acute effects of physical exercise on cognitive functions (see for a review, Tomporowski, 2003). Most of these studies measure performance on different cognitive tasks during or right after the participants have exercised for a predefined time, for example on a treadmill or a stationary bicycle. Facilitating effects of acute exercise have been found repeatedly for basic information processing, for example increased speed in simple and more complex reaction time tasks (Hogervorst et al., 1996; Ellemberg and St-Louis-Deschênes, 2010). Results are more mixed for higher order functions like executive control functions. Studies have found effects of acute exercise on behavior and electrophysiological measures in tasks requiring inhibition (e.g., Stroop task, Hogervorst et al., 1996; Yanagisawa et al., 2010; Flanker task, Magnié et al., 2000; Hillman et al., 2009), working memory (Pontifex et al., 2009), and attention switching (Pesce et al., 2003). However, other studies have failed to find an influence on inhibition (Themanson and Hillman, 2006; Stroth et al., 2009) or mental set-shifting (Tomporowski et al., 2008). A recent meta-analysis by Lambourne and Tomporowski (2010) explored overall effects of acute exercise on cognitive functioning during and after exercise. Results suggest that facilitating effects can be found mostly after exercise and for speed in decision making tasks, memory, and executive functioning tasks.

Although these studies all relate to cognitive performance (not training) right after exercise, several authors such as Hillman et al. (2009) or McDaniel and Bugg (in press) have recently suggested that it may be valuable to look at effects of acute exercise on cognitive control or memory training, respectively. It could be speculated that acute exercise may facilitate or enhance neuronal change that may be induced by cognitive training. Also, if acute exercise directly enhances memory processes (see, e.g., Pesce et al., 2009; Lambourne and Tomporowski, 2010) it may impact learning during cognitive trainings. However, findings have not been consistent as to what cognitive functions are affected and when. Some findings even suggest detrimental effects of physical exercise on executive control functions during or right after exercise (e.g., Dietrich and Sparling, 2004; Dietrich, 2006). For these reasons, as an exploratory third research question, the current study aimed at evaluating the conceptual proposal (Hillman et al., 2009; McDaniel and Bugg, in press) of a possible added value of an acute bout of exercise prior to cognitive training sessions.

In summary, the aims of the current study were the following. The first central question was if executive control functions can be trained in adolescents – an age group where executive control functions are highly relevant and still developing. The study set out to explore whether and which particular training and transfer effects can be achieved in the domain of task switching in adolescents using the training by Karbach and Kray (2009). Specifically, transfer effects would constitute larger gains in performance from pre to posttraining in the task switching training groups as compared to the control groups. Furthermore, as the second aim, the study systematically explored possible transfer effects to all three main executive control facets suggested by Miyake et al. (2000) with RT and accuracy measures. Third, the current study is the first to empirically explore the recent proposition of possible favorable effects of acute bouts of exercise on cognitive control training. If acute bouts of exercise have a favorable effect, we would expect differences in the size of training and transfer effects depending on whether participants received prior acute bouts of exercise or not.

MATERIALS AND METHODS

PARTICIPANTS

The 80 participants of the study were adolescents aged between 10 and 14 years (mean age: 11.9, SD = 1.3). They were recruited in local schools and youth clubs and were reimbursed for their participation with four Euros per hour. All participants and parents received extensive oral and written information about the study. Only if parents and participants gave written informed consent adolescents were included into the study. The study was approved by the ethics committee of the German Society of Psychology. Each participant was individually assigned to one of four groups by randomly drawing group assignments. The study had a three-factorial design with two between-subjects factors, cognitive training (yes vs. no) and exercise intervention (yes vs. no), and one within-subject factor, time of measurement (pretraining vs. posttraining). Hence, there were two cognitive training groups: one combined training group (acute physical exercise right before each cognitive training) and one cognitive training only group; and two control groups: one exercise only control group (acute physical exercise) and a no-contact control group. The four groups of 20 participants were matched in age, gender, BMI, fitness, and basic cognitive functioning (see **Table 1**). The participants were free of any neurological, psychiatric or physical disorders, and did not take medication according to parents' reports. Baseline cognitive functioning was assessed with two tests. Verbal abilities were measured using the vocabulary subscale of the German adaptation of the Wechsler Intelligence Scale for children (WISC-IV, Petermann and Petermann, 2010), where children have to define words. Fluid abilities were assessed with the Digit Span subtest, where children

Table 1 | Participant characteristics of the training groups (with and without prior exercise) and the control groups (exercise only and no-contact, all *n* = 20).

Measure	**Cognitive training groups**		**Control groups**	
	With exercise *M* (SD)	**No exercise *M* (SD)**	**Exercise only *M* (SD)**	**No-contact *M* (SD)**
Gender	9 girls	9 girls	9 girls	9 girls
Age	11.9 (1.2)	11.9 (1.4)	11.8 (1.2)	11.9 (1.3)
BMI	18.0 (1.9)	19.5 (2.8)	18.2 (2.0)	18.1 (2.0)
Fitness in W/kg	3.0 (0.4)	3.0 (0.5)	2.9 (0.5)	2.9 (0.5)
Vocabulary	13.2 (2.3)	13.0 (2.8)	13.2 (3.0)	13.2 (2.7)
Digit span	10.9 (3.2)	10.0 (2.9)	11.0 (2.6)	9.9 (2.2)

have to repeat digit sequences of ascending length in the same or reverse order (Petermann and Petermann, 2010).

COGNITIVE TRAINING TASK

The cognitive training material was closely modeled after Karbach and Kray (2009). The participants' task was to switch as fast and accurately as possible between two simple tasks. The first task was to decide via key press, whether the picture presented was a car or a plane (vehicle task). The second task was to decide via key press whether there were one or two objects on the picture (number task). Both tasks were mapped onto the same keys (left key: "car" or "one"; right key: "plane" or "two") which were to be pressed with the left and the right index finger, respectively. Each training session consisted of two short practice blocks (8 trials each) and 24 mixed-task blocks consisting of 17 trials, each starting with a fixation cross (700 ms), followed by a picture until a response was made. Participants were told to switch between tasks on every second trial, that is to perform the vehicle task twice, then the number task twice, then the vehicle task twice again, and so on. At the beginning of each block, participants were reminded of the sequence and could start over new in case they lost track. During training, participants received a feedback after each block about how many trials they answered correctly and how fast they reacted. Additionally, several times during training, the experimenter verbally encouraged the participants to try to be even more accurate and/or answer faster. The main dependent variables were mean switching cost for RT data (mean RT switch trials – mean RT non-switch trials) and for errors (error rate switch trials – error rate non-switch trials).

ACUTE EXERCISE INTERVENTION

The physical exercise intervention was modeled after similar interventions in other acute exercise studies (e.g., Hillman et al., 2009; Stroth et al., 2009). Participants had to cycle on a stationary bike (Kettler, Model X3) for 20 min at about 60% of their individual maximal heart rate, a moderately intense physical exercise. Heart rate was monitored with POLAR heart rate monitors (Polar Electro, Model FT1) that send their measurements to the stationary bike. The stationary bike was set to a program that automatically adjusted resistance to help the participant stay in the target heart rate zone.

FITNESS ASSESSMENT

Fitness was assessed with a graded maximal exercise test on a stationary bike (Kettler, Model X3) following standards of the WHO to test fitness and a standardized protocol from large German study on fitness in children and adolescents (Bös et al., 2009). Difficulty of cycling started at a resistance of 25 W with watt-load being increased by 25 W every 2 min while the participant was asked to keep the pedaling rate above 60 rotations per minute. Heart rate was monitored with a POLAR heart rate monitor (Polar Electro, Model FT1) and testing was stopped if one of the prespecified stopping criteria was reached. These criteria were: (a) heart rate above 180 bpm for over 15 s, (b) the pedaling rate below 50 for more than 20 s, (c) report of subjective exhaustion, or (d) any sign of discomfort, pain, sudden changes in heart rate, etc. The main measure of physical fitness was maximal watt performance related to body weight (W/body weight in kg, following Bös et al., 2009).

TRANSFER TASKS

To assess transfer to different domains, a range of tasks were used in the current study. Tasks were chosen to cover the three domains of executive control (switching, updating, and inhibition) with tasks including picture or verbal stimuli. Furthermore, tasks were included to cover the speed domain that has been shown to be a relevant outcome variable in acute exercise research. Because effects may be different on the level of RT and accuracy, measures for both levels were included in each domain.

Task switching

To assess near transfer of task switching training, a task switching task was used that was structurally similar to the training task but included different pictures and tasks. The first task was to decide via key press, whether the picture shown was a fruit or a vegetable (food task). The second task was to decide via key press whether the picture was small or large (size task). Both tasks were mapped onto the same keys (left key: "fruit" or "small"; right key: "vegetable" or "large") which were to be pressed with the left and the right index finger, respectively. Participants were instructed on how to perform each single-task separately and had one practice block of 17 trials for each task. After that they were instructed for the mixed-task block: they were told to switch between tasks on every second trial, that is to perform the food task twice, then the size task twice, then the food task twice again, and so on. Thus, trials where participants had to switch and trials where they had to repeat the task alternated. The participants had two mixed-task blocks with 17 trials each to practice. After that there were 20 more blocks with either single-task performance (5 for vehicle task, 5 for number task) or mixed-task performance (10 blocks) with a reminder of the respective instruction at the beginning of each block. Each block consisted of 17 trials each starting with a fixation cross (1400 ms), followed by the picture until a response was made. Main dependent variables on a RT level were mixing costs (mean RT mixed-task blocks – mean RT single-task blocks) and switching costs (mean RT switch trials – mean RT non-switch trials). On the level of error data dependent variables were mixing costs (error rate in mixed-task blocks – error rate in single-task blocks) and switching costs (error rate in switch trials – error rate in non-switch trials).

Furthermore, a switching task with verbal material (numbers 1–4 and 6–9) was used: a number switch task[1] (see, e.g., Koch and Allport, 2006) where participants had to switch between judging whether the number presented on the screen was smaller or larger than five or whether it was even or odd. An external cueing paradigm was used (with a fixed CSI of 0 ms), that is the task to be executed was written above the stimuli ("smaller or larger than 5"? or "even or odd"?) and was present until a response was made. There was a blank interstimulus interval of 1000 ms in between trials. There were two single-task blocks of 40 trials each for the size task and the even/odd-task, respectively. Afterward participants

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[1] In the traditional binary taxonomy of near and far transfer tasks, this number switch task is difficult to allocate, as it assesses the same construct as in training, i.e., task switching. However, because the paradigm is different, it may also require different cognitive functions. Therefore, this task could be considered at an intermediate level of transfer.

performed another block of 80 trials where tasks were randomly intermixed. That is, in approximately half of the trials participants had to switch between tasks, in the remaining trials they had to repeat the previous task. Main dependent variables were the same as in the other switching task, that is mixing and switching cost on the level of RT and error data, respectively.

Updating

As a measure of updating, an animal picture 2-back task was used. The participants were to decide if the animal presented was the same as the one next-to-last with a key press ("yes" if they were the same, "no" if they were not). Line drawings of animals (taken from Snodgrass and Vanderwart, 1980) were presented for 1500 ms each, followed by a 1000-ms blank interstimulus interval. After a short practice of seven trials, participants performed a block of 122 trials (the first two trials were excluded from the analyses because there is no next-to-last picture on these trials), 25% of the pictures were target pictures. Main dependent variables were mean RT for correct decisions and percentage of correct target hits.

As a measure of updating with verbal stimuli a keep track task following Miyake et al. (2000) was used. In this task, words (e.g., uncle) that belong to 6 different semantic categories (e.g., relatives) were presented for 1500 ms one after another. The participants were instructed to remember the last word presented from each target category and name them at the end of each trial. Six to fifteen words were presented in each of five trials and two to four categories were to be tracked in each trial. Target categories were shown on the bottom of the screen for the whole trial. Because several words from each target category were presented on each trial, correct responses required successful updating of working memory content during the trial. Main dependent measure was the percentage of words recalled correctly.

Inhibition

To assess inhibition, a version of a visual Flanker task following the classic paradigm by (Eriksen and Eriksen, 1974) was used. The participants had to decide via key press if the small target square presented in the middle of the screen was red or blue. Two larger, colored squares were presented simultaneously on each side of the small target square: either the same color as the target (congruent trials) or a different color (incongruent trials). After a practice block of 12 trials, participants worked on a block of 100 randomized trials, half of the trials congruent, half of them incongruent. Main dependent variable on the RT level was the difference in mean RTs between correct incongruent and congruent trials (interference score) and percentage of correct answers on the accuracy level.

The Stroop interference task (German version of the color-word-Stroop test taken from the Nürnberger Altersinventar, NAI, Oswald and Fleischmann, 1995) was used to measure inhibitory control with verbal material. Here, the participant first had to read out loud 36 color names (printed in black on a sheet) as fast as possible; in the second run the participant had to name 36 color patches; in the last run he/she had to name the print color of 36 color words printed in different colors. Overall time was taken for each run. The main dependent variable was the difference in overall naming time between the third and the second run (interference score)[2].

Speed

A simple reaction time task was used to assess speed in detection of visual stimuli. A white circle was presented in the middle of the screen with a variable time interval of 1000–2000 ms in between. The participant was to press a key as fast as possible whenever a circle appeared. The circle disappeared at the time of key press. After a practice block of 10 trials, participants worked on a test block of 50 trials. Dependent variable was the mean RT.

A choice reaction time task was used to assess speed in simple decision making. A white arrow, either pointing to the right or the left, was presented in the middle of the screen with a variable time interval of 1000–2000 ms in between. The participant was to press the left arrow key as fast as possible whenever a left-pointing arrow appeared and the right arrow key whenever a right-pointing arrow appeared. The arrow disappeared at the time of key press. After a practice block of 10 trials, participants worked on two test blocks of 54 trials each. Dependent variable was the mean RT on correct trials and percentage of correct decisions.

PROCEDURE

All adolescents participated in a pretraining and a posttraining assessment, where performance in transfer tasks was assessed with parallel versions, respectively. The order of tasks was held constant in all assessments. Testing started with speed tasks, followed by the near transfer switching task, 2-back task, Flanker task, and digit span. After a 5-min break, testing continued with the number switch task, track task, Stroop task, and fitness assessment in the pretest session and vocabulary in posttest session.

Pretraining and posttraining sessions were scheduled in week one and five for each participant. In weeks two to four, participants of the two training groups and the exercise group had three training/exercise sessions, the no-contact control group did not have any sessions. These training sessions were scheduled with up to three adolescents at the same time and lasted for about 20–25 min for the cognitive training group and the exercise only control group and 45 min for the combined training group.

RESULTS

Prior to RT data analyses, for the switching tasks, trials that had RTs faster than 100 ms or longer than 4000 ms were excluded (following Karbach and Kray, 2009). For 2-back, Flanker, and speed tasks all trials with RTs faster than 100 ms and slower than 1500 ms were excluded prior to analyses. Excluded trials were counted as errors in the analyses of accuracy data.

TRAINING GAINS IN TRAINED TASKS

The first set of analyses was conducted with the two training groups to answer the first and third research question: if task switching can be improved in adolescents via cognitive training and if prior physical exercise influences training gains. To test for

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[2] Because error rates are generally extremely low in this task (mean error rate was below 1% in the current study, see **Table 4**), only RT data serves as dependent variable.

significant performance changes over the course of the training days and possible differences between the training groups with and without additional exercise intervention, separate repeated measures ANOVAs were conducted for RT and error data. Training group (cognitive training vs. combined training) served as between-subjects factor and time of measurement (training days) as the within-subject factor.

For the RT data, analyses revealed a significant main effect of time for switching costs, $F(1.6, 61.5) = 25.9$, $p < 0.001$, partial $\eta^2 = 0.41$ (Greenhouse-Geisser corrections for lack of sphericity were applied), indicating that both training groups showed reductions of RT switching costs over the course of all training days (see **Figure 1**). Neither the main effect of training group nor the interaction term (Time × Training group) reached significance, indicating that training groups neither differed in their RT switching costs overall nor in their reduction of switching costs over training. An additional dependent t-test for paired samples revealed that mean reductions in RTs from the first training day to the last training day (see **Table 2** for complete mean RT and error data) were larger for switch trials, $M = -241.5$ ms, $SD = -145.9$, corresponding to a reduction of about 25%, than for non-switch trials, $M = -136.1$ ms, $SD = -84.1$, corresponding to a reduction of about 18%, $t(39) = 6.6, p < 0.001$. Reduction rates did not differ significantly between the two training groups. This indicates that participants of both training groups showed larger improvements in RT on switch trials than on non-switch trials.

For the accuracy data, analyses revealed a significant effect of time for switching costs, $F(2, 76) = 9.3$, $p < 0.001$, partial $\eta^2 = 0.20$, indicating that all trained participants showed reductions of error switching costs over the course of training days (see **Figure 1**). Neither the main effect of training group nor the interaction term (Time × Training group) reached significance, indicating that training groups neither differed in their error switching costs overall nor in their reduction of error switching costs over training. An additional dependent t-test for paired samples revealed that error rates for non-switch trials increased from the first training day to the last training day, $M = 3.2\%$, $SD = 6.5$, whereas error rates for switch trials did not change, $M = 0.4\%$, $SD = 6.9$, $t(39) = 3.8$, $p < 0.001$ (see **Table 2** for complete mean RT and error data). Changes in error rates did not differ significantly between the two training groups.

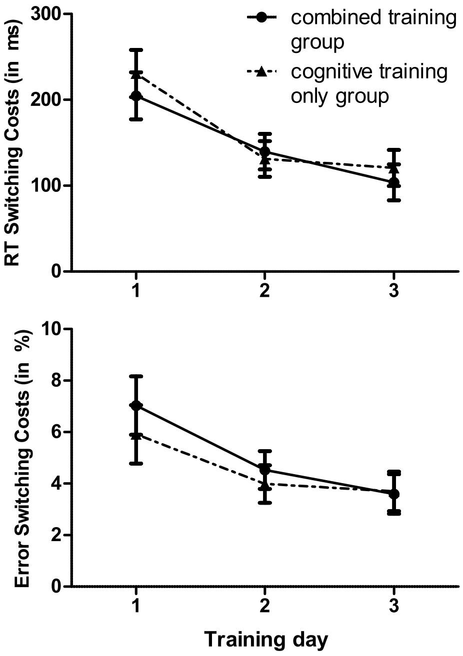

FIGURE 1 | Trajectories of RT switching costs (mean switching costs in ms ± SE) and error rate switching costs (mean switching costs in % ± SE) in the training task over the course of the three training days in the combined training group and the cognitive only training group.

TRANSFER EFFECTS OF TASK SWITCHING TRAINING TO NON-TRAINED TASKS

The second set of analyses was conducted with all participants to answer the second and third research question, that is what specific transfer effects can be found in adolescents after task switching training and if prior exercise influences transfer effects. To explore performance changes in transfer tasks between the pretraining and posttraining assessments, differences between the cognitive training and control groups, and possible differences between exercise and no exercise groups, two separate three-factorial MANOVAs were conducted for RT data (switching and mixing costs, RT, and interference scores) and error data (error rate switching and mixing costs and accuracy rates) in the transfer tasks. Cognitive training (training vs. no training) and exercise intervention (exercise vs. no exercise) served as between-subjects factors and time of measurement (pretraining vs. posttraining) as the within-subject factor. To account for multiple comparisons, we first looked at effects of the three factors on the combined dependent variables of RT and accuracy transfer measures, respectively. If the multivariate analyses were significant, separate follow-up ANOVAs were

Table 2 | Mean RT and error data for task switching training task in all three training sessions for the combined and the cognitive training only group.

	Training session 1 *M* (SD)	Training session 2 *M* (SD)	Training session 3 *M* (SD)
COMBINED TRAINING GROUP			
mean RT in ms			
Non-switch trials	718 (182)	638 (233)	576 (162)
Switch trials	949 (301)	769 (244)	697 (247)
Error rate in %			
Non-switch trials	10.5 (7.9)	12.3 (7.5)	12.9 (9.2)
Switch trials	16.4 (9.4)	16.3 (9.2)	16.6 (8.2)
COGNITIVE TRAINING ONLY GROUP			
mean RT in ms			
Non-switch trials	726 (131)	636 (105)	596 (93)
Switch trials	931 (199)	776 (199)	700 (163)
Error rate in %			
Non-switch trials	6.2 (3.6)	7.6 (4.3)	10.2 (5.1)
Switch trials	13.2 (7.8)	12.1 (5.9)	13.8 (6.7)

conducted to disentangle which of the single dependent variables contributed to the multivariate effect.

Transfer effects to RT measures

A three-factorial MANOVA for RT measures included near transfer mixing and switching costs, number switch mixing and switching costs, RT for correct trials on the 2-back task, Flanker interference score, and Stroop interference score, as well as simple and choice reaction time (see **Table 3** for mean performance on these dependent measures before and after training in the four different groups, and **Table A1** for complete mean RT data for switching and inhibition tasks). Analyses revealed a significant effect of time of measurement on the combined dependent variable of RT transfer measures, $F(9, 68) = 24.9$, Wilks' Lambda $= 0.23$, $p < 0.001$, partial $\eta^2 = 0.77$, indicating overall changes in RT measures from pretraining to posttraining assessments. Furthermore, there was a significant interaction term between time of measurement and cognitive training, $F(9, 68) = 2.7$, Wilks' Lambda $= 0.74$, $p < 0.009$, partial $\eta^2 = 0.26$, indicating that changes from pretraining to posttraining differed between groups with and without cognitive training. None of the other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the individual RT measures for the effects of time and the interaction of time and cognitive training.

For RT mixing costs in the near transfer switching task (i.e., the food-size switching task), the separate ANOVA revealed a significant main effect of time, $F(1, 76) = 70.9$, $p < 0.001$, partial $\eta^2 = 0.48$, and a significant interaction term (Time × Cognitive Training), $F(1, 76) = 7.2$, $p < 0.009$, partial $\eta^2 = 0.09$. That is, the training groups reduced their RT mixing costs more from pre- to posttraining than the control groups – suggesting transfer to RT mixing costs in the near transfer switching task (see **Figure 2**). For switching costs in the near transfer task, analyses

Table 3 | Performance on main dependent RT measures in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**	**Pretraining** ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**
Switching tasks				
Food/size MC (RT in ms)	213 (139)	97 (99)	206 (102)	64 (104)
Food/size SC (RT in ms)	221 (128)	137 (125)	242 (93)	114 (115)
Number MC (RT in ms)	727 (214)	537 (243)	724 (246)	560 (232)
Number SC (RT in ms)	199 (172)	81 (133)	121 (174)	123 (141)
Updating tasks				
2-back RT in ms	875 (118)	793 (111)	861 (97)	752 (130)
Inhibition tasks				
Flanker interference in ms	19 (26)	11 (25)	23 (28)	20 (38)
Stroop interference in s	18 (7)	15 (8)	19 (8)	18 (10)
Speed tasks				
Simple RT in ms	286 (42)	281 (39)	284 (57)	294 (63)
Choice RT in ms	440 (52)	426 (50)	441 (88)	415 (70)
Control groups	**Exercise only**		**No-contact**	
Switching tasks				
Food/size MC (RT in ms)	200 (109)	134 (107)	242 (124)	175 (75)
Food/size SC (RT in ms)	218 (125)	136 (85)	309 (157)	163 (136)
Number MC (RT in ms)	675 (325)	540 (211)	828 (217)	690 (173)
Number SC (RT in ms)	148 (140)	123 (175)	167 (201)	126 (144)
Updating tasks				
2-Back RT in ms	865 (109)	794 (99)	868 (101)	816 (106)
Inhibition tasks				
Flanker interference in ms	17 (41)	21 (26)	9 (20)	10 (33)
Stroop interference in s	17 (8)	13 (4)	18 (11)	15 (5)
Speed tasks				
Simple RT in ms	282 (36)	293 (36)	277 (30)	280 (37)
Choice RT in ms	439 (62)	439 (54)	428 (59)	426 (49)

MC, mixing costs; SC, switching costs; Flanker intereference (RT incongruent trials – RT congruent trials); Stroop interference (overall naming time 3rd run – overall naming time 2nd run).

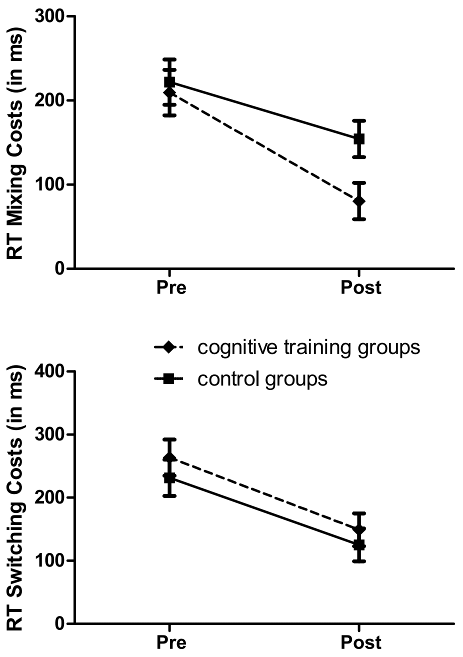

FIGURE 2 | Changes of RT mixing and switching costs (in ms ± SE) in near transfer switching task from pre- to posttraining assessments in the cognitive training groups and the control groups.

revealed a significant main effect of time for RT switching costs, $F(1,76) = 72.5, p < 0.001$, partial $\eta^2 = 0.49$, indicating reductions of switching costs from pre- to posttest. The interaction term (Time × Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of RT switching costs from pre- to posttest.

For the number switch task, analyses revealed a significant effect of time for RT mixing costs, $F(1, 76) = 53.7$, $p < 0.001$, partial $\eta^2 = 0.41$, and for RT switching costs, $F(1, 76) = 4.3$, $p < 0.04$, partial $\eta^2 = 0.05$. This indicates reductions of RT mixing and switching costs from pre- to posttest in all participants. The interaction term (Time × Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of mixing or switching costs from pre- to posttest.

In the domain of updating, a significant effect of time was found for RT on correct responses in the 2-back task, $F(1, 76) = 67.7$, $p < 0.001$, partial $\eta^2 = 0.47$. This indicates that, overall, participants reacted faster posttraining than pretraining on the 2-back task. Importantly, there was a tendency for a significant interaction term (Time × Cognitive Training) for mean RT for correct responses, $F(1, 76) = 3.2$, $p < 0.08$, partial $\eta^2 = 0.04$, that is cognitive training groups tended to reduce their RTs more from pre- to posttest than control groups.

In the inhibition domain, no significant effects were found for the Flanker interference score, indicating neither changes from pre- to posttraining nor differences between cognitive training and control groups. For the Stroop interference score, analyses revealed a significant main effect of time, $F(1,76) = 7.8, p < 0.006$, partial $\eta^2 = 0.09$, corresponding to reductions in the interference score from pretraining to posttraining. No other effects reached significance, indicating no differences between groups in changes from pre- to posttraining.

For mean choice reaction times, analyses revealed a significant main effect of time, $F(1, 76) = 7.1$, $p < 0.009$, partial $\eta^2 = 0.09$, that is participants performed the task faster at posttraining assessments than prior to training. Furthermore, there was a significant interaction term (Time × Cognitive Training) for mean choice reaction time, $F(1, 76) = 5.5$, $p < 0.02$, partial $\eta^2 = 0.07$, that is cognitive training groups reduced their RTs more from pre- to posttest than control groups. No significant effects were found for the simple reaction time task.

In summary, on the level of RT measures, transfer effects of a tasks switching training (as indicated by a significant interaction between time and cognitive training) were found. In particular, mixing costs in the near transfer task (switching) and choice reaction time (speed) contributed to this overall transfer effect. There was also a tendency for a contribution of the 2-back task (updating), but not for any of the other tasks included. Furthermore, on a RT level, there was no indication of an additional effect of the exercise intervention as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention.

Transfer effects to accuracy measures

A three-factorial MANOVA for accuracy measures included near transfer mixing and switching costs derived from error rates, number switch mixing and switching costs derived from error rates, accuracy rate (hits) for the 2-back task, accuracy rate in the keep track, the Flanker, and the choice reaction time task (see **Table 4** for mean performance on these measures before and after training in the four different groups **Table A2** for complete mean error data for switching tasks). Analyses revealed only one significant effect: the effect of cognitive training for the combined accuracy transfer measure, $F(8, 69) = 2.2$, Wilks' Lambda = 0.80, $p < 0.04$, partial $\eta^2 = 0.20$, indicating overall differences in accuracy measures for participants with and without cognitive training. No other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the separate accuracy measures to the cognitive training effect.

On the accuracy level, analyses revealed no significant effect for switching costs in the near transfer tasks. For mixing costs on this tasks, analyses revealed a significant main effect of cognitive training group, $F(1, 76) = 7.2$, $p < 0.009$, partial $\eta^2 = 0.09$, indicating higher error rate mixing costs in the cognitive training groups compared to the control groups. For the number switch task, no significant effects were found for either switching or mixing costs derived from error rates. Neither in the updating domain (for accuracy in the 2-back task) nor in the inhibition domain (for accuracy in the Flanker task), significant effects were found, indicating no differences between cognitive training and control groups. For choice reaction accuracy rates there was a significant effect of cognitive training, $F(1, 76) = 5.9$, $p < 0.02$, partial $\eta^2 = 0.07$, with cognitive training groups having lower accuracy rates than control groups, overall.

To summarize, no transfer effect was found on the accuracy level for any of the tasks (as would be indicated by a significant interaction between time and cognitive training). Furthermore,

Table 4 | Performance on main dependent accuracy measures (in %) in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**	**Pretraining** ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**
Switching tasks				
Food/size MC (error)	3.9 (4.2)	4.5 (5.7)	3.0 (5.2)	5.1 (8.6)
Food/size SC (error)	3.0 (5.1)	3.1 (7.1)	4.7 (4.6)	4.7 (7.4)
Number MC (error)	0.8 (11.3)	4.4 (8.9)	2.1 (6.5)	2.3 (6.4)
Number SC (error)	2.6 (5.7)	6.5 (8.7)	5.0 (9.4)	4.7 (9.2)
Updating tasks				
2-back accuracy (hits)	69.0 (11.2)	72.8 (16.2)	70.5 (11.1)	71.5 (12.4)
Keep track accuracy	59.8 (13.3)	63.8 (17.0)	62.5 (16.4)	67.4 (15.7)
Inhibition tasks				
Flanker accuracy	91.3 (10.8)	93.7 (4.4)	91.6 (6.1)	90.6 (7.2)
Stroop accuracy	99.3 (1.1)	99.8 (0.7)	99.4 (0.8)	99.7 (0.7)
Speed tasks				
Choice reaction accuracy	94.5 (4.5)	93.8 (4.3)	92.2 (5.8)	91.7 (7.7)
Control groups	**Exercise only**		**No-contact**	
Switching tasks				
Food/size MC (error)	1.6 (5.0)	1.3 (4.8)	1.5 (4.4)	2.6 (4.5)
Food/size SC (error)	4.6 (3.9)	1.9 (6.9)	3.4 (4.6)	3.4 (5.5)
Number MC (error)	2.6 (4.8)	3.8 (7.7)	2.9 (5.9)	−0.4 (10.8)
Number SC (error)	1.2 (6.5)	3.1 (7.6)	4.3 (7.5)	5.4 (6.1)
Updating tasks				
2-back accuracy (hits)	66.2 (13.5)	69.7 (15.9)	67.0 (17.2)	71.8 (15.4)
Keep track accuracy	62.2 (12.2)	63.6 (15.5)	63.1 (10.7)	64.2 (16.)
Inhibition tasks				
Flanker accuracy	89.4 (18.0)	93.7 (4.6)	93.6 (3.7)	92.2 (5.5)
Stroop accuracy	99.4 (0.7)	99.6 (0.8)	99.4 (1.0)	99.7 (0.6)
Speed tasks				
Choice reaction accuracy	95.4 (2.9)	95.8 (3.4)	94.9 (2.6)	95.0 (3.2)

MC, mixing costs; SC, switching costs.

there was no indication of an influence of the exercise intervention on the transfer effects on the accuracy level (as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention). Analyses indicated differences between groups with and without cognitive training. In particular, mixing costs (error) in the near transfer task and accuracy on the choice reaction time task contributed to this effect, with control participants performing better overall than trained participants.

RELATIONSHIPS BETWEEN TRAINING GAINS AND TRANSFER GAINS

To explore possible relationships between observed training gains and changes in performance in transfer tasks on the level of RTs, correlational analyses were conducted for the cognitive training groups. Training gains in RT switching costs (difference between first and last training day) were correlated with transfer gains (difference between pre- and posttraining assessment) in tasks where transfer effects had been indicated in the previous analyses, namely RT mixing costs in the near transfer switching task, choice reaction time, and RT for correct responses in the 2-back task. One significant correlation emerged between training gains in RT switching costs and pre-posttraining gains in RT in the 2-back task, $r = 0.42$, $p < 0.007$, indicating larger reductions of RT switching costs during training being associated with larger reductions in 2-back RT from pre- to posttraining in the trained groups.

DISCUSSION

Current study set out to explore if executive control can be trained in the age group of adolescents with a task switching training. Transfer was investigated systematically in all three executive control facets, i.e., switching, updating, and inhibition. Furthermore, current study aimed at exploring the recently proposed favorable effect of acute bouts of exercise on cognitive training. Analyses indicated that both training groups significantly reduced their switching costs (both on a RT and error rate level) over the course of three training sessions and also reduced their RT mixing costs in a near transfer task more from pre- to posttraining than the non-trained control groups. These findings indicate that executive control can be enhanced in adolescents through cognitive training. This is the first study to demonstrate plasticity of cognitive control in a group of adolescents and thus adds some novel findings to the growing literature on plasticity of executive control in different non-clinical age groups (Jaeggi et al., 2008; Karbach and Kray, 2009; Loosli et al., 2012). Interestingly, reductions of switching costs in this task switching training were found to be rather similar to those reported by Karbach and Kray (2009) for children and adults. This suggests a robust finding of significant reductions in switching costs over the course of very few (three or four, respectively) sessions of training with one session per week. A comparison of RTs over the course of training suggests that this training effect was driven by larger reductions in RTs in switch trials as compared to non-switch trials. This may indicate that training specifically improves processes necessary to switch from one task to the other as compared to a general speed up of responses. For error rates analyses indicated slight increases over training for non-switch trials whereas error rates in switch trials remained stable. Speculating on this finding, these changes in error rates may relate to slight reductions in motivation over training or increases in the relative focus on switch trials because of increased salience of the switching requirement.

Regarding transfer of the task switching training, current findings indicate some, but limited transfer of the training on the level of RT measures. First, transfer was found to a near transfer task, that was structurally similar to the one trained. Specifically, transfer was observed for RT mixing costs but not for RT switching costs. In contrast to the study by Karbach and Kray (2009), that found transfer for both types of costs in a near transfer switching task, our findings correspond to other studies that found transfer only to mixing costs (Minear and Shah, 2008). In Minear and Shah's and the current study transfer was found for the type of costs that corresponds to the more global ability to maintain and select two different task sets as opposed to switching costs that reflect more specifically the actual act of switching from one task to the other (Kray and Lindenberger, 2000; Braver et al., 2003). One may speculate that the specific task switching training used emphasizes the ability to maintain different tasks at the same time because there are no external cues and may therefore transfer reliably to other instances where maintenance is needed. During the task switching training, the participant has to maintain the tasks to be executed, keep track of how many times one task is executed, and keep track of which task to perform next. There is some evidence from other studies suggesting that updating or working memory (especially verbal rehearsal) is indeed crucial for performing these kinds of task switching tasks (Allen and Martin, 2010; Kray et al., 2010), especially if they are not cued trial-by-trial. The current study design does not allow to specifically investigate the changes of mixing costs during training. Because the training regimen by Karbach and Kray (2009) that we used in the current study does not include single-task blocks comparing performance between single and mixed tasks blocks (mixing costs) is not possible. Exploring changes of both types of performance costs over the course of training (that includes single-task blocks) and their relationship with transfer would therefore be an important avenue for future studies and would help to support our tentative suggestions about involved processes.

Improvements in the task switching training on a RT level were correlated with improvements in the speed of responses in an updating task. Furthermore, although not significant, a tendency for a transfer effect was found for the speed of responses in the updating task. This may support the importance of updating as a process possibly underlying the training and transfer effects in task switching trainings and may indicate that this particular (self-cued) task switching training improved the more general ability to update. This is in line with a recent study that demonstrated transfer of the same task switching training to a near transfer switching and an updating task that was associated with changes in right prefrontal and superior parietal brain regions as well as the striatum (Karbach and Brieber, 2011).

However, findings of transfer were generally rather limited as has also been suggested in other studies (e.g., Dowsett and Livesey, 2000; Li et al., 2008; Strobach et al., in press). In addition to transfer in one task switching and one updating task, transfer was found for a speed task on the RT measure (suggesting larger improvements in speed of simple decisions in the training as compared to the control groups), but neither for inhibition tasks nor to the other updating or switching tasks. Furthermore, in contrast to the RT measures, no indication of transfer was revealed on the level of accuracy in the transfer tasks. This may point to differential effects for speed- and accuracy-related measures. Findings may suggest that effects of a task switching training in adolescents manifest more in faster task execution (possibly related to faster updating and decision making) than in more accurate execution of tasks.

The transfer effects were not as strong as the ones reported by Karbach and Kray (2009) although the training regimen were very similar. Different possible factors may explain this discrepancy. Firstly, it may be that one modification we did to their protocol in terms of duration (three versus four sessions) has resulted in a training dose that was not enough to produce robust transfer effects. That is a possibility, especially when comparing current training regimen with considerably more extensive training regimen like the ones used by Jaeggi et al. (2008, with 8–19 sessions) or Klingberg et al. (2005, with 25 sessions) and recent study that even included as many as 100 training sessions (Schmiedek et al., 2010). However, Karbach and Kray (2009) found a range of transfer effects with only four training sessions. In addition, more importantly, training improvements in the current study were comparable to those reported by Karbach and Kray (2009). Nevertheless, it is reasonable to assume that a certain amount or intensity of executive control training may be a prerequisite for substantial changes to occur (see, e.g., Klingberg, 2010) and we would find broader transfer effects with a larger amount of training. Considering plasticity as the potential of brain and behavior to change in response to environmental challenges (e.g., cognitive demands of an executive control training), the amount of plastic changes, and therefore the amount of transfer may strongly depend on the intensity and duration of the challenge. Spacing of the cognitive training sessions may also play a role here, that is, whether training sessions are concentrated over a short period of time (e.g., daily sessions like in the study by Jaeggi et al., 2008) or spaced over several weeks like in the current study.

Furthermore, the target age group of the current study may be of relevance for the observed lower amounts of transfer. It may be that in the group of adolescents, although there are still mean level changes observable in normative developmental studies, domains of executive control may show different developmental trajectories (Huizinga et al., 2006) and may therefore be more or less prone to training and transfer effects than in other age groups. It is also possible that the specific transfer tasks used did not share enough relevant features or required processes with the trained task to find reliable transfer. For example, it could be that task switching training enhanced aspects of maintenance ability and transfer to the number switch task was not found because task choice was cued and requirements to maintain task order and number were very low in this transfer task (the cue was present the whole time until a response was made, thus very little maintenance is needed). Thus, future studies on the plasticity of executive control functions should explore the moderating effects of training domain and training intensity, as well as the role of age-dependent differences on the effects of cognitive trainings (Klingberg, 2010).

The third exploratory research question concerned a novel proposal in the training literature (e.g., Hillman et al., 2009), i.e., possible effects of a combination of an acute exercise intervention with the cognitive training. Analyses revealed no reliable effects of this intervention on training or transfer tasks. Thus, our initial data does not provide strong evidence in favor of the suggestion that this type of exercise intervention may have a positive impact on the effects of cognitive training. However, of course, our findings are preliminary and could be due to different factors. It could be that, in this context, acute exercise has no effect on task switching and/or learning. This is in accordance with studies that have not been able to show an effect of acute exercise on switching (e.g., Tomporowski et al., 2008, but, see, e.g., Pesce et al., 2003 for findings of positive effects). Other domains of cognitive control may be more receptive for these kinds of effects, e.g., there are a range of studies showing improvements in inhibition tasks (e.g., Hillman et al., 2009; Yanagisawa et al., 2010, but, see, e.g., Stroth et al., 2009 for findings of no such effect). It is also possible that different intensities or types of exercise would have different effects, for example exercise that requires more coordination skills than cycling as has been suggested in a study by Budde et al. (2008). In addition, it is important to note from a methodological point of view that most studies on acute exercise effects used a within-subjects design (see, e.g., Pontifex et al., 2009; Stroth et al., 2009; Yanagisawa et al., 2010) whereas current study employed a between-subjects design to compare exercise to non-exercise. That may have made it more difficult to detect possibly small effects. To further explore the proposed effects of exercise, future research will have to further examine these issues by exploring the effects of different types of exercise on cognitive training efficiency.

To summarize, current study showed that task switching abilities can be trained in adolescents. Transfer was revealed at the level of RT measures in a similar task switching task, a speed task and a (tendency for) an updating task. Conceptually interesting, updating seems to play a crucial role in this task switching training and its possible transfer effects. The importance of updating processes is in line with a range of cognitive training studies that have used updating and working memory tasks and have been able to show robust training and transfer effects. An additional positive effect of acute exercise could not be demonstrated – thus, possible factors that influence the amount of training and transfer effects remain to be explored in future studies.

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APPENDIX

Table A1 | Mean RT data for transfer task switching and inhibition tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining *M* (SD)	**Posttraining *M* (SD)**	**Pretraining *M* (SD)**	**Posttraining *M* (SD)**
Food/size switching task (mean RT in ms)				
Single trials	684 (109)	611 (100)	686 (171)	612 (180)
Non-switch trials	789 (166)	642 (103)	774 (188)	621 (180)
Switch trials	1010 (263)	778 (180)	1016 (252)	735 (260)
Number switching task (mean RT in ms)				
Single trials	656 (85)	636 (104)	661 (118)	633 (171)
Non-switch trials	1285 (246)	1135 (223)	1329 (293)	1135 (314)
Switch trials	1484 (276)	1216 (280)	1450 (364)	1258 (313)
Flanker inhibition task (mean RT in ms)				
Congruent trials	554 (60)	507 (59)	559 (99)	515 (100)
Incongruent trials	573 (58)	518 (65)	582 (104)	535 (93)
Stroop inhibition task (overall time in s)				
Second run (color patches)	26 (7)	24 (5)	25 (5)	24 (5)
Third run (color names)	44 (10)	39 (12)	44 (10)	42 (11)
Control groups	**Exercise only**		**No-contact**	
Food/size switching task (mean RT in ms)				
Single trials	691 (133)	641 (123)	726 (147)	650 (117)
Non-switch trials	783 (186)	707 (169)	816 (175)	745 (138)
Switch trials	1002 (273)	843 (225)	1125 (301)	908 (189)
Number switching task (mean RT in ms)				
Single trials	678 (132)	659 (111)	671 (92)	621 (87)
Non-switch trials	1279 (367)	1147 (266)	1420 (277)	1244 (183)
Switch trials	1427 (450)	1269 (326)	1586 (257)	1371 (245)
Flanker inhibition task (mean RT in ms)				
Congruent trials	559 (87)	537 (63)	539 (64)	523 (79)
Incongruent trials	575 (96)	558 (71)	548 (63)	532 (70)
Stroop inhibition task (overall time in s)				
Second run (color patches)	26 (5)	26 (6)	27 (6)	26 (6)
Third run (color names)	43 (11)	38 (6)	45 (16)	41 (9)

Table A2 | Mean error data for transfer task switching tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact).

Training groups	**Combined training**		**Cognitive training**	
	Pretraining ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**	**Pretraining** ***M*** **(SD)**	**Posttraining** ***M*** **(SD)**
Food/size switching task (mean error rate in %)				
Single trials	8.2 (5.0)	13.2 (10.3)	8.9 (6.2)	16.4 (10.0)
Non-switch trials	10.5 (6.7)	16.1 (12.1)	9.5 (6.3)	19.2 (14.4)
Switch trials	13.6 (8.0)	19.1 (12.7)	14.2 (7.5)	23.9 (12.5)
Number switching task (mean error rate in %)				
Single trials	9.3 (11.2)	8.8 (4.4)	8.4 (7.0)	11.6 (7.2)
Non-switch trials	10.3 (8.1)	11.4 (11.4)	11.3 (13.2)	12.4 (9.0)
Switch trials	12.9 (7.2)	17.9 (13.2)	16.3 (11.9)	17.1 (11.6)
Control groups	**Exercise only**		**No-contact**	
Food/size switching task (mean error rate in %)				
Single trials	7.4 (4.2)	8.5 (5.7)	6.4 (4.2)	8.4 (6.3)
Non-switch trials	6.7 (4.1)	8.9 (5.9)	6.3 (4.0)	9.3 (6.4)
Switch trials	11.3 (5.7)	10.8 (8.9)	9.7 (5.7)	12.7 (6.2)
Number switching task (mean error rate in %)				
Single trials	7.5 (10.1)	7.9 (6.2)	5.7 (4.6)	10.1 (9.4)
Non-switch trials	10.5 (10.7)	11.2 (11.5)	7.9 (5.3)	7.1 (5.3)
Switch trials	11.7 (10.7)	14.4 (12.6)	12.2 (8.0)	12.6 (7.7)