Effects of motor-cognitive coordination training and cardiovascular training on motor coordination and cognitive functions

Verena E. Johann a, b, *, Katharina Stenger a, Stephanie Kersten c, d, Julia Karbach a, b

a Department of Educational Science, Saarland University, Saarbrücken, Germany
b Department of Psychology, Goethe-University, Frankfurt, Germany
c Sports Science Institute, Saarland University, Saarbrücken, Germany
d Faculty of Health & Social Sciences, Hochschule Fresenius, University of Applied Sciences, Idstein, Germany

Article history:
Received 18 December 2014
Received in revised form 25 December 2015
Accepted 20 January 2016
Available online 27 January 2016

Keywords:
Exercise
Cardiovascular training
Coordination training
Cognitive plasticity
Executive functions

Abstract

Objectives: Numerous recent studies showed that physical training can enhance cognitive abilities, such as attention, spatial ability, memory performance, and executive functions. However, most of these studies focused on the efficiency of cardiovascular training, whereas evidence for combined motor-cognitive training emphasizing coordination abilities is scarce. Therefore, the aim of the present study was to investigate the effects of motor-cognitive coordination training and moderate cardiovascular training on cognitive functions and to test whether these effects were related to participant’s fitness level.

Design and method: We tested 50 physically active (mean age = 23.5 years, SD = 3.2) and 56 sedentary participants (mean age = 23.4 years, SD = 3.2) in a pretest-training-posttest design with 12 sessions of moderate cardiovascular training (≥60% HRmax) or motor-cognitive coordination training. The training groups were compared to a passive control group. At pretest and posttest, participants performed an untrained motor-cognitive coordination task, measures of executive control (cognitive flexibility, inhibition, working memory), spatial ability, and fluid intelligence.

Results and conclusions: We found improved coordination abilities in the coordination training group, but no transfer of training to cognitive measures in physically active participants. However, sedentary participants showed larger improvements in terms of inhibition in the coordination training group compared to the remaining groups, while the cardiovascular training group improved in cognitive flexibility compared to the remaining groups. In sum, there are positive but differential effects of cardiovascular training and coordination training on cognitive performance in sedentary young participants, suggesting that coordination training may be a useful intervention especially for individuals that cannot perform cardiovascular training.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Many recent studies have shown that physical exercise can improve cognitive abilities: Cross-sectional work indicated that the level of physical fitness was associated with cognitive performance in various tasks measuring aspects of attention, spatial ability, memory performance, processing speed or executive functions like cognitive flexibility or inhibition control (e.g., Budde, Voelcker-Rehage, Pietrassyk-Kendziorra, Ribeiroc, & Tidowa, 2008; Chaddock, Pontifex, Hillman, & Kramer, 2011; Chang, Labban, Gapin, & Etnier, 2012; Ozel, Larue, & Molinaro, 2004; Pontifex, Scudder, Drollette, & Hillman, 2012). Moreover, longitudinal studies showed that physical training, particularly in the domain of cardiovascular training (e.g., running or swimming), resulted in improved cognitive performance from childhood to older age (e.g., Chapman et al., 2013; Davis et al., 2011; Dresen & Netelenos, 1983; Kramer & Erickson, 2007; Voelcker-Rehage, Godde, & Staudinger, 2011; for reviews, see Hillman, Erickson, & Kramer, 2008; McMorris & Hale, 2012). For instance, Dresen and Netelenos (1983) showed that a ten-week ergometer training lead to better performances in attention tasks in children with an attentional deficit compared to untrained peers. In older adults, meta-analytic evidence revealed
significant positive effects of cardiovascular training in the domain of executive control and medium-sized effects regarding controlled processing, speed of processing, and spatial abilities (Colcombe & Kramer, 2003). Voelcker-Rehage et al. (2011) provided evidence for improved performances on tasks measuring aspects of executive functions and processing speed after a 12-month walking training in older adults. These positive effects of cardiovascular fitness on cognitive abilities have been explained by training-induced changes in the brain. Animal and human studies showed functional and structural changes in the brain as a response to cardiovascular training, pointing to neuronal plasticity (Chaddock et al., 2010, 2011; Colcombe et al., 2004; Ratey & Hagerman, 2009; Shors, 2013). These changes are assumed to result in improved cognitive performance.

The changes in cognitive performance after coordination training have so far received less scientific attention. It typically includes demands on motor abilities and cognitive abilities. So far, well controlled longitudinal studies investigating the effects of coordination training on cognitive performance are scarce. Grünke (2011) provided evidence for improvements in terms of attention and fluid intelligence in 9–12 year-old children with attentional deficits compared to untrained peers after 12 sessions of coordination training. Hötting et al. (2012) compared the effects of six-months coordination/stretching training to the effects of cardiovascular training in middle-aged sedentary adults. In contrast to a control group, both training groups benefitted in terms of episodic memory. While this improvement in episodic memory was more pronounced in the cardiovascular training group, the coordination training group improved more in terms of attention. Moreover, Voelcker-Rehage et al. (2011) found that performance improvements on an interference control task were larger after coordination training than after cardiovascular training in older adults. According to Hötting and Röder (2013), this advantage of coordination training over cardiovascular training may be attributed to the requirement to manage cognitive as well as physical demands during training. Thus, training on dual tasks from different modalities involving demands on the neurocognitive system and the skeletal muscles seems to be particularly efficient for improving executive control and attentional processes (Hötting & Röder, 2013; Kubesch & Walk, 2009; Weinbeck, Schreyer, & Schatz, 2010). Furthermore, there is evidence that these demands on the neurocognitive system can initiate functional and structural changes in the brain (for a review, see Voelcker-Rehage & Niemann, 2013). Niemann, Godde, and Voelcker-Rehage (2014) found that motor fitness was associated with hippocampal volume and that both a 12-month cardiovascular and coordination training led to increases in hippocampal volume in older adults. Moreover Taubert, Lohmann, Margulies, Villringer, and Rager (2011) provided evidence for structural gray matter alterations and functional connectivity changes in prefrontal and supplementary-motor areas after six training sessions in a dynamic balancing task.

In sum, there are only a few studies directly comparing coordination training and cardiovascular training which makes it hard to contrast the effects of cardiovascular training and coordination training on cognitive performance. Nevertheless, these studies suggest that there may be positive but differential effects of cardiovascular training and coordination training on cognitive performance and functional and structural changes in the brain.

So far, most training studies investigated samples of children or older adults and focused on compensatory effects of cardiovascular training on age-related differences in cognitive development or cognitive aging (e.g., Chang et al., 2012; Chapman et al., 2013; Dresden & Netelenbos, 1983; Grünke, 2011; Hillman et al., 2008; Hillman & Schott, 2013; Jansen, Lange, & Heil, 2011; Lange, 2009; Voelcker-Rehage et al., 2011). As a consequence, there are only very few studies investigating healthy young adults. Draganski et al. (2004), for instance, found structural changes in brain areas supporting visuo-spatial abilities after three months of juggling training in young adults. However, this study did not provide evidence for improvements in the performance of cognitive tasks.

The aim of the present study was to test the effects of two types of physical training (coordination and cardiovascular) on (a) coordination abilities and (b) cognitive functions in younger adults as compared to a passive control condition (transfer). We expected larger improvements on the untrained coordination task in the coordination training group than in the remaining groups (cf. Hötting & Röder, 2013). With respect to the transfer of cardiovascular and motor-cognitive coordination training to cognitive abilities, we expected larger pretest-to-posttest improvements in both training groups than in the control group (cf. Colcombe et al., 2004; Voelcker-Rehage et al., 2011). Finally, we also investigated whether these transfer effects were different (c) as a function of training protocol (coordination vs. cardiovascular). Given that previous studies found better performance on cognitive and motor coordination tasks in professional athletes than in untrained non-athletes (Jansen, Lehmann, & Van Doren, 2012; Ozel et al., 2004) we explored training-related benefits in physically active and sedentary participants by means of two separate experiments: The first one included physically active participants that regularly engaged in physical activity. The second experiment included physically inactive participants that rarely or never engaged in physical activity.

2. Method

2.1. Participants

2.1.1. Experiment 1

Fifty individuals regularly following an exercise regimen participated in Experiment 1. They were recruited via advertisements posted on campus and distributed through a university mailing list. Participants in the two training groups (see below) received 65 EUR for participating in the pretest, posttest and 12 training sessions; participants in the control group received 20 EUR for participating in the pretest and posttest sessions. To ensure that all participants exercised regularly, they completed a questionnaire assessing habitual physical activity. Exclusion criteria were color blindness, achromatopsia, injuries preventing physical activity, chronic physical or psychiatric diseases, psychotropic medication, and blood pressure medication assessed by a biographic questionnaire. Active participants of experiment 1 and Sedentary participants of experiment 2 were recruited together. Based on their answers on a questionnaire measuring their habitual physical activity they were assigned to the group of active participants (experiment 1) or the group of sedentary participants (experiment 2). Participants were matched for age and gender and then randomized into a motor-cognitive coordination training group, a moderate cardiovascular training group, or a passive control group. Five participants had to be excluded from the analysis because they failed to complete the exercise regimen. The final sample consisted of 16 (9 male) participants in the coordination training group, 19 (9 male) participants in the cardiovascular training group, and 10 participants (6 male) in the control group. Their mean age was 23.5 years (SD = 3.2) with a range of 18–31 years. The three groups were comparable in terms of age (p = .49) and gender (p = .88).

2.1.2. Experiment 2

The second experiment was conducted with 56 participants not regularly following an exercise regimen. Recruitment procedure, matching to the three groups, and exclusion criteria were the same.
as in Experiment 1. We additionally excluded participants indicating on the questionnaire that they exercised regularly. 10 participants had to be excluded from the analysis because they failed to complete the exercise regimen. The final sample size was 16 (5 male) participants in the motor-cognitive coordination training group, 16 (6 male) participants in the moderate cardiovascular training group, and 14 participants (4 male) in the control group. Their mean age was 23.4 years ($SD = 3.2$) with a range of 19–30 years. The three groups were comparable in terms of age ($p = .14$) and gender ($p = .86$).

2.2. Procedure

The procedure was the same for both experiments. Participants in the two training conditions and the control condition were first invited to the pretest session ($\approx 2$ h). It included a biographic questionnaire, a questionnaire for the measurement of habitual physical activity and a cognitive test battery. Afterward, 12 training sessions were scheduled twice a week for 45 min at the university. After the training, participants completed a posttest session that was identical to the pretest session. Thus, the whole study lasted for 6–8 weeks for each participant.

2.3. Pretest and posttest measures

We used IBM-compatible laptops with 17-inch color monitors for data collection. All computer based tasks were programmed with the experimental software E-Prime 2.0. Materials and tasks were same for experiment 1 and 2.

2.3.1. Questionnaire for the Measurement of Habitual Physical Activity (Wagner & Singer, 2003)

In order to estimate participant’s initial physical fitness we applied the “Questionnaire for the Measurement of Habitual Physical Activity” (Wagner & Singer, 2003). This Questionnaire measures the habitual physical activity at work, sports, and leisure activity. Participants rated the intensity and frequency of their physical activity on a Likert scale from 1 to 5. The questionnaire included 7 items referring to “physical activity at work”, 3 items referring to “leisure activities”, and 4 items referring to “sports”. It allows the calculation of a weighted physical activity index (from $1 = \text{very low} \leq 5 = \text{very high}$). Participants with an index $\geq 3$ were classified as physically active and participants with an index $< 3$ as physically inactive (cf. Baecke, Burema, & Frijters, 1982). The internal consistencies of the three scales ranged from $\alpha = .57$–.86.

2.3.2. Motor-cognitive coordination transfer task

In order to test transfer from the motor-cognitive coordination training to a new untrained motor-cognitive task, another coordination task was performed before and after the training (cf. Lutz & Neureuther, 2009). In this exercise, participants were to turn and catch a ball in different manners (e.g., even number = turn to the left and catching the ball with the right hand; odd number = turn to the right and catching the ball with the left hand). At advanced levels commands were animals or animals and numbers that had to be categorized (e.g., land animal = turn to the left and catching the ball with the right hand; aquatic animal = turn to the right and catching the ball with the left hand). Participants reached a new level if they had finished 5 of 10 trials successfully. The highest level reached in the motor-cognitive coordination transfer task served as test score for motor-cognitive coordination abilities.

2.3.3. Cognitive test battery

2.3.3.1. Verbal working memory: Counting span (adapted from Kane et al., 2004). In the counting span task, participants recalled digits against a background counting task. Each display included 3–9 dark blue circles as well as 1, 3, 5, 7, or 9 dark blue squares, and 1–5 light green circles on a gray background. Participants were to count the number of dark blue circles in each display and repeat the total number. There was no time limit but participants were instructed to count continuously. The experimenter then pressed a key and another display or the recall cue appeared. At the recall cue, participants had to recall the respective numbers of dark blue circles in the correct order. Set sizes ranged from two to five items, with a total of eight sets. The task started with three practice items. The test score was the number of correctly recalled sets.

2.3.3.2. Spatial working memory: Navigation span (adapted from Kane et al., 2004). In the navigation span task, participants recalled the paths of moving balls across the screen against a background counting task. A box of approximately 400 × 400 pixels (20 × 20 cm) was presented on the display. Instantly after the onset of the box, a dark ball appeared in one of eight locations inside the box. It moved vertically, horizontally, or diagonally across the box. The display was followed by the processing task, consisting of polygonal figures whose angles had to be counted aloud but not memorized. After that, the moving ball or the recall cue appeared. Participants had to recall the path of each ball in the set in the correct order and draw the paths on an answer sheet. Set sizes ranged from two to five items, with a total of eight sets. The task started with three practice items. The test score was the number of correctly solves sets.

2.3.3.3. Inhibitory control: Flanker task (Eriksen & Eriksen, 1974).

In the Flanker task, stimuli were presented in black against a white background. Each stimulus consisted of five letters. Participants were to respond to the central target letter by pressing a key with their left or right index finger. The central target letter was either a “H” or an “S” and was surrounded by two “H” or two “S” on the left and the right side. Participants were to respond as quickly as possible while avoiding errors. They performed 20 practice trials followed by five experimental blocks (40 trials each). The presentation order of the stimuli was randomized within blocks. The response interference effect was calculated as the difference in performance between congruent (SSSSS, HHHHH) and incongruent (SSSSH, HHHSH) trials.

2.3.3.4. Cognitive flexibility: Task switching (Karbach & Kray, 2009).

In the switching task, visual stimuli consisted of 18 images of vegetables and 18 images of fruits. Each image was available in two sizes (small and big). The participants were instructed to perform two different tasks, a “food” task and a “size” task. In the food task, participants were asked to decide whether the image showed a vegetable or a fruit. In the size task they had to decide whether the vegetable or fruit was present small or large. The same two response keys were used for both tasks. If the picture showed a fruit (food task) or was presented in a large size (size task) participants had to press the left response key with the left index finger. If the image showed a vegetable (food task) or was presented in a small size (size task) participants were instructed to press the right response key with the right index finger. In task-homogeneous blocks, they were instructed to perform either the food or the size task. In task-heterogeneous blocks, they were asked to switch between both tasks. The task sequence was predictable and participants knew that they had to switch tasks on every second trial. They completed two practice blocks and twelve test blocks. The test blocks consisted of six task-homogeneous blocks and six task-heterogeneous blocks. Each block comprised 17 trials (the first one was always excluded from the analyses). The presentation order of trials within a block was randomized. This design allows
calculating two types of switch costs: General switch costs (i.e., the difference in performance between task-homogeneous and task-heterogeneous blocks) measuring the ability to maintain two task sets in working memory and select the appropriate one, and specific switch costs (i.e., the difference in performance between switch and stay trials within task-heterogeneous blocks) representing the ability to flexibly switch between tasks.

2.3.3.5. Visual-spatial ability: Mental rotation test (MRT, Peters et al., 1995). The MRT is a computer-based test to assess visuo-spatial ability. Each item consisted of a criterion figure, two correct alternatives, and two incorrect ones (distractors). Correct alternatives were always identical to the criterion in structure but are shown in a rotated position. Participants were to find the rotated figures. The test included four practice items and 24 test items presented in two blocks. In both blocks, participants had 3 min to complete as many items as possible. The test score was the number of trials in which participants correctly identified the rotated figures.

2.3.3.6. Fluid intelligence: Raven Advanced Progressive Matrices (Raven, Raven, & Court, 1998). In the Raven’s task, participants selected one of eight figures that best completed a pattern. They first performed three practice items, followed by up to 36 test items increasing in difficulty. The task was aborted after 20 min. The test score was the number of correctly solved items.

2.4. Weekly training log

In order to control for the influence of physical activity outside of the study setting, participants completed an online questionnaire that was sent to them every weekend via e-mail. It included questions regarding any additional coordination or cardiovascular training besides their guided training sessions. Participants in both training groups provided the type, intensity, and duration of these activities in the previous week. In addition, they indicated whether they had started any coordination exercises beside the guided training sessions. Data from this questionnaire confirmed that participants neither changed their usual training routines in the active group nor started any type of physical training in the sedentary group. Moreover, none of the participants started additional coordination exercises outside of the study.

2.5. Training conditions

Four students majoring in sports science held both the cardiovascular and the motor-cognitive coordination training. Participants were trained individually or in small groups with a maximum of four participants at the same time. If the group size exceeded two participants, a second trainer guided the session.

2.5.1. Motor-cognitive coordination training

The coordination training started with a 5-min juggling exercise as a short warm-up. Afterward, two of the three coordination exercises described below were practiced for 20 min per training session, respectively. The sequence of exercises was randomized, but at the end of the 12 sessions, each one had been trained eight times (total time spent on training: 8 h). The difficulty of the training exercises was adaptive: Participants started on the first level and if they successfully completed at least five out of ten trials the difficulty level was increased by one. For each exercise, the highest level per session was documented and served as starting level the next time that task was trained. The training tasks were based on the LifeKinetics training regime (Lutz, 2012) designed to train motor-cognitive coordination ability. The LifeKinetic training includes motor coordination tasks of increasing complexity that are combined with cognitive tasks assumed to tap working memory, inhibition, cognitive flexibility, and attentional processes.

2.5.5.1. Training Exercise 1. In Exercise 1, participants had to jump in a 2 × 2 grid in a predefined sequence. The jumping task was successively increased in difficulty and combined with arm movements (e.g., throwing balls in the air and catching them with crossed arms) and cognitive tasks (e.g., repeating different sequences of numbers).

2.5.5.2. Training Exercise 2. For exercise 2, ten pylons were arranged in a semi cycle. Standing in the middle, participants had a racket in each hand and played a tennis ball from one racket to the other. In addition, the trainer regularly gave commands indicating which pylons the subject had to hit with the ball (e.g., “number 5”, “red” etc.). On top of that, participants at advanced levels had to perform predefined motions with increasing difficulty (e.g., even number = moving the left foot forward; odd number = moving the right foot forward) and cognitive tasks (e.g., animals and numbers as commands; land animal and number 5 = hitting pylon number 5 with the right hand; aquatic animal and number 5 = hitting pylon number 5 with the left hand).

2.5.5.3. Training Exercise 3. For exercise 3, at least 30 different colored plastic bonnets were arranged on the floor. The trainer announced a color and participants had to move from one bonnet of this color to another. Additionally, they had to catch a ball in different ways with increasing difficulty (e.g., even number = catching the ball with the left hand; odd number = catching the ball with the right hand). On top of that, participants at advanced levels had to perform specific motions (e.g., throwing a ball with one hand in the air and catching it while moving from one bonnet to another).

2.5.2. Moderate cardiovascular training

The cardiovascular training was performed on stationary bikes. Participants trained twice a week for 40 min at 50–70% of their maximum pulse rate (200 beats per minute – age, cf. Hollmann & Strüder, 2009). Their pulse rate was controlled and documented 5, 15, 30, and 45 min into the training. To make the training adaptive and comparable to the motor-cognitive coordination training, the resistance was increased or decreased (60–160 Watt) if the pulse rate was too low (that is under 50% of the maximum pulse rate) or too high (that is above 70% of the maximum pulse rate).

3. Results

3.1. Experiment 1

3.1.1. Training effects

Coordination training group. To test for training-related benefits we compared the training performance in the beginning and the end of the training period. In order to increase the reliability of the measurement, we averaged across the highest training levels of the first two and the last two performances of a given exercise and ran paired t-tests. The analyses revealed significant training-related improvements in all three exercises (exercise 1: t(16) = –45.57, p < .001, r = .96; exercise 2: t(16) = –7.17, p < .001, r = .79; exercise 3: t(16) = –16.05, p < .001, r = .77) (see Table 1).

Cardiovascular training group. To investigate training-related benefits in the cardiovascular training group we compared the maximal resistance (in watt) in the beginning and the end of the training period. There were 17.6% missing values due to technical reasons, but they occurred completely at random (Little’s MCAR test: all p’s < .05). We therefore imputed missing data using the
Table 1
Training performance as a function of Training group (coordination training, cardiovascular training) and Testing time (beginning of the training, end of the training) in Experiment 1.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Beginning of the training</th>
<th>End of the training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordination training group (n = 17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exercise 1 (mean difficulty level)</td>
<td>3.97 (0.55)</td>
<td>15.32 (1.06)</td>
</tr>
<tr>
<td>Exercise 2 (mean difficulty level)</td>
<td>1.21 (0.44)</td>
<td>3.26 (1.47)</td>
</tr>
<tr>
<td>Exercise 3 (mean difficulty level)</td>
<td>3.76 (0.47)</td>
<td>9.85 (1.66)</td>
</tr>
<tr>
<td>Cardiovascular training group (n = 17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance (mean watt)</td>
<td>100.28 (27.82)</td>
<td>109.85 (34.57)</td>
</tr>
</tbody>
</table>

Note: Beginning of the training: mean of first and second session; end of the training: mean of 11th and last session.

Table 2
Training performance as a function of Training group (coordination training, cardiovascular training) and Testing time (beginning of the training, end of the training) in Experiment 2.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Beginning of the training</th>
<th>End of the training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordination training group (n = 16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exercise 1 (mean difficulty level)</td>
<td>3.75 (0.58)</td>
<td>14.00 (1.98)</td>
</tr>
<tr>
<td>Exercise 2 (mean difficulty level)</td>
<td>1.00 (0.01)</td>
<td>2.59 (1.13)</td>
</tr>
<tr>
<td>Exercise 3 (mean difficulty level)</td>
<td>3.63 (0.43)</td>
<td>9.50 (1.94)</td>
</tr>
<tr>
<td>Cardiovascular training group (n = 16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance (mean watt)</td>
<td>86.09 (18.99)</td>
<td>96.25 (18.48)</td>
</tr>
</tbody>
</table>

Note: Beginning of the training: mean of first and second session; end of the training: mean of 11th and last session.

3.1.3. Transfer to coordination abilities
To assess transfer of the coordination training to the untrained coordination task, we ran an ANOVA including the between-subjects factor Group (coordination training, cardiovascular training, control group) and the within-subjects factor Testing time (pretest, posttest). The ANOVA revealed a main effect of Testing time, $F(1,42) = 4.31, p < .05, \eta^2_p = .09$ ($d = .21$), indicating that coordination performance improved from the first session to the last session (see Fig. 1). The main effect of Group was not significant ($p = .39$), but the interaction between Group and Testing time reached significance, $F(2,42) = 4.36, p < .05, \eta^2_p = .17$. There were larger performance improvements in the coordination training group than in the control group, $F(1,42) = 8.58, p < .01, \eta^2_p = .17$ ($d = .28$). Performance gains were comparable in the coordination training group and the cardiovascular group ($p = .11$). Data of all transfer measures are shown in Table 3.

3.1.4. Transfer to cognitive abilities
We used a similar ANOVA design to examine transfer effects of the training interventions to experimental measures of cognitive abilities. We first report the results on transfer to executive control tasks, that is, to inhibitory control, task switching, and working memory, followed by the findings on visuo-spatial ability and fluid intelligence.

**Inhibitory control.** Analyses were based on mean reaction time (RT) and error rates. Latencies faster than 200 ms, 2.5 SD above the mean group, and the first trial in each block were excluded from the analysis. Data were submitted to a three-way ANOVA with the factors Group (coordination training, cardiovascular training, control group), Testing time (pretest, posttest 1), and Trial type (congruent, incongruent).

Latencies. We found a marginally significant main effect of Testing time, $F(1,42) = 3.56, p = .06, \eta^2_p = .07$ ($d = .09$), indicating that participants responded faster at posttest than at pretest. The main effect of Trial type pointed to reliable interference costs, $F(1,42) = 90.54, p < .001, \eta^2_p = .68$ ($d = .25$) (see Fig. 2). No further effects reached significance (all $p$'s > .43).

Error rates. We found a significant main effect of Trial type, $F(1,42) = 46.95, p < .001, \eta^2_p = .53$ ($d = .59$). No further effects reached significance (all $p$'s > .24).

**Task switching.** The analytic strategy was the same as for the inhibition task, except that the factor Trial type had three levels (single, stay, switch).

Latencies. The overall ANOVA showed a main effect of Testing time, $F(1,42) = 22.27, p < .001, \eta^2_p = .35$ ($d = .20$), indicating that the participants responded faster at posttest than at pretest and a main effect of Trial type, $F(2,41) = 34.89, p < .001, \eta^2_p = .63$, revealing...
significant general switch costs and specific switch costs, \( F(1, 42) = 56.71, p < .001, \eta^2_p = .57 (d = .42) \) and \( F(1, 42) = 69.49, p < .001, \eta^2_p = .62 (d = .29) \), respectively. An interaction between Trial type and Testing time, \( F(2, 41) = 9.38, p < .001, \eta^2_p = .31 (d = .28) \), showed that both general and specific switch costs decreased from pretest to posttest, \( F(1, 42) = 7.98, p < .01, \eta^2_p = .16 (d = .21) \) and \( F(1, 42) = 18.66, p < .001, \eta^2_p = .31 (d = .28) \), respectively. Moreover, there was a significant interaction between Testing time and Group, \( F(2, 42) = 4.46, p < .05, \eta^2_p = .17 \). A planned comparison showed a greater reduction of overall reaction times in the coordination training group than in the cardiovascular training group, \( F(1, 42) = 7.51, p < .01, \eta^2_p = .15 (d = .50) \), and in the control group, \( F(1, 42) = 5.13, p < .05, \eta^2_p = .11 (d = .39) \). There was no significant difference between the cardiovascular training group and the control group (\( p > .95 \)).

**Error rates.** We found a significant main effect of Trial type, \( F(2, 42) = 8.21, p < .001, \eta^2_p = .28 \), revealing significant general switch costs, \( F(1, 42) = 16.10, p < .001, \eta^2_p = .28 (d = .29) \), but no specific switch costs (\( p = .06 \)) (see Fig. 3). Furthermore, there was a marginally significant interaction between Testing time and Trial type, \( F(2, 42) = 3.2, p = .05, \eta^2_p = .13 \), indicating that general but not specific switch costs improved over time (\( F(1, 42) = 6.17, p < .05, \eta^2_p = .13 (d = .21) \) and \( F(1, 42) = 22, p = .64, \eta^2_p = .01 \), respectively). No further effects reached significance (all \( p's > .13 \)).

**Verbal working memory.** We found a marginally significant main effect of Testing time, \( F(1, 42) = 3.85, p = .06, \eta^2_p = .08 (d = .18) \), indicating that the participants improved their performance from pretest to posttest. The main effect of Group (\( p = .62 \)) and the interaction between Testing time and Group were not significant (\( p = .86 \)).

**Spatial working memory.** The overall ANOVA neither showed a main effect of Testing time and Group nor an interaction between Testing time and Group (all \( p's > .13 \)).

**Visuo-spatial ability.** The ANOVA showed a significant main effect of Testing time, \( F(1, 42) = 3.85, p = .06, \eta^2_p = .08 (d = .29) \), pointing to improved performance from pretest to posttest, but no main effect of Group (\( p = .14 \)) and no interaction between Testing time and Group (\( p = .17 \)).

**Fluid intelligence.** The ANOVA revealed a significant main effect of Testing time, \( F(1, 42) = 22.2, p < .001, \eta^2_p = .35 (d = .23) \), indicating that participants improved from pretest to posttest, but no main effect of Group (\( p = .32 \)) and no interaction between Testing time and Group (\( p = .89 \)).

### 3.2. Experiment 2

All analytic strategies were the same as in Experiment 1.

**3.2.1. Training effects**

**Coordination training group.** The analyses revealed significant training-related improvements in all three exercises (exercise 1: \( t(15) = -21.61, p < .001, d = 3.94 \); exercise 2: \( t(15) = -2.65, p < .001, d = 1.45 \); exercise 3: \( t(15) = -12.19, p < .001, d = 2.57 \) (see Table 2).

**Cardiovascular training group.** The imputation of missing data...
and the analytic strategy was the same as in Experiment 1. There were 6.25% missing values. A paired t-test revealed a significant training effect with an increase in aerobic endurance ($t(15) = -3.8, p < .01, d = .28$) (see Table 2).

3.2.2. Analyses of pretest data

There were no significant group differences except for error rates in task switching, $F(2, 43) = 3.76, p < .05, \eta^2_p = .15$. Error rates were significantly higher in the cardiovascular training group than in the control group and in the coordination training group (both $p < .05$).

3.2.3. Transfer to coordination abilities

For technical reasons, there were three missing values (3.3%) for posttest data but they occurred completely at random (Little’s MCAR test: all $p’s > .05$). We therefore imputed missing data using the expectation-maximization (EM) algorithm in SPSS 19. We found a main effect of Testing time, $F(1, 43) = 22.12, p < .001, \eta^2_p = .34$ ($d = .37$), indicating that coordination performance improved from the first session to the last session (see Fig. 1). The main effect of Group ($p = .34$) and the interaction between Testing time and Group ($p = .62$) were not significant. Data of all transfer measures are shown in Table 4.

3.2.4. Transfer to cognitive abilities

3.2.4.1. Inhibitory control. Latencies. We found a significant main effect of Testing time, $F(1, 43) = 4.88, p < .05, \eta^2_p = .11$ ($d = .10$), indicating that participants responded faster at posttest than at pretest. The main effect of Trial type pointed to reliable interference costs, $F(1, 43) = 30.95, p < .001, \eta^2_p = .42$ ($d = .15$). Moreover, we found a marginally significant interaction between Testing time, Trial type and Group $F(2, 43) = 2.64, p = .08, \eta^2_p = .11$. A planned comparison showed a larger pretest-to-posttest reduction of interference costs in the coordination training group than in the cardiovascular training group and the control group, $F(1, 43) = 4.97, p < .05, \eta^2_p = .10$ ($d = .26$) (see Fig. 2). No further effects reached significance (all $p’s > .31$).

Error rates. We found a significant main effect of Trial type, $F(1, 43) = 25.68, p < .001, \eta^2_p = .37$ ($d = .44$). No further effects reached significance (all $p’s > .13$).

3.2.4.2. Task switching

Latencies. The overall ANOVA showed a main effect of Testing time, $F(1, 43) = 22.76, p < .001, \eta^2_p = .35$ ($d = .19$), indicating that participants responded faster at posttest than at pretest and a main effect of Trial type, $F(2, 42) = 41.8, p < .001, \eta^2_p = .66$, revealing significant general and specific switch costs ($F(1, 43) = 77.32,$

<table>
<thead>
<tr>
<th>Measure</th>
<th>Pretest M (SD)</th>
<th>Posttest M (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coordination TG</td>
<td>Cardiovascular TG</td>
</tr>
<tr>
<td>Coordination transfer task</td>
<td>2.62 (.34)</td>
<td>1.94 (3.0)</td>
</tr>
<tr>
<td>Inhibitory control</td>
<td>3.93 (.44)</td>
<td>3.23 (.43)</td>
</tr>
<tr>
<td>Interference effect (ms)</td>
<td>40.18 (73.69)</td>
<td>15.47 (26.49)</td>
</tr>
<tr>
<td>Interference effect (error rates)</td>
<td>2.91 (6.02)</td>
<td>4.50 (5.39)</td>
</tr>
<tr>
<td>Task switching</td>
<td>196.35 (175.24)</td>
<td>208.18 (157.24)</td>
</tr>
<tr>
<td>GSC (ms)</td>
<td>163.65 (138.39)</td>
<td>130.20 (168.32)</td>
</tr>
<tr>
<td>SSC (ms)</td>
<td>1.76 (3.98)</td>
<td>4.82 (8.64)</td>
</tr>
<tr>
<td>GSC (error rates)</td>
<td>3.13 (4.75)</td>
<td>4.30 (6.74)</td>
</tr>
<tr>
<td>SSC (error rates)</td>
<td>5.56 (1.86)</td>
<td>5.12 (2.30)</td>
</tr>
<tr>
<td>Verbal WM</td>
<td>4.56 (1.36)</td>
<td>4.06 (1.84)</td>
</tr>
<tr>
<td>Spatial WM</td>
<td>10.25 (5.69)</td>
<td>12.25 (5.70)</td>
</tr>
<tr>
<td>Visuo-spatial ability</td>
<td>18.62 (5.84)</td>
<td>21.5 (6.68)</td>
</tr>
<tr>
<td>Fluid intelligence</td>
<td>20.88 (5.21)</td>
<td>21.38 (7.73)</td>
</tr>
</tbody>
</table>

Note. Values for the coordination transfer task refer to the level of task difficulty; values for task switching and interference control refer to reaction times and error rates; values for the remaining tasks refer to the number of correctly solved items. GSC = general switch costs; SSC = specific switch costs; TG = training group; WM = working memory.
of Testing time, effect of Testing time, (all effects of Testing time and Group nor an interaction between them) (all $p > .23$), but not specific switch costs ($p = .23$). No further effects reached significance (all $p > .05$).

**Error rates.** We found a significant main effect of Trial type, $F(2, 42) = 8.98$, $p < .01$, $n_g^2 = .30$, and a significant interaction between Testing time, Trial type, and Group $F(4, 86) = 2.98$, $p < .05$, $n_g^2 = .12$. For specific switch costs, planned comparisons showed larger performance improvements in the cardiovascular training group than in the control group, $F(1, 43) = 6.61$, $p < .05$, $n_g^2 = .13$ ($d = .16$) and marginally larger performance improvements in the coordination training group than in the control group, $F(1, 43) = 2.88$, $p = .097$, $n_g^2 = .06$ (see Fig. 3). The reduction of general switch costs was larger in the cardiovascular training group than in the control group, $F(1, 43) = 6.08$, $p < .05$, $n_g^2 = .12$ ($d = .44$), but there was no difference between the coordination training group and the control group ($p = .78$). No further effects reached significance (all $p > .05$).

**Verbal working memory.** We neither found significant main effects nor an interaction (all $p > .15$).

**Spatial working memory.** The ANOVA neither showed main effects of Testing time and Group nor an interaction between them (all $p > .47$).

**Visuo-spatial ability.** The ANOVA showed a significant main effect of Testing time, $F(1, 43) = 17.85$, $p < .001$, $n_g^2 = .29$ ($d = .17$), but no significant main effect of Group ($p = .65$) and no significant interaction between Testing time and Group ($p = .22$).

**Fluid intelligence.** There was a marginally significant main effect of Testing time, $F(1, 43) = 3.95$, $p = .05$, $n_g^2 = .08$, but no significant main effect of Group ($p = .30$). Furthermore, there was a marginally significant interaction between Testing time and Group, $F(2, 43) = 2.71$, $p = .08$, $n_g^2 = .11$. Further analyses did not reveal a difference between the coordination training group and the control group ($p = .12$), between the cardiovascular training group and the control group ($p = .57$), or between the two training groups ($p = .26$).

### 4. Discussion

The primary aim of this study was to investigate the transfer of two types of physical training (motor-cognitive coordination training and cardiovascular training) to coordination abilities and cognitive functions in younger adults as compared to a passive control group.

First, the analysis of training data revealed training-related performance improvements in both experiments and after both types of training. Consistent with prior studies (Ferguson, Jelsma, Jelsma, & Smits-Engelsman, 2013; Niemeijer, Smits-Engelsman, & Schoemaker, 2007) participants in the coordination training group improved their coordination performance in all three training exercises. Participants in the cardiovascular training group increased their maximal training resistance from the beginning to the end of the training as it had been demonstrated previously (e.g., Colcombe et al., 2004; Hötting et al., 2012; Jones & Carter, 2006).

Second, we tested for transfer of the coordination training to a structurally similar, untrained coordination task after training. Practicing coordination tasks should train different motor and higher cognitive processes resulting in performance improvements in an untrained coordination task (Voelcker-Rehage & Niemann, 2013). As expected, transfer to an untrained exercise was more pronounced in the coordination training group than in the control group in physically active participants (Experiment 1). In Experiment 2 (sedentary participants), we found no evidence for transfer to the structurally similar coordination exercise, suggesting that physically inactive participants might need a more extensive coordination training to show improvements in untrained coordination tasks.

The third aim of this study was to investigate transfer of the two types of physical training to cognitive functions. In Experiment 1, we found no training-specific transfer to inhibitory control, cognitive flexibility, visuo-spatial ability, verbal working memory, spatial working memory, and fluid intelligence.

Regarding inhibitory control and cognitive flexibility, our findings are consistent with the result from Hötting et al. (2012), who compared the effects of six-month coordination/stretching training to the effects of cardiovascular training in middle-aged adults. Despite the large training period, none of the groups showed larger performance improvements in executive functions than a control group. In contrast, Colcombe and Kramer (2003) provided evidence for positive effects of cardiovascular training especially in the domain of executive control. However, Colcombe and Kramer included in their meta-analytic study only studies conducted with sedentary, older adults. Furthermore, they stated that the magnitude of fitness effects on cognition was also moderated by a number of factors including the length of the fitness training intervention, the type of the intervention and the duration of training sessions. According to their classification, the length of the exercise intervention in our study was short (1–3 month) and the duration of the training sessions moderate (31–45 min). In our study, participants’ young age, their fitness status, the length of exercise and the moderate training intensity may explain the lack of broader transfer effects to executive functions in experiment 1.

Previous studies revealing positive transfer of physical activity training to visuo-spatial ability were almost exclusively conducted with older adults (Colcombe & Kramer, 2003), which may have lowered the threshold for demonstrating training-related changes because their visuo-spatial ability has already declined providing room for compensatory effects.

Furthermore, we found no transfer of the cardiovascular training or the coordination training to fluid intelligence. This finding is in line with results from meta-analyses reporting no relationship between physical activity and reasoning (Etter et al., 1997; Etter, Nowell, Landers, & Sibley, 2006). Finally, results from the switching task did not reveal a significant reduction of switch costs after the training (cf. Zinke, Einert, Pfennig, & Kliegl, 2012), but we found a larger reduction of general reaction times in the coordination group as compared to the remaining groups, indicating that the coordination training improved the speed of responding in the switching task.

In experiment 2, results concerning working memory, visuo-spatial ability, and fluid intelligence were the same as in experiment 1. There were no training-dependent transfer effects after coordination training and cardiovascular training to those abilities. In contrast, analyzing inhibitory control and cognitive flexibility revealed several important new insights. First, there was a significantly larger reduction of interference costs after the coordination training than after the cardiovascular training and the control condition. Our finding is consistent with the result from Voelcker-Rehage et al. (2011), who provided evidence for improvements in inhibitory control after coordination but also after cardiovascular training. However, the study was conducted with older adults aged 62–79 years who were trained over 12 months. Second, specific switch costs on the basis of error rates were reduced after coordination and cardiovascular training as compared to the control condition, indicating that the ability to flexibly switch between tasks improved after the training. General switch costs on the basis of accuracy were reduced after cardiovascular training as compared to the coordination training and the control condition, indicating
that the ability to maintain task sets in working memory and to select between them improved after the training. Experiment 2 was conducted with physically inactive individuals, suggesting that physical training of the length and intensity applied in the present study can be effective at least in physically untrained participants. This finding is consistent with results from cognitive training research, indicating that training-induced performance gains are often related to participant’s initial performance at baseline (pre-test). For instance, process-based cognitive training from the domain of executive control or working memory often resulted in larger gains in individuals with poor initial performance than in participants with high initial performance (e.g., Bherer et al., 2008; Cepeda, Kramer, & Gonzalez de Sather, 2001; Karbach & Kray, 2009; Zinke et al., 2014; for reviews, see Karbach & Unger, 2014; Karbach & Verhaeghen, 2014).

4.1. Limitations

This study provided new insights into the effect of coordination training on cognitive abilities. However, we could not find transfer effects of cardiovascular training and motor-cognitive coordination training to all investigated cognitive abilities. Furthermore, the magnitude of transfer effects to inhibitory control and cognitive flexibility in sedentary participants (experiment 2) and the magnitude of transfer effect to an untrained exercise in physically active participants (experiment 1) were low to moderate. There are some limitations that may explain the lack of broader effects and the magnitude of the transfer effects.

First, we examined young adults, who were probably at the top of their cognitive abilities and thereby had less room for improvement than the children and older adults examined in most of the previous studies (Salthouse & Davis, 2006). Especially participants in the physically active group (Experiment 1) may have exhibited less training-related benefits because they already performed better than the sedentary group in terms of task switching, inhibition and coordination abilities at pretest: Error rates in the switching task as well as specific switch costs were significantly higher in the sedentary group than in the physically active group ($F(1, 90) = 6.76, p < .05$ and $F(1, 90) = 4.91, p < .05$), error rates in congruent trials in the inhibition task were marginally higher in the sedentary group than in the physically active group ($F(1, 90) = 3.33, p = .07$), and the physically active group also outperformed sedentary participants in the motor-cognitive coordination task ($F(1, 90) = 15.21, p < .001$). Another explanation might be that exercising was more challenging for sedentary participants because they were not accustomed to cardiovascular and coordination training, thereby benefitting cognitive abilities.

Second, our intervention included only six weeks of training. There is some evidence that physical training has to be more intensive to yield transfer on cognitive abilities (e.g., Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012). In fact, many previous studies reporting transfer of physical training to cognitive performance have trained participants over several months up to a year (e.g., Holting et al., 2012; Voelcker-Rehage et al., 2011). Aside from the number of training sessions and the duration of the intervention, an adjustment of the training intensity to the initial cardiovascular fitness status might be an important factor affecting training-induced improvements in cognitive abilities. Since both training types should be comparable and coordination training was not adjusted to participants’ initial coordination abilities, cardiovascular training intensity was also not adjusted to participants’ initial cardiovascular fitness level. An individually adjusted cardiovascular and coordination training by means of an endurance test and a more extensive coordination pretest might have induced larger improvements in cognitive and coordination abilities.

4.2. Conclusion

To summarize, the results of this study showed that coordination and cardiovascular training can improve different cognitive functions in physically inactive young adults. Especially, executive functions like inhibitory control and cognitive flexibility were improved after the training. Coordination training resulted in larger gains than moderate cardiovascular training in terms of inhibitory control. In sum, these findings suggest that coordination training may be a useful intervention in sedentary populations. It may also be an appropriate intervention for individuals that cannot perform cardiovascular training. Future studies should investigate the impact of more intensive training regimes and the effects in different age groups.

Note. Values for the coordination transfer task refer to the level of task difficulty; values for task switching and interference control refer to reaction times and error rates; values for the remaining tasks refer to the number of correctly solved items. GSC = general switch costs; SSC = specific switch costs; TG = training group; WM = working memory.

Acknowledgment

We would like to thank Jessica Baumgartner, Lisa Degen, Frank Engel, Pascal Meiser and Andreas Janto for their support recruiting and testing the participants and Oliver Michaely for his expert comments on choosing and implementing the coordination training tasks.

References


Shors, T. J. (2013). Training your brain: do mental and physical (MAP) training enhance cognition through the process of neurogenesis in the hippocampus? *Neuropsychopharmacology, 64*, 506–514.


