Effects of Motor versus Cardiovascular Exercise Training on Children's Working Memory

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ABSTRACT

KOUTSANDRÉOU, F., M. WEGNER, C. NIEMANN, and H. BUDDE. Effects of Motor versus Cardiovascular Exercise Training on Children's Working Memory. *Med. Sci. Sports Exerc.*, Vol. 48, No. 6, pp. 1144–1152, 2016. **Purpose**: The aim of this investigation was to examine the influence of different types of exercise exertion on primary school children's working memory (WM). **Methods**: Participants (N = 71, 9.4 yr, 39 girls) were randomly assigned to a cardiovascular exercise (CE), a motor exercise (ME), or a control group (CON). They underwent a letter digit span task (WM) before and after an intervention period that involved 10 wk of an additional afterschool exercise regimen, which took place three times a week for 45 min. Students in the control group participated in assisted homework sessions. **Results**: WM performance of the 9- to 10-yr-old children benefited from both the cardiovascular and the motor exercise programs, but not from the control condition. The increase in WM performance was significantly larger for children in the ME compared with the CE or CON. **Conclusion**: These findings add to the knowledge base relating different types of exercise and WM. Besides the efficiency of cardiovascular exercise training, a special motor-demanding intervention seems to be a beneficial strategy to improve WM in preadolescent children. **Key Words:** EXERCISE TYPES, BILATERAL COORDINATION, EXECUTIVE FUNCTIONS, COGNITION, PHYSICAL ACTIVITY, LONGITUDINAL INTERVENTION

Only an average of 18% of children in Europe meet the World Health Organization's physical activity (PA) recommendations (22). However, an active lifestyle contributes significantly to health and the prevention of diseases (19) and has been further linked to an adequate development of motor and cognitive functions (14). Especially in children, cognitive functions seem to benefit from PA, with their highly plastic brains as one possible explanation (39). As a key aspect of cognitive functioning, working memory (WM) reflects the ability to hold and manipulate information to regulate thoughts and behavior (11). WM performance (WMP) was shown to predict academic performance such as math in preadolescent school children (e.g., [15]). Findings suggest that prolonged PA participation supports improvements in WM (e.g., [18,20,32]). Especially in children, it was shown that WM capacity is the only executive function to benefit from chronic exercise (18). Therefore WMP is a crucial cognitive aspect in children for success in school. Although more investigations have emerged in the last decade, the specific effects of qualitatively different PA programs on cognition in children still remain unknown. Several previous investigations of children showed the effect of cardiovascular fitness and/or cardiovascular exercise on cognitive functions (20,32). Other exercise types, like motor exercise, have been studied in cross-sectional studies so far (25,33), but sufficiently controlled intervention studies on the chronic exercise effect for this age group are missing. With motor-demanding exercise in the present study, we are referring to coordinative exercise or motor coordination, respectively, as used elsewhere (5,33,42).

A recent study of 9- to 10-yr-old children (32) showed the relationship between cardiovascular fitness and cognition using a task requiring key components of WM. However, this study was cross-sectional in nature and therefore it is difficult to infer from the results whether there is a directional link between cardiovascular exercise and WM. The only longitudinal study in this context investigated the effects of a 9-month randomized controlled exercise intervention on the changes in WMP in preadolescent children compared with a waiting list control group (20). Participants took part in a 2-h multifaceted afterschool program daily, which included 70 min of moderate to vigorous exercise focused on cardiorespiratory fitness. Additionally, muscle fitness was addressed at least two times a week. Refinement of motor skills was also included in the intervention. The

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study found an increase in WMP for the intervention group. Nonetheless, the effect of the different exercise components remains unclear, especially what effect the motor exercise had in contrast to the cardiovascular exercise components.

This leads to the question whether increases in cardiovascular fitness through cardiovascular exercise are crucial to achieve cognitive benefits or if there are also other types of PA that may moderate the exercise–cognition link.

The first results in this area from 2008 revealed that highly demanding acute bilateral motor exercise (example tasks including balancing, reacting to, adjusting to, and differentiating between various objects) improves adolescents' attention capacity to a higher degree than acute exercise without specific motor requests (5). The results indicate that different PA interventions might have different effect on cognition in children, and this may have to do with the extent to which motor-demanding activities are included (e.g., bimanual coordination, eye–hand coordination, and rhythmic movements) (for review, see [13]). Findings of a recent cross-sectional study revealed that children with higher motor coordination abilities performed better on cognitive tasks than children exhibiting lower levels of motor abilities (25). This link is also supported by a study on motor coordination and academic achievement using correlational data of adolescents (33). The structural equation model shows that motor coordination (especially aiming and catching skills) has an indirect effect on academic outcomes via WM.

The observed effects from a single exercise bout cannot be used to infer the effects from an extended exercise program. With regard to cross-sectional studies, it is difficult to make causal inference because it is unknown if the parameter itself (e.g., being cardiovascularly fit) caused the benefit (e.g., enhanced cognition) or if other factors might have accounted for the resultant differences. Thus, it remains unclear whether an improvement in motor fitness is responsible for better cognitive functions.

In a recent longitudinal study, 9- to 10-yr-old children were assigned to either a 6-month cardiovascular exercise regimen, including motor and cognitive-demanding activities, or curricular physical education only (9). Intervention effects on cognitive functions were only found in participants of the motor and cognitive-demanding exercise group. The findings were not mediated by cardiovascular fitness gains. However, the effect appeared to be isolated to overweight children and the study was not sufficiently controlled in that there was no inactive control group (9).

The suggested motor–cognition link is supported by the recruitment of neural regions during performance of motor tasks, which are typically associated with cognitive operations (5,10,33). This earlier suggestion is now supported by neuroimaging techniques, which show that there is a closely coupled activation of the prefrontal cortex and the cerebellum, which are both related to motor and cognitive skills (24,36). This activation suggests that motor exercise leads to specific adaptation of respective brain areas, which might benefit cognition more than mere cardiovascular exercise.

The mechanisms underlying the relationship between exercise and enhanced cognitive functions are diverse and need further investigation but are not part of the present investigation.

The limited interpretation of earlier findings (largely due to poor standardization or insufficient experimental designs) indicates the need for longitudinal investigations on the link between chronic exercise and children's cognition.

Long-term positive lifestyle changes, e.g., being more active, offer a possible explanation for enhanced cognitive processes. Because most children spend a majority of their active day at school, schools are highly relevant to the promotion of a healthy lifestyle through additional PA interventions. Further, schools seem to be the optimal environment for implementing longitudinal PA studies of children (for an overview, see [27]).

Although a few studies vaguely suggested that motor exercise may benefit WMP in children and adolescents, no randomized controlled study has been reported so far that directly compared the effects of motor versus cardiovascular exercise in children and adolescents in a longitudinal design, despite several calls for such intervention studies (2,12,13,30). Thus, the purpose of this study was to compare the WMP effects of additional cardiovascular exercise with exercise with high motor demands in 9- to 10-yr-old school children. With regard to the current literature, it was predicted that both cardiovascular- and motor-demanding exercises enhance children's WMP. Because the execution of highly motor-demanding movements involves the cerebellum and the prefrontal cortex (1,5) and because of initial evidence of acute and cross-sectional studies in the motor cognition area, the second hypothesis was that motor-demanding exercise enhances WMP to a larger extent than cardiovascular exercise.

MATERIALS AND METHODS

Participants. Seventy-one healthy elementary school children (third grade and fourth grade) from three different schools in two small towns in Westphalia, Germany, age 9–10 yr participated in this study (39 girls; mean age, 9.35 yr; SD = 0.6). The students were randomly assigned to one of two experimental groups or a control group (CE, cardiovascular exercise group, $n = 27$; ME, motor exercise group, $n = 23$; CON, control group, $n = 21$). The participants and their parents signed an informed consent waiver before inclusion approved by the ethics committee of the German Psychological Society. The study was performed in accordance with the declaration of Helsinki. Other inclusion criteria for study participation were the absence of mental or physical impairments (like obesity) and no history of psychoactive substances (e.g., Ritalin). One of the initial 99 participants had to be excluded on the basis of these criteria. Further, 27 participants had to be excluded because of missing at least one testing day or not attending at least 75% of the intervention sessions. Thus, the final sample included 71 children. Participants, together with their parents, completed the Tanner staging system (38) to make sure that their pubertal status was at or below a score of 2 (i.e. prepubescent) on a five-point scale.

Procedures. One week before the baseline testing, subjects performed a motor fitness test (Heidelberg Gross Motor Test [26]) and a cardiovascular fitness test (20-m Shuttle Run Test [4]). The assessment of cardiovascular and motor fitness served to determine the individual's maximum HR (HR_{max}) to control exercise intensity during the intervention and to monitor the effects of cardiovascular and motor fitness on WMP. At the baseline testing day, each participant completed the cognitive testing. One week before the last intervention, the fitness tests had to be performed again, and on the last day of intervention, participants attended posttest assessments, which were identical to the baseline assessments. Outcome assessors were blinded to group assignment throughout all testing procedures.

Intervention. The 10-wk intervention took place between January and April 2014 and did not include uncontrollable periods like holidays. Interventions took place three times per week for 45 min after school and were led by an experienced exercise instructor in groups of 7–14 participants.

The cardiovascular exercise program focused on improvement of cardiovascular fitness through running and running-based games of moderate to vigorous intensity (recorded on three occasions by F1 Polar HR monitors; Polar, Kempele, Finland) without any high motor demand.

The motor-demanding exercise program focused on the improvement of fine and gross motor body coordination through playful balance, bilateral coordination, hand–eye coordination, and leg–arm coordination exercises as well as spatial orientation and reaction to moving objects/persons. The exercise program was highly variable and designed to be constantly challenging for the participants to prevent automation. Different balls, rackets, skipping ropes, speed ladders, balloons, and balance pads were used as the equipment.

In the control condition, participants took part in assisted homework sessions to prevent attention bias and to control for retest effects.

Assessments. The cardiovascular and motor fitness assessments served as manipulation checks to assess the physical training effects. The cardiovascular exercise intervention was intended to improve cardiovascular fitness, and the motor training was intended to improve motor fitness, whereas activities of the CON should not improve results in either metric.

Cardiovascular fitness test. The Shuttle Run Test is a standard method for determining cardiorespiratory fitness in school children and can be used for a reliable and valid estimation of the maximal oxygen uptake ($\dot{V}O_{2max}$) in children (9). In accordance with the standardization used elsewhere (40), the children ran back and forth continuously between two lines set 20 m apart, with an initial speed of 8.0 $km \cdot h^{-1}$, increasing the level by 0.5 $km \cdot h^{-1}$ each minute. Acoustic signals in a given frequency were used to control the pace, and subjects had to reach the line in time for each signal. The test was terminated when a child could not maintain the pace for two consecutive signals. We determined the HR_{max} as well as the maximum score reached, which is the level and number of shuttles reached before being unable to keep up the pace.

Motor fitness test. The Heidelberg Gross Motor Test (Heidelberger großmotorischer Geschicklichkeitstest [26]) was applied to measure children's gross motor skills. The test includes motor skill-based tasks such as balance, rhythm, spatiotemporal orientation, and motor adaption to moving objects. We included the performance of six motor tasks that were quantitatively measurable and calculated a sum score. In the first task, children had to perform a somersault while running. The participants had to run on a mat, jump over a small box, turn, and on the way back perform a somersault on the mat. In this task, the time was measured. The second task included balancing on an upside down gym bench and doing a 360° turn while transporting two volleyballs with arms outstretched. The fastest time out of three trials was used in the sum score calculation. The third task was a 12-m run, in which two steps of running were followed by a 180° turn also including two steps. An 80-cm-wide straight corridor defined the boundaries allowed for the task. Time was measured and penalties were applied for traveling violations and for trespassing mistakes. The fourth task included throwing a ball backward through straddled legs against a 3-m distant wall (five repetitions). Successfully catching the rebounding ball earned two points, whereas an active touch or dropping it earned only one point. The fifth task included single-legged hopping along an 8-m-long, 20-cm-wide line. While hopping, participants had to reach their right hand under the left arm to touch their left ear and point to the line using their left index finger. Time was measured and penalties were applied for trespassing mistakes and for violation of arm position. The sixth and last task included bouncing a ball while balancing on an upside down gym bench. The fastest time out of three trials was used for analysis.

Letter Digit Span. The Letter Digit Span (LDS [16]) was applied to measure children's WMP. The task involves a standardized auditory presentation of an increasing mixed series of alternating numbers and letters. After an acoustic signal, each participant was asked to respond by first writing the numbers in order from the smallest to the largest, followed by writing the letters in alphabetical order. For example, a participant audibly presented with "w7t4" would be expected to write down "47tw." After a series of practice trials, the test involved four trials at each string length, beginning with two-item strings (such as "m3") incrementing up to seven-item strings (such as "c7g4qls") for a total of 24 trials. The total number of correct responses (of 24 possible) was used for the analyses. The internal consistency of the LDS was documented at Cronbach's alpha of 0.85 (16). In our study, the internal consistency was satisfactory with 0.88. As described in the above study design, the LDS was completed two times (before and after the intervention).

During the test, students were not allowed to talk to each other and they were asked to remain silent to prevent any possible interference by other students.

Statistical analysis. Data were analyzed using 2 × 3 repeated-measures ANOVA with time (pre- and posttest) as the within-subject variable and group (CE, ME, and CON) as the between-subject variable for each dependent measure. Partial η^2 effect sizes were calculated, expressing the amount of variance explained in the dependent variables by the respective effect. $\eta^2 \geq 0.01$ indicates a small effect, ≥0.059 a medium effect, and ≥0.138 a large effect, respectively (8). Planned contrasts were conducted to determine pre- to posttest changes within and between the experimental and control groups. Effect sizes for pairwise comparisons were reported in terms of Pearson's correlation coefficient r, with $r = 0.1$ indicating a small relationship, $r = 0.3$ a moderate relationship, and $r = 0.5$ a strong relationship. In a supplementary analysis, the differences between post- and pre-WMP have been compared conducting ANOVA and planned contrasts.

RESULTS

Preliminary Analyses

Descriptive data are presented with means and SD in Table 1. Experimental groups (cardiovascular exercise group (CE) and motor exercise group (ME)) and the control group (CON) were statistically similar to one another on measures of anthropometrical data, pubertal status, and fitness (Table 1). These measures had no significant effect on the results reported below, and therefore, we abstained from including them as covariates. There were no group differences in the baseline measures for motor fitness ($F(1,68) = 1.276$, $P = 0.286$, $\eta^2 = 0.036$), cardiovascular fitness ($F(1,68) = 1.207$, $P = 0.306$, $\eta^2 = 0.034$), or WMP ($F(1,68) = 1.897$, $P = 0.158$, $\eta^2 = 0.055$) (Table 1). Furthermore, groups were statistically similar to one another regarding the attendance rate (Table 2).

Because of the different exercise modes, the exercise intensity of the different groups as measured by HR differed (Table 2; $F(2,64) = 4.926$, $P < 0.010$, $\eta^2 = 0.133$). The CE ($t(45) = 27.270$, $P < 0.001$, $r = 0.98$) and ME ($t(35) = 17.750$, $P < 0.001$, $r = 0.95$) significantly differed regarding average HR during the intervention when compared with the CON. Moreover, the average HR in the CE was significantly higher than that in the ME ($t(43) = 4.696$, $P < 0.001$, $r = 0.58$). We conducted both ANCOVA including participants' average HR as covariates and ANOVA without this covariate. Both analyses yielded similar results regarding the effects on WM and fitness. For the Results section, we report the ANOVA without average HR as covariates. To compare the efficiency of the intervention programs, we analyzed the effects on cardiovascular and motor performance for all three groups.

Motor fitness had no significant effect on the cardiovascular fitness performance; therefore, we abstained from

TABLE 1. Mean (SD) values for the anthropometrical, fitness data, and pubertal status.

	Age (yr)		Height (cm)				Weight (kg)				Shuttle Run (Level Reached)				Shuttle Run (HR_{max})				HGT (Sum Score)				Tanner (Score)			
		(SD)	Pretest	(SD)	Posttest	(SD)	Pretest	(SD)	Posttest	(SD)	Pretest	(SD)	Posttest	(SD)	Pretest	(SD)	Posttest	(SD)	Pretest	(SD)	Posttest	(SD)	Pretest	(SD)	Posttest	(SD)
CE	9.3	(0.6)	136	(7)	138	(8)	33.6	(9.1)	33.9	(9.3)	5.3	(1.9)	5.9	(1.8)	203	(13)	205	(10)	540	(52)	576	(45)	1.1	(0.4)	1.2	(0.6)
ME	9.4	(0.7)	138	(7)	140	(9)	33.6	(9.4)	33.8	(9.3)	5.4	(2.0)	5.6	(1.8)	208	(12)	207	(10)	561	(34)	598	(39)	1.1	(0.5)	1.2	(0.6)
CON	9.3	(0.6)	141	(6)	142	(6)	33.4	(4.6)	33.9	(4.7)	6.1	(1.5)	6.1	(1.6)	213	(10)	213	(9)	552	(54)	565	(46)	1.3	(0.6)	1.2	(0.4)
Overall	9.4	(0.6)	138	(7)	140	(8)	33.5	(8.0)	33.9	(8.1)	5.6	(1.8)	5.9	(1.7)	207	(13)	208	(10)	550	(48)	580	(45)	1.2	(0.5)	1.2	(0.6)

HGT, Heidelberg Gross Motor Test.

APPLIED SCIENCES

TABLE 2. Mean (SD) values for attendance rate and exercise intensity.

	Attendance Rate (%)		Exercise Intensity (Mean HR)	
	Mean	(SD)	Mean	(SD)
CE	94.2	(4.1)	138.8	(9.1)
ME	93.8	(4.5)	125.4	(10.8)
CON	93.5	(4.8)	79.4	(5.9)
Overall	93.8	(4.4)	116.9	(26.6)

including covariates. With an average HR of 139 ± 9.1 bpm (Table 2), children of the CE group remained in the range of 60%–70% of HR_{max} (128–149 bpm).

Cardiovascular performance. For cardiovascular performance, we found a significant main effect for time ($F(1,68) = 10.030$, $P = 0.002$, $\eta^2 = 0.129$) as well as a time–group interaction effect ($F(2,68) = 4.432$, $P = 0.016$, $\eta^2 = 0.115$). There was no effect for the group ($F(1,68) = 0.638$, $P = 0.531$, $\eta^2 = 0.018$). Only participants in the CE significantly improved their cardiovascular performance with a large effect ($F(1,25) = 12.535$, $P = 0.002$, $r = 0.58$) (Table 1 and Fig. 1). No significant changes could be observed in the ME ($F(1,22) = 1.570$, $P = 0.223$, $r = 0.26$) or the CON ($F(1,20) = 0.002$, $P = 0.963$, $r = 0.01$). The cardiovascular performance at the posttest did not differ between any of the groups: CE compared with CON ($t(67) = -0.330$, $P = 0.743$, $r = 0.04$), ME compared with CON ($t(67) = -0.827$, $P = 0.411$, $r = 0.10$), or CE compared with ME ($t(67) = -0.534$, $P = 0.595$, $r = 0.07$). Confirming the efficacy of the cardiovascular exercise intervention, children in the CE benefited significantly through their participation in the additional cardiovascular exercise regarding their cardiovascular fitness. This was not the case in the ME or the CON.

Cardiovascular fitness had no significant effect on the motor fitness performance; therefore, we abstained from including covariates. With an average HR of 125 ± 10.8 bpm, children of the ME remained in the range of 55%–65% of HR_{max} (117–139 bpm).

Motor performance. For the overall change in motor performance, we found a main effect for time ($F(1,68) = 64.662$, $P < 0.001$, $\eta^2 = 0.487$) and a significant time–group

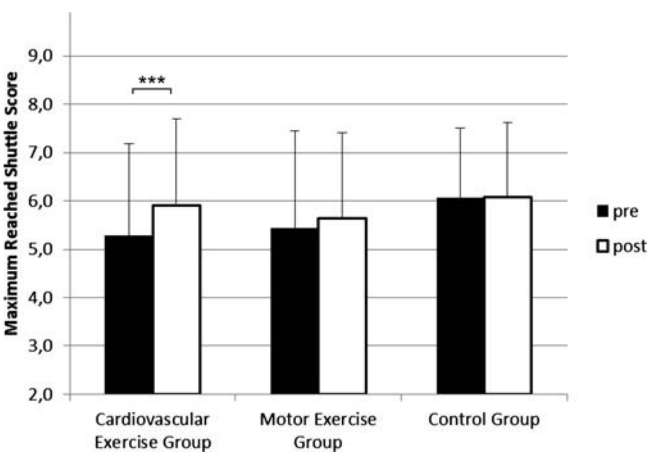

FIGURE 1—Pre- and posttest means of shuttle run performance for cardiovascular exercise, motor exercise, and the control group. ***P < 0.001.

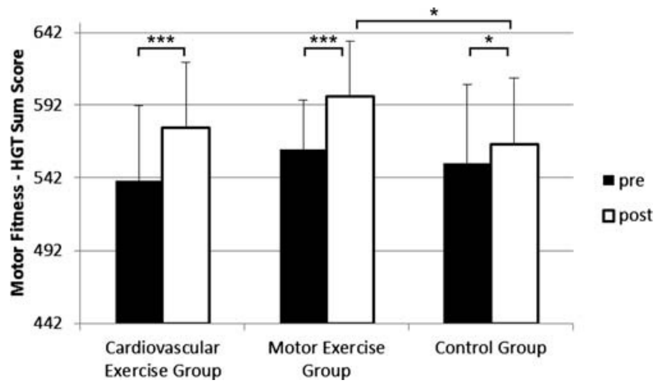

FIGURE 2—Pre- and posttest means of motor task performance for cardiovascular exercise, motor exercise, and the control group. ***P < 0.001, *P < 0.050.

interaction ($F(2,68) = 4.786$, $P = 0.011$, $\eta^2 = 0.123$) (Table 1 and Fig. 2). There was no group effect ($F(1,68) = 1.893$, $P = 0.159$, $\eta^2 = 0.053$). After the intervention, participants in all three groups showed significantly improved motor performance (CE: $F(1,26) = 32.726$, $P < 0.001$, $r = 0.75$; ME: $F(1,22) = 40.571$, $P < 0.001$, $r = 0.81$; CON: $F(1,20) = 4.448$, $P = 0.048$, $r = 0.43$), which can be partly attributed to developmental processes. However, the motor performance score of the ME was significantly higher than that of the CON at posttest ($t(68) = 2.515$, $P = 0.014$, $r = 0.29$), which was not the case for CE compared with CON ($t(68) = 0.912$, $P = 0.365$, $r = 0.11$). The difference between motor performance of CE and ME failed to reach significance ($t(68) = 1.740$, $P = 0.086$, $r = 0.21$).

Effects of Different Exercise Programs on WMP

For WMP, we found a significant effect of time ($F(1,68) = 60.131$, $P < 0.001$, $\eta^2 = 0.469$) (Fig. 3). The interaction effect of group–time was also significant ($F(2,68) = 12.377$, $P < 0.001$, $\eta^2 = 0.267$). There was no GROUP effect ($F(2,68) = 0.221$, $P = 0.803$, $\eta^2 = 0.006$). Planned contrasts identified improvements in WMP from pre- to posttest in the

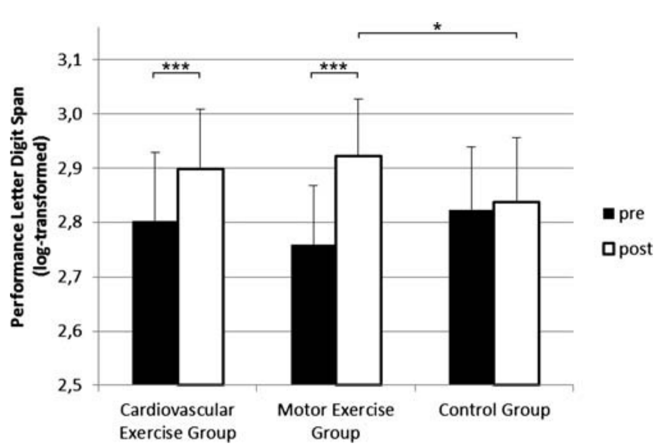

FIGURE 3—Pre- and posttest means of WMP for cardiovascular exercise, motor exercise, and the control group. ***P < 0.001.

two exercise groups with large effect sizes (CE: $F(1,26) = 19.709$, $P < 0.001$, $r = 0.66$; ME: $F(1,22) = 62.718$, $P < 0.001$, $r = 0.86$), but not in the CON ($F(1,20) = 0.769$, $P = 0.391$, $r = 0.19$).

In the postmeasurement, only the ME differed significantly from the CON ($t(68) = 2.521$, $P = 0.014$, $r = 0.29$), but not from the CE ($t(68) = 0.746$, $P = 0.458$, $r = 0.09$), nor did the CE differ significantly from the CON ($t(68) = 1.887$, $P = 0.063$, $r = 0.22$).

Supplementary Analysis

In order to deepen the understanding of the changes in WMP between the groups and to test the second hypothesis, a supplementary analysis was conducted. Therefore, the change of WMP (difference between post- and preperformance) was compared between the groups. There was a significant between-groups effect ($F(2,65) = 11.873$, $P < 0.001$, $\eta^2 = 0.268$), which turned out to be significantly larger in the ME compared with CE ($t(68) = 2.345$, $P = 0.022$, $r = 0.27$), meaning that children in the ME benefited more strongly regarding their WMP from the exercise intervention than children in the CE. Furthermore, the difference of the ME turned out to be significantly larger compared with the CON ($t(68) = 4.971$, $P < 0.001$, $r = 0.52$), and the difference between CE and CON also gained significantly, meaning that children of the CE improved more regarding their WMP when compared with the CON ($t(68) = 2.869$, $P = 0.005$, $r = 0.33$).

DISCUSSION

We investigated the effects of a 10-wk cardiovascular versus motor exercise intervention program on cognitive performance in children age 9–10 yr using a WM task (LDS). The children performed the intervention in addition to their regular physical education regimen, which includes three lessons per week in Germany. Interventions took place three times a week for 45 min, avoiding uncontrollable holiday time. The main finding indicated that WMP of the 9- to 10-yr-old children benefited from both the cardiovascular and the motor afterschool exercise programs. Second, the results illustrate that WMP improved to a larger degree in response to the motor exercise intervention when compared with the cardiovascular intervention.

Effects of motor exercise on WM. The motor performance of the CE, ME, and CON showed significant increases from pre- to posttest, but to a different extent (effect size *r*: CE = 0.75, ME = 0.81, CON = 0.43). Despite the changes in the CON, which seems to reflect a possible developmental influence (17), the motor intervention seemed to be the most efficient. At postmeasurement, only the ME showed a significantly better motor performance compared with the CON.

The motor exercise intervention increased WMP by 49.2% (CON 3.8%), which turned out to be a large effect ($r = 0.86$). Our longitudinal results support a directional relationship between motor and cognitive domains and add evidence to initial cross-sectional and acute intervention results. This is similar to the findings by Rigoli et al. (33) showing that motor coordination (specifically aiming and catching skills) has an indirect effect on academic outcomes via WM.

Our results are also in line with an uncontrolled 8-wk longitudinal study of kindergarten children, which examined the causal link between motor-demanding exercise training and cognitive functioning (7). Their findings support a beneficial effect of coordinative exercise on inhibition in kindergarten children. However, Chang et al. (7) did not include a control group; thus, it is not clear whether the observed improvements in cognitive functions after coordinative exercise can be clearly attributed to the intervention.

The positive link between motor exercise and WM in our study may be explained from a neuroscientific and behavioral learning perspective. The motor exercise intervention was composed of both fine and gross motor body coordination exercises, for example, bimanual coordination tasks, in which the hands performed complex temporal and/or spatial tasks. Such motor tasks were shown to activate neural networks in frontal and parietal areas (34). Training of WM through motor tasks induced positive changes in WM, which similarly could be associated with increases in prefrontal and parietal activity (29). As previously shown in the findings by Serrien et al. (34) and Olesen et al. (29), similar brain regions seem to be involved in both complex motor tasks as well as WM tasks. Furthermore, an increased activation of the cerebellum during the execution of motor-demanding tasks is accompanied by an activation of the prefrontal cortex (for review, see [10]). Such an additional use of this brain region might also facilitate cognitive task processes in the prefrontal cortex (e.g., WMP) as suggested by Budde et al. (5).

Effects of cardiovascular exercise on WM. The 10-wk cardiovascular exercise intervention was designed to enhance cardiovascular fitness through running activities with low demand on complex motor functions. A cardiovascular fitness increase of 11.2% in the CE confirms the efficacy of our cardiovascular exercise intervention. Statistically, this increase represents a large effect ($r = 0.58$).

We found a large positive effect of the cardiovascular exercise intervention on WMP ($r = 0.66$). This is in line with our assumptions from the results of previous cross-sectional studies in children, which have demonstrated that cardiovascular fitness is positively related to cognitive functions in this age group (for review, see [21]). However, the reviewed studies are only cross-sectional in nature or the interventions include exercise types beyond cardiovascular exercise; thus, a causal relationship between cardiovascular fitness and cognitive functions cannot be assumed from these findings (e.g., [20,32]). Although longitudinal studies with adults across the lifespan revealed no consistent positive effect of cardiovascular exercise on cognitive functions like WM (35), we found a positive effect for preadolescent children. It is reasonable to assume that children's cognitive functions might benefit from or mature faster through certain experiences like exercise because these can affect the ongoing cognitive and neural development at this immature stage (e.g., [11]).

The positive effects of cardiovascular exercise on WMP may be explained through general physiological and metabolic mechanisms related to improved cardiovascular function. Human data further reveal the possibility of changed steroid hormones (3) as well as changes in gray matter structures of 9- to 10-yr-old children (6) responsible for the observed positive effects of CE on WMP. The authors of the recently published cross-sectional study revealed that individual differences in cardiovascular fitness play a role in the childhood cortical gray matter structure, which is important for scholastic success.

Differential effects of cardiovascular exercise and motor exercise on WM. To our knowledge, this is the first report of a controlled longitudinal study that compared the effects of cardiovascular and complex motor exercises on children's WM. WMP in both experimental groups improved after the intervention, suggesting that both exercise regimens are capable of improving WM. Indeed, both ME and CE demonstrated large effects in WMP with the ME having larger increases compared with the CE as was assumed in our second hypothesis. Additionally, the ME was the sole group whose WMP at postmeasurement was significantly larger compared with the control condition.

The ME exercised with a lower intensity (55%–65% of HR_{max}) compared with the CE (60%–70% of HR_{max}), which supports the assumption of differential brain mechanisms for the link of cardiovascular versus motor-demanding exercises and cognition seen in older adults (28). In the ME, the effects were achieved with a minor stimulation of the cardiovascular system. Because of the lower cardiovascular demands, the motor exercise intervention did not cause a significant increase in cardiovascular fitness in participants of the ME (3.6%). With an exercise intensity of 55%–65% HR_{max}, the lack of fitness gains observed in the ME may be due to a threshold phenomenon. According to Stratton (37), an exercise intensity equal to or greater than 60% of HR_{max} reserve is necessary for promoting fitness in young children.

Research with older adults provides possible explanations for these different mechanisms, e.g., different brain activation patterns after training of cardiovascular or motor exercise (42). Furthermore, with regard to brain volume of subcortical structures, motor exercise showed superior effects on volume of the hippocampus and the basal ganglia compared with cardiovascular exercise (28). These brain changes may be partly responsible for changed cognitive processes. On the behavioral level, these results provide some support for the argument that motor and cognitive development (particularly executive functions) are fundamentally interrelated (10,23). Motor training requires perceptual and higher level cognitive processes that are essential for action and ensuring anticipatory and adaptive aspects of postural control or coordination. Thus, motor training might facilitate the handling of information (41), which is important for cognitive processes.

The present study is subject to some limitations. First, it has to be mentioned that only WM was emphasized, which limits the scope of this study and allows for little generalization to other aspects of cognition. Consequently, future research should expand on these results by further examining other cognitive functions like attention or inhibitory control, which have previously shown to be linked to motor skills in cross-sectional studies (31). Furthermore, regarding our second hypothesis, we would have expected the ME to more clearly exhibit a WMP benefit in comparison with CE. This result was not clearly evidenced. However, we observed significantly higher WMP improvements in the ME compared with the CE. Moreover, only the ME showed significantly larger posttest scores in WM than the CON. Although academic performance has not been evaluated in this study, several studies have demonstrated a relationship between chronic exercise (for review, see [39]) as well as performance on WM tasks (33) and academic achievement in the areas of reading, mathematics, or language. An additional limitation is that no follow-up data have been collected to demonstrate the extent to which the effects of cardiovascular and motor exercise regimens were maintained over longer periods. Future research may gain additional insight into the underlying mechanisms contributing to the observed differences of cardiovascular and motor exercise intervention effects on cognition, beyond behavioral outcomes.

CONCLUSION

In conclusion, both cardiovascular and motor exercises improved WM in preadolescent children. Yet, WM seems to benefit more from motor exercise than cardiovascular exercise. To the best of our knowledge, this is the first controlled longitudinal study reported to reveal the directional nature of the relationship between cardiovascular and motor exercise regimens and cognitive functioning in school children. These findings carry significant implications for PA in schools, given the strong predictive ability of WM for academic achievement. Our results underline the need for additional exercise regimens in schools rather than reductions considering the dual advantages of academic achievement and physical health. Cardiovascular as well as motor exercise regimens should be equally addressed in schools because of the different underlying brain mechanisms, which might benefit more from a variety of activities. By establishing a causal link between exercise and cognition in children, educators and policy makers should carefully consider additional PA programs in schools. More interventional research that focuses on a possible neurobiological explanation for the exercise–cognition link is needed.

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