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THE EFFECTS OF A SINGLE BOUT OF EXERCISE ON MOTOR MEMORY INTERFERENCE IN THE TRAINED AND UNTRAINED HEMISPHERE

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Abstract—Increasing evidence suggests that cardiovascular exercise has positive effects on motor memory consolidation. In this study, we investigated whether a single session of high-intensity interval training (HIIT) mitigates the effects of practicing an interfering motor task. Furthermore, learning and interference effects were assessed in the actively trained and untrained limb as it is known that unilateral motor learning can cause bilateral adaptations. Subjects performed a ballistic training and then the HIIT either before (HIIT_before) or after (HIIT_after) practicing an interfering accuracy task (AT). The control group (No_HIIT) did not participate in the HIIT but rested instead. Performance in the ballistic task (BT) was tested before and after the ballistic training, after the exercise and practice of the AT and 24 h later. After ballistic training, all groups showed comparable increases in performance in the trained and untrained limb. Despite the practice of the AT, HIIT_before maintained their BT performance after the high-intensity interval training whereas HIIT_after (trend) & No_HIIT showed prominent interference effects. After 24 h, HIIT_before still did not show any interference effects but further improved ballistic motor performance. HIIT_after counteracted the interference resulting in a comparable BT performance after 24 h than directly after the ballistic training while No_HIIT had a significantly lower BT performance in the retention test. The results were similar in the trained and untrained limb. The current results imply that a single session of cardiovascular exercise can prevent motor interference in the trained and untrained hemisphere. Overall learning was best, and interference least, when HIIT was performed before the interfering motor task.

Key words: ballistic training, exercise, interference, motor memory.

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Abbreviations: AT, accuracy task; BDNF, brain-derived neurotrophic factor; BT, ballistic task; HIIT, high-intensity interval training; VEGF, vascular endothelial growth factor; VT, visuomotor tracking task.

INTRODUCTION

One possibility to improve or enhance memory consolidation is cardiovascular exercise. Using mainly psychological measures, it has been shown that a single bout of exercise, i.e. acute exercise, can enhance the recall of previously memorized pictures (Segal et al., 2012) and accelerate the rate of vocabulary learning (Winter et al., 2007) while long-term (chronic) cardiovascular excise can improve episodic memory and perceptual speed (Hötting et al., 2012). Much less is known about the effects of cardiovascular exercise on motor memory formation, though. With respect to the consolidation of a newly learnt motor task, a recent study by Roig et al. (2012) demonstrated that a single bout of cardiovascular exercise positively influenced motor memory. In this study, a visuomotor tracking task (VT) was practiced either before or after a single session of high-intensity interval training (HIIT) and the results were compared to a group that did not participate in the HIIT. The results show that the groups who practiced the VT had a better performance 24 h and seven days after the exercise than the group who did not participate in the HIIT. It was further shown that the group which practiced HIIT after learning the VT achieved a higher performance in the retention tests. Furthermore, physiological correlates like norepinephrine, brain-derived neurotrophic factor (BDNF), vascular endothelial growth factor (VEGF), insulin-like growth hormones IGF-1, epinephrine and lactate, factors that have been assumed to contribute to learning-related changes in the central nervous system, were higher when HIIT was performed after the learning (Roig et al., 2013). This demonstrates that a single bout of HIIT can enhance motor memory consolidation. However, it is not known at this stage, whether HIIT also has the potential to prevent or reduce motor interference. Motor interference is commonly described as the decrease in performance when a new task B is learnt after the acquisition of a task A. This means that for motor interference to occur, the memory consolidation of task A was not terminated before learning of task B. This has been shown for various tasks like visuomotor rotations (Krakauer, 2009), sequence learning (Stephan et al., 2009) or ballistic motor learning (Lundbye-Jensen et al., 2010). The latter study showed when a VT is practiced after the learning of a ballistic task (BT) within a time frame of three hours, severe motor interference can be observed. In a similar design to the one used by Lundbye-Jensen et al. (2010), it was recently demonstrated that interference effects, i.e. the reduction in performance of a BT, caused by the practice of a VT, can not only be observed in the trained limb but also in the contralateral untrained limb (Lauber et al., 2013). The phenomenon that unilateral practice can cause transfer effects to the non-trained side has been described for motor learning and was first described by Scripture et al. (1894) and has later been termed "cross education" or "cross-limb transfer" but the study by Lauber et al. (2013) was the first to show that this also hold true for interference effects.

The present study therefore tries to answer the following questions: *first*, whether a single bout of HIIT is able to reduce the effects of an interfering motor task (task B) on the consolidation of a previously learnt task A. *Second*, if the effect is different whether the HIIT is performed before or after the interfering motor task and *third*, if this holds also true for the contralateral untrained hand.

EXPERIMENTAL PROCEDURES

Thirty subjects participated in this study (Table 1). All subjects were right handed according to the Oldfield handedness inventory (Oldfield, 1971) and gave written informed consent before participating in the project. The experiments were approved by the local ethics committee and were in accordance with the declaration of Helsinki. All subjects were free of any known neurological and orthopaedic disorders.

One week prior to the actual experiment subjects performed a graded exercise protocol to determine their individual maximal oxygen uptake on a cycle ergometer (Ergobike medical 8, Daum electronic GmbH, Fuerth, Germany). This test was used to determine the $VO2_{max}$ and the cycling intensity for the single session of HIIT in the main experiment. The graded exercise started with a warm up for 5 min at a constant work load of 50 Watts (W). Following the warm-up, subjects were instructed to maintain a constant pedaling rate above 75 rpm while the workload was constantly increased by 30 W every 30 s until voluntary exhaustion. Breath by breath oxygen consumption was measured using a stationary CPX system (Oxycon Pro, Care Fusion, San Diego CA, USA) during the entire test.

After the $VO2_{max}$ testing, all subjects were randomly assigned to one of three groups who performed the HIIT either before (HIIT_before) or after (HIIT_after) practicing an interfering motor task (Fig. 1). The control group (No_HIIT) did not participate in the HIIT but rested instead. The randomization of the subjects was done according to their age and maximum oxygen uptake ($VO2_{max}$) obtained in the exercise protocol prior to the actual experiment (please see Table 1) in a similar way as in a previous experiment (Roig et al., 2012). Subsequently, one week after the completion of the $VO2_{max}$ testing, all groups initially performed a ballistic movement training (BT) followed by the practice of an interfering accuracy task (AT). However, HIIT_before underwent a single session of HIIT on the bicycle directly after BT before practicing the AT. In contrast, HIIT_after practiced both the BT and the AT before the single session of HIIT took place. Finally, No_HIIT had the same course as HIIT_before but had a rest period instead of performing the HIIT. At the end of this laboratory session, subjects' BT performance levels were measured again. Finally, 24 h after the completion of the experiment, subjects reported back to the laboratory to test the retention of the BT performance (RT 24 h, Fig. 1).

Table 1. Subjects' data (group mean ± SEM), (BMI: body mass index)

	HIIT_before	HIIT_after	No_HIIT
Number of Subjects	10 (5 females)	10 (5 females)	10 (5 females)
Age (years)	23.5 ± 0.5	23.5 ± 0.5	23.5 ± 0.7
BMI (kg/m^2)	22.4 ± 0.6	22.6 ± 0.5	21.6 ± 0.5
$VO2_{max}$ (ml O2/min/kg)	47.1 ± 2.9	48.1 ± 3.8	48.4 ± 3.4

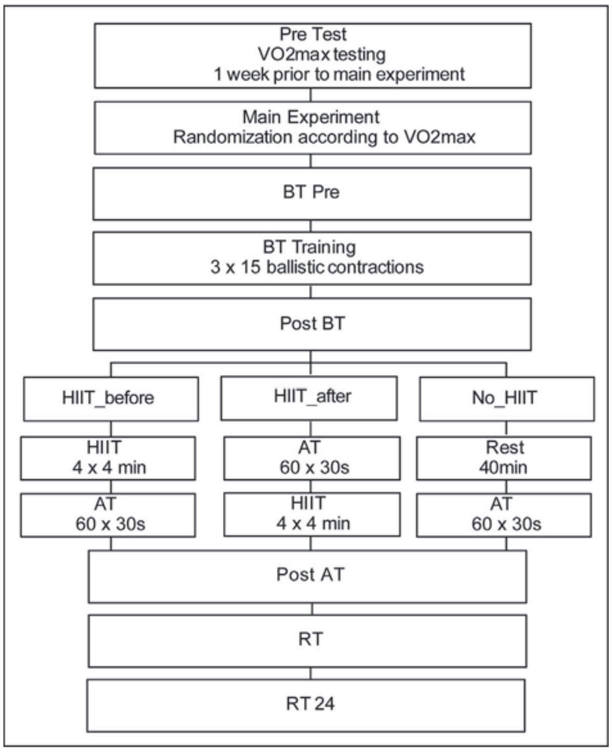

Fig. 1. Overview of the course of the experiment.

General experimental procedure

The BT and the AT consisted of isometric contractions of the right and left index fingers using a custom built robotic device which has been previously used in the same fashion (Lauber et al., 2013). Subjects were seated in an adjustable chair while the right and left forearms were fixed in custom made arm and hand rests to prevent movements of the arm and wrist. The index finger was fixed to a splint which was mounted to the robot arm while it was taken care that the center of rotation of the robot arm was aligned with the center of rotation of the metacarpophalangeal joint of the subject's right and left hand, respectively (Fig. 2). The robot arm was equipped with torquemeter (LCB 130, ME-Meßsysteme, Neuendorf, Germany). Before the first test (Pre), subjects were

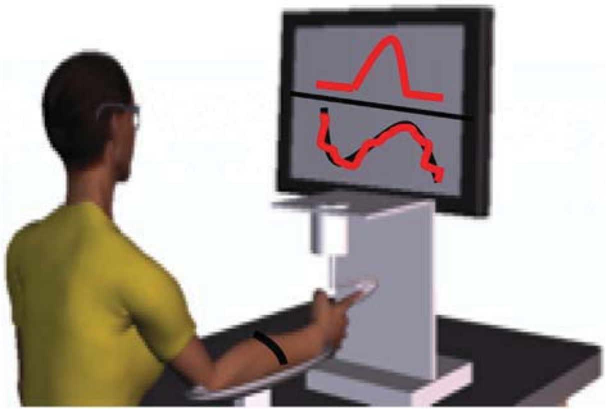

Fig. 2. Graphical illustration of the experimental setup.

allowed to perform 10 submaximal isometric contractions with either hand at their preferred pace to warm up.

Cardio-pulmonary measurements

During the incremental cycling test, minute ventilation (VE), oxygen uptake (VO2), carbon dioxide output (VCO2) and heart rate (HR) were measured using the CPX system. The heart rate data were obtained by a Polar strap T31 (Polar, Helsinki, Finland) and transmitted to the CPX system. All variables were measured breath-by-breath and binned into 10-s means. Before each test, manual calibration of the sensing turbine took place using a 3-l syringe. Oxygen and carbon dioxide concentration were detected by paramagnetic and infrared analysers. A certified calibration gas (CO2: 4.95 vol%, O2: 15.99 vol%) was used to calibrate gas analysers. Peak values for oxygen uptake ($VO2_{max}$) were taken from the rolling average of 15 breaths (Robergs et al., 2010) and expressed in relation to body weight.

Ballistic task (BT)

The goal of the BT was to improve the rate of force development (RFD). It was previously shown that this task can cause very rapid performance enhancements (Carroll et al., 2011; Lee et al., 2011; Lauber et al., 2013; Lundbye-Jensen et al., 2010). Before the recording started, all subjects were instructed to produce maximal lateral force as fast as possible by solely flexing the index finger. All contractions were timed by using auditory cues. A first tone (100 ms, 500 Hz sine wave) indicated the subjects to get ready and a different second tone two seconds later (200 ms, 600 Hz sine wave) signaled the start of the contraction. Subjects were instructed to contract as soon as they heard the second tone but after a few trials used for customization, they were able to anticipate the second tone. After each trial, subjects were provided with visual feedback about their RFD calculated from their force–time curve as it has been shown that augmented feedback is very effective to improve performance and foster motor learning (Lauber and Keller, 2014). The feedback was presented on a computer screen placed 1 m in front of the subjects and was provided 1 s after each contraction for a duration of 5 s. For each trial, subjects were instructed to increase the number presented on the computer screen throughout the training and they were also verbally encouraged during the training.

Initially, subjects performed five contractions (Pre) with the dominant followed by five contractions with the non-dominant hand without the presentation of feedback serving as the baseline values. During the BT Training, subjects performed three sets of 15 contractions with 3-min break between the sets. All contractions during the BT training were solely executed with their dominant right hand. After the BT training, subjects again performed five contractions with the right and left hand without feedback (Post BT). Augmented feedback was prevented in test trials in order to exclude the immediate influence of feedback on motor performance that does not necessarily reflect motor learning (Kantak and Winstein, 2012). The five contractions without feedback were repeated in the same manner at Post AT, Post RT and RT 24.

Accuracy task (AT)

The AT was identical to the one previously used (Lauber et al., 2013) and consisted of tracking a computer generated sinusoid curve. The duration of the tracking was 30 s and the total path consisted of alternating sine waves of different frequencies ranging from 0.5 to 3 Hz. This task was solely executed with the dominant hand. On two occasions within the tracking cycle, there were periods of null potentials (one in the middle and one at the end) lasting for 2 s where the subjects were allowed to rest to avoid fatigue. The curve was presented on the same computer screen as the feedback during the BT and was displayed as a running black line from the right to the left side with a visible sequence of 6 s. A red line at the trough of the sine wave indicated force output produced by the subjects when flexing their index finger. Subjects were told to maintain the red line as closely as possible to the black target line by an isometric contraction of the right index finger pushing against the robot arm. The required force which was needed to match the highest point of the sine was 9 N meaning that the forces to perform the task were very low requiring fine-tuned adjustments of motor output. This is in contrast to contractions during the BT. However, similar to performing the BT, the AT also depended on augmented feedback and on the activation of the same muscles acting in the same movement direction as during the BT as this configuration was shown to induce strong interference effects in the trained (Lundbye-Jensen et al., 2010) and untrained limb (Lauber et al., 2013). Subjects were verbally encouraged to improve their performance every trial while practicing the 30-s sequence 60 times. They were allowed to rest for 3 min after the completion of 20 trials.

HIIT

HIIT_before and HIIT_after were exercised on the same bike as during the $VO2_{max}$ test. The exercise consisted of a warm up of 4 min at 50 W followed by 4 min of high-intensity cycling at the work load the subjects had at 75% of their individual $VO2_{max}$ followed by 4 min of low-intensity cycling at 50 W. Heart rate was measured using a heart rate monitor (Polar RS800CX) to monitor the exercise intensity. After the HIIT, subjects were allowed to rest for 20 min before the next step of the protocol (Fig. 1). Like in the study by Roig et al. (2012), cycling was chosen to avoid fatigue in the upper limb and because it was shown that cycling is more effective in improving cognitive performance than treadmill running (Lambourne and Tomporowski, 2010).

DATA ANALYSES AND STATISTICS

BT: Performance in the BT was determined as the increase in force over time produced by the subjects. RFD was defined as the maximal slope of the force time curve (dT/dt) in each trial in a time window around the produced force (Gruber et al., 2007; Lauber et al., 2013). Taking the same time window, the peak torque was calculated. Afterward, the mean torque values for the Pre, Post BT, Post AT, RT, RT 24 trials were calculated. First, the Pre values were compared to the Post BT values to evaluate the effect of the BT training. To test the effect (interference) of the AT on the BT performance, we compered the BT performance before and after the AT (Post BT vs. Post AT). The performance changes during the training were tested by comparing the mean of the initial five with the last five trials. *AT:* The performance in the AT was calculated as the mean absolute difference between the target curve and the curve produced by the subjects over the 30 s period of each trial. All values were normalized to the initial trial. In order to quantify changes in performance, the average of the initial five values of the AT training were compared to the final five values.

All data analyses were performed offline using custom written Matlab scripts (Mathworks Inc., Chatswool, MA, USA).

Statistics

Normal distribution of the data was confirmed using the Shapiro–Wilks test. To test for differences in baseline performance (Pre), separate one-way ANOVAs for the trained and untrained hand were calculated.

Overall BT performance changes: To evaluate changes in BT performance, a repeated measures of ANOVA with factors $\text{Time}_{\text{Pre, Post BT, Post AT, RT, RT 24)}}$ and $\text{Group}_{\text{(HIIT\_before, HIIT\_after, No\_HIIT)}}$ was calculated independent for each hand.

In the case of significant interactions, planned contrasts were calculated comparing the Post BT values with the Post AT, RT and RT24 values independent for the trained and untrained hand.

The effect of the BT training: BT training effects were quantified by an ANOVA with factors $\text{Time}_{\text{(Pre, Post BT)}}$ and $\text{Group}_{\text{(HIIT\_before, HIIT\_after, No\_HIIT)}}$ for the trained and untrained hand separately.

Effects of the AT practice: Changes in the course of the AT practice between the groups we calculated with a ANOVA with the factors $\text{TIME}_{\text{(initial 5 values, last 5 values)}}$ and $\text{Group}_{\text{(HIIT\_before, HIIT\_after, No\_HIIT)}}$.

All data were represented as mean ± standard error of the mean (SEM). SPSS 22.0 (SPSS®, Chicago, IL, USA) software was used for all statistical analyses.

RESULTS

Baseline performance

During the Pre test, there was no significant difference in BT performance between the groups for the trained (GROUP: $F_{2,29} = 1.06$, $p = 0.26$) and untrained hand (GROUP: $F_{2,29} = 1.54$, $p = 0.23$).

Changes in BT performance

Overall trained hand: The results show a significant TIME effect ($F_{4,108} = 18.25$, $\eta = 0.40$; $p < 0.001$) as well as a TIME*GROUP interaction ($F_{8,108} = 2.81$, $\eta = 0.17$; $p = 0.007$).

Overall untrained hand: For the untrained hand, similar results could be observed for the factors TIME ($F_{4,108} = 14.01$, $\eta = 0.34$; $p < 0.001$) and TIME*GROUP ($F_{8,108} = 2.01$, $\eta = 0.13$; $p = 0.044$).

BT training

Trained hand: The BT training caused a significant change in BT performance indicated by a significant TIME effect ($F_{1,27} = 32.12$, $\eta = 0.54$; $p < 0.001$, Fig. 3). The change of BT performance over time was not different between the groups (TIME*GROUP ($F_{2,27} = 0.47$, $\eta = 0.06$; $p = 0.78$).

Untrained hand: The BT training also caused a significant change in BT performance over TIME ($F_{1,27} = 24.56$, $\eta = 0.48$; $p < 0.001$, Fig. 3) without being different between the groups (TIME*GROUP $F_{2,27} = 1.77$, $\eta = 0.12$; $p = 0.19$).

Overall learning

Trained hand. HIIT_before: The results show that there were no significant changes from the Post BT to the Post AT ($F_{1,9} = 0.29$, $\eta = 0.03$; $p = 0.60$, Δtorque −2.5 ± 4.67 Nm) as well as from the Post BT to the RT test ($F_{1,9} = 1.39$, $\eta = 0.13$; $p = 0.27$, Δtorque + 6.91 ± 5.85 Nm, Fig. 5). From the Post BT to the RT 24, there was a significant increase in BT performance ($F_{1,9} = 5.82$, $\eta = 0.39$; $p = 0.039$) as torque increased by 16.95 ± 7.02 Nm (+24.18 ± 10.21%, Fig. 4).

HIIT_after: The results show a weak trend as BT performance declined (−21.18 ± 6.20%) from the Post BT to the Post AT ($F_{1,9} = 3.58$, $\eta = 0.29$; $p = 0.09$, Δtorque −13.43 ± 7.10 Nm). There was no significant change in BT performance from the Post BT to the RT ($F_{1,9} = 0.91$, $\eta = 0.09$; $p = 0.36$, Δtorque + 3.30 ± 3.44 Nm,) and also not from Post BT to RT 24 ($F_{1,9} = 0.16$, $\eta = 0.02$; $p = 0.69$, Δtorque + 1.59 ± 3.94 Nm, Fig. 4).

No_HIIT: For the No_HIIT group, planned contrasts revealed significant changes from Post BT to Post AT

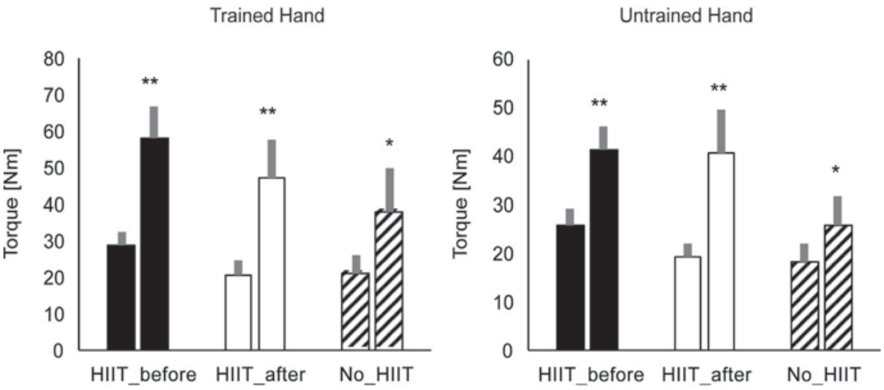

Fig. 3. *Changes in BT performance from the Pre to the Post BT test.* All groups significantly ($^{*}p \leq 0.05$, $^{**}p \leq 0.01$) increased their performance from the Pre- to the post BT-test in the trained as well as in the untrained hand. Data show group mean values.

($F_{1,9} = 9.27$, $\eta = 0.51$; $p = 0.01$) as torque decreased by -3.48 ± 1.14 Nm ($-14.11 \pm 4.98\%$). Performance decreases were also seen when comparing Post BT to the RT ($F_{1,9} = 7.92$, $\eta = 0.47$; $p = 0.02$, Δtorque $+8.08 \pm 2.87$ Nm, $-21.19 \pm 9.28\%$) and Post BT to the RT 24 ($F_{1,9} = 5.05$, $\eta = 0.36$; $p = 0.05$, Δtorque $+6.55 \pm 2.91$ Nm, $-13.17 \pm 7.53\%$, Fig. 4).

Untrained hand. HIIT_before: There was no change in BT performance from Post BT to the Post AT ($F_{1,9} = 0.26$, $\eta = 0.03$; $p = 0.62$, Δtorque $+2.75 \pm 5.39$ Nm) as well as from the Post BT to the Post RT ($F_{1,9} = 0.96$, $\eta = 0.10$; $p = 0.35$, Δtorque $+6.67 \pm 6.92$ Nm) and from the Post BT to the RT 24 test ($F_{1,9} = 2.51$, $\eta = 0.22$; $p = 0.15$, Δtorque $+11.82 \pm 7.46$ Nm, Fig. 4).

HIIT_after: Analogous to the trained hand, there was a weak trend ($F_{1,9} = 3.61$, $\eta = 0.29$; $p = 0.09$) toward a decrease in BT performance from the Post BT to the Post AT (Δtorque -13.43 ± 87.10 Nm, $-19.69 \pm 6.06\%$). From the Post BT to the RT, BT performance did not significantly change ($F_{1,9} = 0.02$, $\eta = 0.001$; $p = 0.913$, Δtorque $+0.33 \pm 2.94$), which was also the case from the Post BT to the RT 24 test ($F_{1,9} = 0.41$, $\eta = 0.04$; $p = 0.53$, Δtorque $+1.63 \pm 2.53$, Fig. 4).

No_HIIT: For the No_HIIT group, no differences were found from the Post BT to the Post AT ($F_{1,9} = 0.003$, $\eta = 0.001$; $p = 0.96$, Δtorque -0.1 ± 1.6 Nm) as well as from the Post BT to the RT ($F_{1,9} = 0.25$, $\eta = 0.03$; $p = 0.63$, Δtorque -1.17 ± 2.33 Nm) and also from the Post BT to the RT 24 ($F_{1,9} = 0.002$, $\eta = 0.001$; $p = 0.96$, Δtorque -0.2 ± 3.82 Nm, Fig. 4).

AT performance. All three groups showed a significant increase in performance (TIME: $F_{1,27} = 49.26$, $\eta = 0.64$, $p < 0.0001$) when comparing the initial five trails with the last five trials (HIIT_before: $-18.73 \pm 4.12\%$, $p < 0.01$, HIIT_after: $-16.99 \pm 4.48\%$, $p < 0.001$, No_HIIT: $-15.08 \pm 2.45\%$, $p = 0.02$; Fig. 6). Between the groups was no difference in the overall learning of the AT (TIME*GROUP: $F_{2,27} = 0.97$, $\eta = 0.06$, $p = 0.39$).

DISCUSSION

The first aim of the present study was to investigate whether acute exercise (HIIT) has a positive effect on memory consolidation of a ballistic motor task. The results show that a single bout of exercise does have positive effects by minimizing interference effects. The second aim was to test whether it is important *when* the HIIT is performed. Results show that only the HIIT_before group could significantly improve its BT performance from the Post BT to the RT24 indicating that HIIT may prevent the occurrence of immediate interference only when it is executed *before* the interfering task (Fig. 4). The third aim was to test the hypothesis that HIIT may also mitigate motor interference in the untrained hemisphere. This was only partly confirmed by the results of the present study.

Influence of HIIT on BT performance

We wanted to test if a single bout of high-intensity exercise positively influences the consolidation of a ballistic motor task. The results show that a single session of HIIT has the potential to enhance motor memory consolidation as HIIT_before did not show any interference effects due to the learning of the AT. Furthermore, even though HIIT_after displayed a drop in BT performance after AT, a rapid recovery of the BT performance was observed. Finally, No_HIIT which did not participate in the HIIT displayed a significant reduction in BT performance at RT 24 which was not the case for the other groups. The results are therefore in accordance with a recent study from Roig et al. (2012) who used a similar approach to the one of the present study but did not assess motor interference. In this latter study, three groups of subjects were asked to perform a visuomotor tracking task either before or after a single bout of exercise or after rest. Like in the current study, initial learning rates were not different but both exercise groups showed a significantly better retention performance 24 h and seven days post exercise compared to the group who did not exercise. Furthermore, the group which exercised after the learning of the visuomotor tracking showed a better retention 24 h later compared to the group which exercised prior to the practice of the visuomotor tracking. The results of the present study are complementary as the two groups which participated in the HIIT showed no interference whereas the group which did not exercise demonstrated a significant reduction in performance. When regarding the groups performing the HIIT, it is noteworthy that even though HIIT_after showed a decrease in BT performance directly after the learning of the AT, BT increased again and was similar compared to after

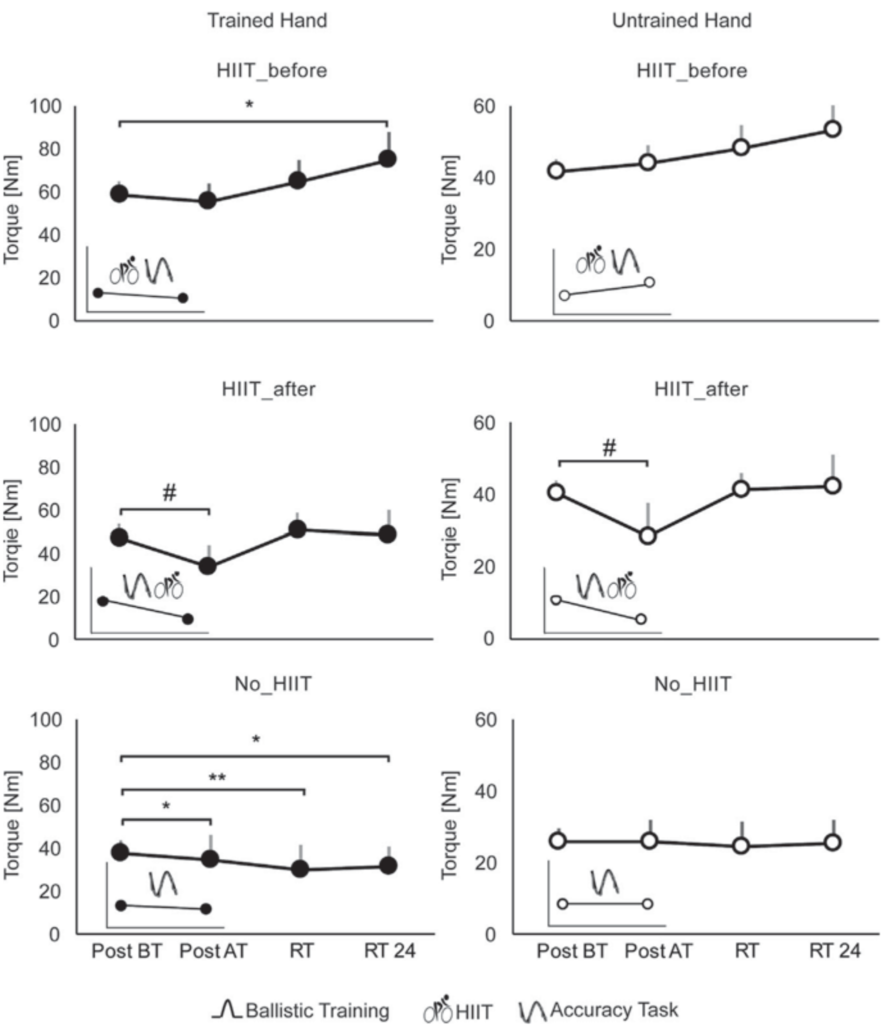

Fig. 4. *BT performance from the Post BT to the Post AT, the RT and the RT 24 test for the trained and untrained hand.* All statistical comparisons were made in relation to the Post BT test. The small picture within each graph displays how the groups differed in terms of their experimental design (i.e. course of the experiment between the Post BT and the Post AT). HIIT_before did neither show any changes in BT performance as a result of the AT practice ex. In the retention test 24 h later, however, HIIT_before was able to significantly improve its performance in the trained hand ($^{*}p \leq 0.05$). No changes were observed in the untrained hand. HIIT_after showed a trend ($^{\#}p = 0.08$) toward a reduction in BT performance from the Post BT to the Post AT in the trained and untrained hand but performance recovered again and performance measured at the RT and RT 24 was not significantly different compared to the Post BT. This was comparable for the trained and untrained hands. No_HIIT showed a significant interference effect as a result of the AT practice at all time points ($^{*}p \leq 0.05$, $^{**}p \leq 0.01$) in the trained but not in the untrained hand.

the BT training when tested 24 h later (RT 24). Thus, it seems that for HIIT_after, the consolidation of the BT was not terminated before the practice of the AT but continued later on despite the interfering AT. This is in line with findings showing that motor memory consolidation continues even hours after practice. Using a sequential motor task, it was shown that when subjects were not allowed to sleep during the night after the practice, performance gains were very little. If they were allowed to sleep during the next night, however, performance started to increase again showing that memory consolidation continues even after 24 h (Fischer et al., 2002).

The notion that the BT performance in HIIT_after increased again from Post BT to RT also supports the idea that the practice of the AT, most likely causing the decrease in BT performance, did not permanently interfere with the motor memory of the BT. Thus, physical exercise by means of HIIT may have caused a retrieval of the memory of the BT resulting in enhanced performance in the RT in HIIT_after. Remarkably, exercise performed before the interfering AT task (HIIT_before) resulted in a more rapid memory consolidation indicated by no detrimental effects by practicing the AT in this group. Furthermore, the HIIT_before was the only group which demonstrated performance improvements in BT from Post BT to RT24.

Overall, our results indicate, in line with previous experiments (Roig et al., 2013), that cardiovascular exercise has very positive effects on memory consolidation. Furthermore, the study from Roig et al. (2013) also showed that the retention of the motor memory was better when the exercise was performed before the learning of the motor task. This is similar in the present study as HIIT_before showed a greater improvement in BT performance at RT24 than HIIT_after (Fig. 5).

Potential mechanisms of the HIIT

There are psychological mechanisms like an increased arousal (Audiffren et al., 2008) that are caused by the cardiovascular activity that can have a positive effect on memory consolidation (McGaugh, 2006). There are also a number of physiological correlates like norepinephrine, BDNF, VEGF, insulin-like growth hormones IGF-1, epinephrine and lactate that have recently been identified as potential biomarkers for changes in the central nervous system contributing to optimization of motor memory as they all increase immediately after exercise (Skriver et al., 2014). As we have not taken any blood samples, we can only speculate that these factors might have contributed to the positive effects on BT performance after HIIT.

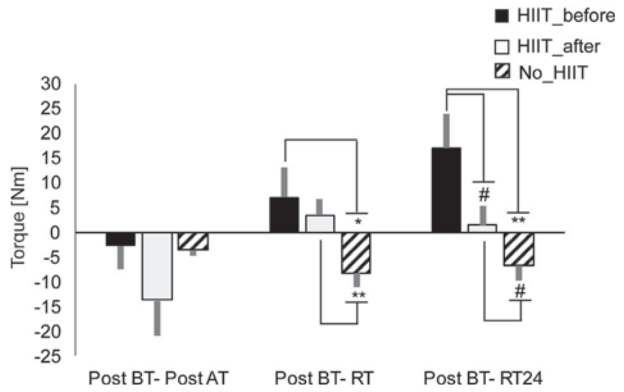

Fig. 5. Comparison of the changes in BT performance between the groups at the individual time points. Between the Post BT and the Post AT, there was no significant difference between the groups. Between the Post AT and the RT however, No_HIIT had a greater reduction on torque compared to HIIT_before and HIIT_after which was also the case between the RT and the RT 24 test ($^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{\#}p = 0.06$).

Cross-limb transfer

There are many studies available that looked at the effects of unilateral motor learning on bilateral performance changes using tasks such as visuomotor rotations (Sainburg and Wang, 2002; Taylor et al., 2011; Carroll et al., 2014; Wang and Sainburg, 2003) or ballistic type of movements (Carroll et al., 2013). Up until recently, no study ever looked at potential interference effects of unilateral motor learning. The only study existing so far shows that interference effects can not only become apparent in the trained but also in the untrained limb (Lauber et al., 2013). In order to gain a better understanding about these cross-educational interference effects, the present study also tested for the presence of learning related interference effects in the untrained hand. The present results show that BT performance was improved in all three groups after the BT training ($p = 0.044$) and the interference effects and the influence of HIIT were very similar in the non-trained hand compared to the actually trained hand. Similar to the trained hand, the HIIT_before group did not display any significant interference after practicing the AT. In contrast, the results for the HIIT_after group displayed a weak trend toward a decline in BT performance from the Post BT to the Post AT in the non-trained hand ($p = 0.09$). Only the No_HIIT group, showing strong interference effects in the trained hand, did not show any signs of interference in the untrained hand. This is rather surprising as it is well known that the practice of ballistic types of movements can lead to bilateral behavioral as well as neural adaptations. Thus, we would have expected to observe similar results in the trained and untrained hand. The cross-activation hypothesis actually states that unilateral motor learning causes adaptations in the trained as well as in the untrained hemisphere and is supported by a number of studies showing that ballistic types of movements result in increased levels of cortical and/or corticospinal excitability in both hemispheres (Carroll et al., 2011; Lee et al., 2011). It was additionally shown that changes in ballistic performance as well as after learning a visuomotor tracking task correlate with changes in corticospinal excitability (Lauber et al., 2013). As exercise has been shown regularly to promote motor learning, it seems that HIIT has very similar effects in promoting memory consolidation in the trained as well as untrained hemisphere.

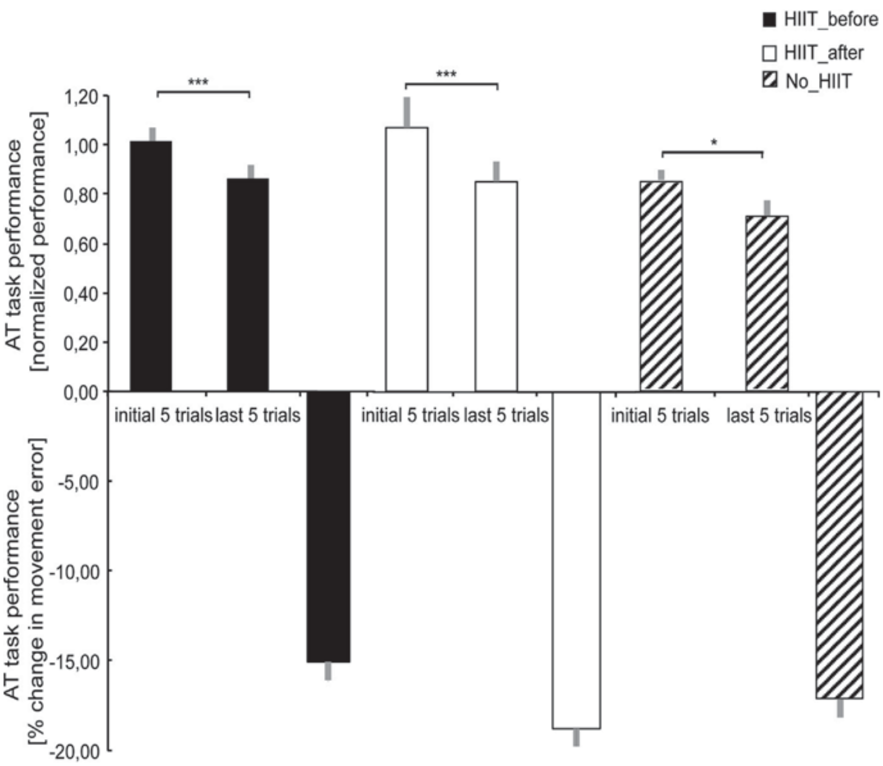

Fig. 6. *Changes in performance in the AT*: All groups significantly reduced their movement error in the course of the AT training (expressed as percentage change compared to the initial five trials). HIIT_before decreased the error by 15.0 ± 2.4% ($^{***}p \leq 0.001$), HIIT_after by 18.7 ± 4.1% ($^{***}p \leq 0.001$) and No_HIIT by 16.9 ± 4.4% ($^{**}p \leq 0.01$).

CONCLUSION

The present evaluated if a single session of HIIT can reduce learning-related interference effects in the trained as well as untrained limb. Results show that HIIT has the potential to mitigate interference effects independent if it performed before or after the learning of the interference task and that similar results can be observed for the trained and untrained hand.

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