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Research article

Comparison of whole-body sensorimotor skill learning between strength athletes, endurance athletes and healthy sedentary adults

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ABSTRACT

Motor sequences represent an integral part of human motor ability. Apart from simple movement sequences, complex coordinated movement sequences are the building blocks for peak athletic performance. Accordingly, optimized temporal and spatial coordination of muscle action across multiple limbs may be a distinguishing feature between athletes and non-athletes in many sports. In the present study, we aimed to assess differences between strength and endurance athletes and non-athletes during learning of a complex whole-body serial reaction time task (CWB-SRTT). For this purpose, 26 nonathletes (NAG) and 25 athletes (AG) learned the CWB-SRTT over 2 days separated by 7 days. Mean response times of participants were recorded and statistically analyzed for sequence-specific and non-sequence-specific improvements, as well as differences in learning rates and retention. Furthermore, AG was subdivided into strength (SG) and endurance (EG) athletes, and all analysis steps were repeated. Our results show a better mean response time of AG compared to NAG. However, we could not detect differences in sequence-specific or non-sequence-specific learning, as well as different retention rates between NAG and AG or SG and EG. We assume here that a potential lack of motor transfer between general athletic abilities and the specific complex motor sequence mainly accounts for our findings.

1. Introduction

The acquisition of motor skills is a basic prerequisite for mastering activities of daily living as well as for achieving top athletic performance. In this context, motor sequences represent an important element of motor skills. Everyday tasks, such as typing on a smartphone or computer, but also the execution of simple and complex athletic movements require the ability to integrate motor sequences into movement patterns in a coordinated manner. Motor sequence learning involves two main mechanisms. On the one hand, the recognition of the sequence or subsequences within a movement sequence and, on the other hand, the ability to link these sequences into a complete, practiced movement (Moisello et al., 2009). Serial reaction time tasks (SRTT) are employed to assess motor sequence learning ability. These tests capture components within the motor sequence learning process such as temporal organization of the sequence, higher-order associations, and prediction of future events (Robertson, 2007). In SRTT execution, a participant is presented with cues to one of several positions (items) to which a particular action, such as pressing the appropriate key or touching the appropriate plate, should be performed as soon as and accurate as possible after the cue presentation. SRTT traditionally include several sequence blocks (fixed sequence of items) and random blocks (random arrangement of items), which are completed one after the other, separated by a break. This separation allows for the detection of sequence-specific and non-sequence-specific learning effects (Robertson, 2007).

SRTT are mainly performed in the form of simple upper and lower extremity tasks. However, underlying many everyday and athletic performances is the learning and mastery of complex whole-body movements that place demands on postural control and intermuscular coordination in addition to fine motor skills. For this reason, we developed a complex whole-body SRTT (CWB-SRTT) to assess serial reaction times of lower extremities. In an initial study, we demonstrated that the brains of non-athletes undergo functional reorganization within the early learning phase of CWB-SRTT (Mizuguchi et al., 2019). Since athletes in particular are characterized by functionally reorganized motor systems (Nakata et al., 2010), the question arises whether athletes have different initial abilities and learning rates in CWB-SRTT when compared to non-athletes.

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SRTT performance depends on neurocognitive abilities, mainly related to information intake and processing (Robertson, 2007). In addition to superior physical abilities (Hughes et al., 2018), many athlete populations show enhanced cognitive abilities compared to non-athletes across a number of sport disciplines (Florkiewicz et al., 2014). This combination of superior physical and cognitive abilities presumably enables athletes of various sports to better use performance-specific information to achieve a specific movement goal (Yarrow et al., 2009). Accordingly, certain athlete populations have been shown to outperform non-athletes in neurocognitive abilities. For example, football players demonstrated superior sport-specific perceptual and visual skills compared to non-athletes (Savelsbergh et al., 2005) while volleyball players showed better task-relevant inhibitory skills (Alves et al., 2013). Regarding spatial perception ability, it could be shown that elite gymnasts have an improved capacity compared to amateur gymnasts (López and Postigo, 2012). Further, a more extensive study confirmed better performance of various athletes compared to non-athletes in terms of attention and task-relevant decision making (Mann et al., 2007). It should be noted that the cognitive abilities of different athletes may also depend on the level of expertise. Accordingly, some studies show elite athletes of different sports to outperform lower-level athletes in cognitive functions (Scharfen and Memmert, 2019). Generally, these enhanced abilities potentially enable many athlete populations to better anticipate upcoming motor events and prepare and carry out optimal motor responses (Barrett et al., 2020). On a behavioral level, this is, for example, expressed by lower reaction times of athletes within simple reaction time paradigms (Atan and Akyol, 2014; Riedesel and Mahoney, 2013). Interestingly, some athletes such as football players (Verburgh et al., 2016) and gymnasts (di Cagno et al., 2014) demonstrate an increased ability to learn complex movement sequences.

As shown by these results, the influence of athletic expertise on neurocognitive abilities is predominantly assessed through performance evaluation of athletes of specific sports with concise technical performance characteristics, i.e., open-skills (e.g., football (Ali, 2011)) and closed-skills (e.g., gymnastics (Grandjean et al., 2002)). Closed-skills are performed in a stable environment whereas open-skills are performed in a variable environment (Gu et al., 2019). Critically, although this is an important approach, most sports disciplines, and therefore the ability to adequately and continuously execute sports-relevant open-skills and closed-skills, are governed by fundamental capabilities such as strength and endurance (Bangsbo, 2015). Thus, an important aspect of athletic ability is neglected unless the influence of these fundamental performance-determining capabilities is also considered separately. Importantly, recent research indicates positive effects of strength and endurance exercise on neurocognitive aspects such as executive functions, composite cognitive scores, and memory (Landrigan et al., 2020; Mandolesi et al., 2018). On the other hand, the effect of strength and endurance exercise on skill acquisition has not been investigated thoroughly. Furthermore, there is a lack of knowledge concerning differences between strength and endurance athletes in terms of differential effects on cognitive performance aspects or motor skill acquisition (Chang et al., 2017). This issue seems to be relevant in sports since both strength and endurance athletes in fact acquire complex whole-body movement patterns over the course of many years of training (Novacheck, 1998; Storey and Smith, 2012), e.g. squatting or clean & jerks (strength athletes) as well as running or cycling (endurance athletes), which may potentially facilitate motor performance improvement within CWB-SRTT.

Taken together, these findings suggest a potentially greater capacity in strength and endurance athletes compared to non-athletes to acquire complex motor skills determined by both physical and neurocognitive abilities. In this study, we therefore aimed to investigate how such potentially enhanced neurocognitive and motor skills manifest themselves during the learning of a novel complex serial reaction time task, the CWB-SRTT. Because this task represents a novel paradigm, we chose to examine athletes with pronounced fundamental motor abilities, i.e., strength and endurance athletes, to provide an informative reference point for future discipline-specific studies to build upon. We hypothesized that both strength and endurance athletes would exhibit superior sequence-specific learning rates than non-athletes, as both types of training have been shown to positively affect neurocognitive abilities, which in turn influence SRTT performance (Robertson, 2007). Lastly, as outlined above, exercise can induce better retention rates in motor learning (Roig et al., 2012), which is why we additionally hypothesized to find improved retention rates in both athlete groups compared to non-athletes.

2. Materials and methods

2.1. Ethical approval

This study was supported by the local ethics committee of the University of Leipzig (ref. nr. 394/16-ek). All participants gave written informed consent to participate in the experiment, according to the Declaration of Helsinki.

2.2. Participants

A total of 51 participants (19 female, 32 male; age (mean $\pm$ standard deviation): 27.1 $\pm$ 4.2 years) were enrolled in the present study. Participants were recruited through public advertisement based on the following inclusion criteria: age 18–35 years, neurological healthy, right-handedness (based on individual self-report). Furthermore, participants were separated into two groups according to their participation in organized sports (measured in hrs/week): a non-athlete group (NAG; n = 26; age: 27.5 $\pm$ 3.7 years) and an athlete group comprising both strength and endurance athletes (AG; n = 25; age: 26.7 $\pm$ 4.7 years). As non-athletes were considered those participants with an upper limit of 3 hrs of sports participation a week (0.7 $\pm$ 0.8 hrs) while AG had to perform at least 7 hrs of exercise during an average week (13.8 $\pm$ 5.7 hrs). All athletes included in this study had to have participated regularly in organized training for at least the past two years.

On an exploratory level, we additionally split AG into two subgroups, based on the athletes preferred type of exercise: strength training (SG; n = 10; age: 27.3 $\pm$ 4.5 years, exercise hours per week: 8.8 $\pm$ 1.3 hrs) or endurance training (EG; n = 15; age: 26.6 $\pm$ 1.3 years, exercise hours per week: 16.6 $\pm$ 5.1 hrs). Participants, who reported to be trained in resistance-type exercise were active in disciplines like weightlifting, CrossFit, and powerlifting while endurance exercise included disciplines like cycling, running, triathlon.

2.3. Experimental procedure

Participants completed a CWB-SRTT on two days separated by one week, with one participant's measurements taking place at similar day times. On each day, the participants of both AG and NAG completed 15 consecutive sequence blocks and one random block before and after all sequence blocks (Figure 1A). The CWB-SRTT lasted approximately 15 min, including 15-s inter-block intervals.

2.4. Sensorimotor skill learning task: whole-body serial reaction time task (CWB-SRTT)

A four-directional CWB-SRTT for the lower extremities was implemented in this experiment as a model of whole-body sensorimotor skill learning. This task imposes high demands on agility ability because participants have to rapidly step in any of the four directions in response to a stimulus (Sheppard and Young, 2006). We introduced this CWB-SRTT in our previous publication (Mizuguchi et al., 2019). The plate to be stepped on was indicated by a target cue shown on any of four squares on a monitor, which was placed 2 m in front of the participant (Figure 1C). Each square represented one of four custom-designed plates (100 mm $\times$ 200 mm). The plates were separated by 0.5 m in the lateral direction and 0.5 m in the longitudinal direction. Participants were told

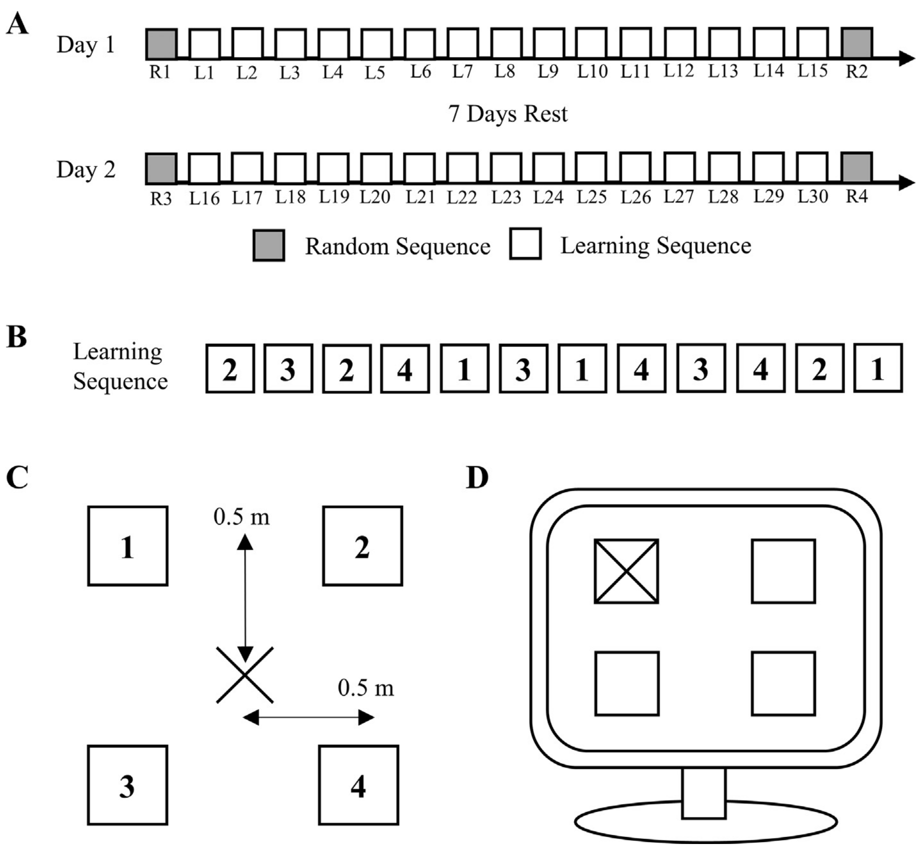

Figure 1. Complex whole-body serial reaction time task (CWB-SRTT) as a model of whole-body sensorimotor skill learning. (A) General experimental overview. Participants of both AG and NAG performed CWB-SRTT on two days separated by a week. Each day consisted of 15 learning blocks (L1-L15; L16-L30) and 1 random sequence before and 1 random sequence after the learning blocks (R1, R2, R3, R4). (B) The sequence during all learning blocks always appeared in the following fixed order: 2-3-2-4-1-3-1-4-3-4-2-1. (C) The initial position of participants during CWB-SRTT performance. Target plates were separated by 0.5 m in the lateral direction and 0.5 m in the longitudinal direction. All left-side plates had to be operated with the left foot, and all right-side plates with the right foot. The position of the plates corresponded to a specific number of the learning sequence (1: front left; 2: front right; 3: back left; 4: back right). (D) The plate to be stepped on was indicated by a target cue shown on any of four squares on a monitor placed 2 m in front of the participant.

to step on the target plate as fast as possible when a target cue emerged. All left-side plates had to be operated with the left foot, and all right-side plates with the right foot (Figure 1B). Participants were instructed to stand in the center of these four plates for the CWB-SRTT's initial position and to always return to this position after each motor response. After a correct motor response, the next target cue appeared 500 ms later. The target cue remained visible until the correct answer was given by the participant. Regarding the presented target cues, we chose 12 items per trial for reasons of comparability to our previous study (Mizuguchi et al., 2019). The target cue appeared in the following fixed order during the sequence block: 2-3-2-4-1-3-1-4-3-4-2-1 (1: front left; 2: front right; 3: back left; 4: back right). The number of steps in each direction was counterbalanced during the learning sequence (i.e., 3 steps front left, 3 steps front right, 3 steps back left & 3 steps back right) and all participants were naïve regarding the learning sequence. Additionally, we kept the existence of any sequence hidden from the participants, making this an implicit sensorimotor learning task. During the random sequences at the beginning and end of each day, the target cue appeared pseudo-randomly with equal probabilities regarding each number. We determined a limit of maximally three consecutive repetitions per item. The main outcome parameter was response time, defined as the time difference between the appearance of the target cue to initially hitting the corresponding plate to be stepped on. The electronic plates functioned like contact sensors, i.e., when participants stepped on the target plate, an electrical trigger was generated through capacitive touch sensing, that defined the time delay between stimulus onset and correct response. A custom-made script operated the CWB-SRTT (C#, Microsoft Visual Studio 2017).

2.5. Statistical analyses

First, we calculated the mean of response times over each performed sequence for each participant separately, resulting in 17 response times (2 random and 15 learning sequences) per experimental day and participant. All further statistical analyses were performed using JASP (Version 0.14.1.0, JASP Team 2020). The normality of the majority of response time variables was assessed and confirmed by Shapiro-Wilk testing ($\alpha = 0.05$).

To check whether the initial performance was different between the two groups, we compared response times at the first random sequence on day 1 (R1) using a two-sample t-test, respectively.

Sensorimotor skill learning was assessed within and between groups using a repeated-measures ANOVA with the between-subject factor GROUP (NAG, AG) and within-subject factor SEQUENCE (17 sequences) for each experimental day separately. In the case of a violation of the sphericity assumption, Greenhouse-Geisser correction was implemented.

Sequence-specific improvements in response times were evaluated by calculating the time difference between the last random sequence and last learning sequence on day 1 (R2-L15) and day 2 (R4-L30) separately. Both quantities were then compared using two-sample t-tests to evaluate differences in learning rates between NAG and AG.

Non-sequence-specific improvements in response time were evaluated by calculating the time difference between the first random sequence and the last random sequence on day 1 (R2-R1) and day 2 (R4-R3), respectively. Again, these parameters were compared between groups using two-sample t-tests.

Furthermore, to assess the retention of sequence-specific performance within and between groups, we compared response times at the last learning sequence on day 1 (L15) and the first learning sequence on day 2 (L16) using a repeated-measures ANOVA with the between-subject factor GROUP (NAG, AG) and the within-subject factor SEQUENCE (L15, L16).

The whole procedure of analyses outlined before was repeated for exploratory comparison between SG and EG. The statistical threshold for all analyses was set at $p < 0.05$. No outliers were removed from the analyses. Effect sizes were expressed either using partial eta squared (η_p^2) for ANOVAs or Cohen's d for t-tests.

3. Results

3.1. Non-athlete vs. athlete comparison (NAG vs. AG)

Initial performance in response times did not differ between NAG and AG ($t_{(49)} = 1.083$, $p = 0.284$, $d = 0.303$).

Repeated measures ANOVA indicated a significant effect for the factor GROUP ($F_{(1,\ 49)} = 5.347$, $p = 0.025$, $\eta_p^2 = .098$) and SEQUENCE ($F_{(5.501,\ 269.568)} = 40.346$, $p = 5.752 \times 10^{-33}$, $\eta_p^2 = .452$) on mean response times during day 1 (see Figure 2A). However, a significant interaction effect GROUP×SEQUENCE was not observed ($F_{(5.501,\ 269.568)} = 1.415$, $p = 0.214$, $\eta_p^2 = .028$), suggesting the absence of differential motor skill learning rates in NAG and AG. Post-hoc comparison for the factor GROUP revealed that response times in AG were significantly lower by approximately 50 ms compared to NAG (Mean Difference (MD) = 47.71, SE = 20.63, p = 0.025, d = .324).

A similar relation was observed for repeated-measures ANOVA on day 2 with a significant within-factor SEQUENCE ($F_{(3.380,\ 165.606)} = 48.312$, $p = 3.088 \times 10^{-24}$, $\eta_p^2 = .496$) and a non-significant interaction effect GROUP×SEQUENCE ($F_{(3.380,\ 165.606)} = 0.424$, $p = 0.759$, $\eta_p^2 = .009$; see Figure 2A). However, the factor GROUP failed to reach significance on day 2 ($F_{(1,\ 49)} = 3.876$, $p = 0.055$, $\eta_p^2 = .073$). Again, post-hoc comparison for the factor GROUP showed that response times in AG were lower compared to NAG on day 2 (MD = 42.96, SE = 21.82, p = 0.055, d = .276).

No differences were found on day 1 (97.42 ms vs. 98.83 ms; $t_{(49)} = -0.057$, $p = 0.955$, $d = -0.016$; see Figure 2B) and on day 2 (163.30 ms vs. 172.01 ms; $t_{(49)} = -0.271$, $p = 0.788$, $d = -0.076$; see Figure 2C) for sequence-specific improvement between NAG and AG. Furthermore, no differences in non-sequence-specific improvement were found between NAG and AG on day 1 (6.43 ms vs. -17.85 ms; $t_{(49)} = 1.438$, $p = 0.157$, $d = 0.403$) and day 2 (30.49 ms vs. 17.30 ms; $t_{(49)} = 0.820$, $p = 0.416$, $d = 0.230$).

Regarding retention of sequence-specific performance from day 1 to day 2, repeated-measures ANOVA showed a significant effect for the factors GROUP ($F_{(1,\ 49)} = 4.292$, $p = 0.044$, $\eta_p^2 = .081$) and SEQUENCE ($F_{(1,\ 49)} = 14.695$, $p = 3.609 \times 10^{-4}$, $\eta_p^2 = .231$). Post-hoc comparison for the factor SEQUENCE revealed that response times during L16 on day 2 were significantly higher compared to response times during L15 on day 1 (MD = 46.25, SE = 12.07, $p = 3.609 \times 10^{-4}$, d = .537). Post-hoc comparison for the factor GROUP showed that AG again had lower response times by approximately 40 ms compared to NAG (MD = 39.68, SE = 19.15, p = 0.004, d = .290). However, no significant interaction effect GROUP×SEQUENCE ($F_{(1,\ 49)} = 0.374$, $p = 0.544$, $\eta_p^2 = .008$) was found, indicating that groups did not differ in the degree of retention.

3.2. Athlete subgroup comparison (SG vs. EG)

Initial performance in response times did not differ between SG and EG ($t_{(23)} = -0.684$, $p = 0.501$, $d = -0.279$).

Repeated measures ANOVA indicated a significant effect for the factor SEQUENCE ($F_{(5.424,\ 124.760)} = 27.074$, $p = 2.355 \times 10^{-19}$, $\eta_p^2 = .541$) on mean response times during day 1. However, no significant effect for GROUP ($F_{(1,\ 23)} = 0.066$, $p = 0.799$, $\eta_p^2 = .003$) or interaction effect GROUP×SEQUENCE was observed ($F_{(5.424,\ 124.760)} = 1.157$, $p = 0.334$, $\eta_p^2 = .048$), suggesting the absence of differential learning rates in SG and EG.

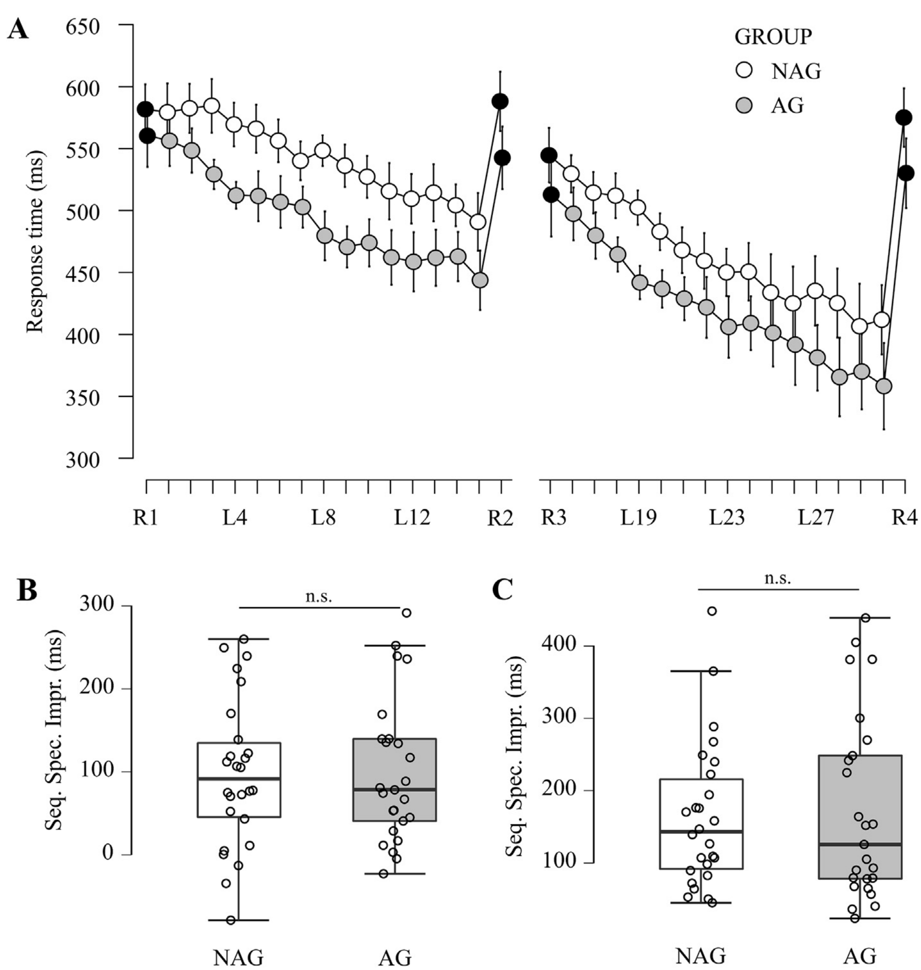

Figure 2. Results of complex whole-body serial reaction time task (CWB-SRTT). (A) Line graph illustrating CWB-SRTT learning on day 1 and day 2 for the non-athlete group (NAG) and the athlete group (AG). Shown are mean response times for each performed sequence. Error bars indicate 95% confidence interval of the mean. Black points indicate random sequences. (B) Between-group comparison of sequence-specific improvement (R2-L15) on day 1 (NAG vs. AG). (C) Between-group comparison of sequence-specific improvement (R4-L30) on day 2 (NAG vs. AG).

The same relation was observed for repeated-measures ANOVA on day 2 with a significant effect of the factor SEQUENCE ($F_{(2.482,\ 57.076)} = 26.170$, $p = 8.217 \times 10^{-10}$, $\eta_p^2 = .532$), a non-significant effect of GROUP ($F_{(1,\ 23)} = 1.508$, $p = 0.232$, $\eta_p^2 = .062$) and a non-significant interaction effect GROUP×SEQUENCE ($F_{(2.482,\ 57.076)} = 1.592$, $p = 0.207$, $\eta_p^2 = .065$).

No differences were found for sequence-specific improvement between SG and EG on day 1 (128.51 ms vs. 79.04 ms; $t_{(23)} = -1.439$, $p = 0.164$, $d = -0.588$) and on day 2 (211.04 ms vs. 145.99 ms; $t_{(23)} = -1.260$, $p = 0.220$, $d = -0.515$). Furthermore, no differences in non-sequence-specific improvement were found between SG and EG on day 1 (-19.34 ms vs. -16.82 ms; $t_{(23)} = 0.121$, $p = 0.905$, $d = 0.049$) and day 2 (16.97 ms vs. 17.53 ms; $t_{(23)} = 0.020$, $p = 0.984$, $d = 0.008$).

Regarding retention of sequence-specific performance from day 1 to day 2, repeated-measures ANOVA revealed no significant effect for the factors GROUP ($F_{(1,\ 23)} = 0.394$, $p = 0.536$, $\eta_p^2 = .017$) and no significant interaction effect GROUP×SEQUENCE ($F_{(1,\ 23)} = 0.178$, $p = 0.677$, $\eta_p^2 = .008$) was found, indicating that subgroups did not differ in the degree of retention. However, a significant effect for the within-subject factor SEQUENCE was found ($F_{(1,\ 23)} = 7.501$, $p = 0.012$, $\eta_p^2 = .246$). Post-hoc comparison for the factor SEQUENCE revealed that response times during L16 on day 2 were significantly higher compared to response times during L15 on day 1 (MD = 55.35, SE = 20.20, $p = 0.012$, $d = .548$).

4. Discussion

In the present study, we aimed to characterize differences between a group of athletes that included both strength and endurance athletes (AG) and non-athletes (NAG) in their ability to perform and learn a complex whole-body serial reaction time task (CWB-SRTT). When comparing NAG and AG, initial performance did not differ between the two groups. Furthermore, there were no differences in sequence-specific nor non-sequence-specific improvements comparing NAG with AG. However, mean response times of AG were significantly lower compared to NAG on day 1. Analysis of motor skill learning rates between NAG and AG revealed no significant differences between the two groups at either day 1 or on day 2. Although we found significant effects of the factors GROUP and SEQUENCE on retention rates, we were unable to demonstrate a significant interaction between the two factors, suggesting that there were no significant differences in retention between the two groups. We further divided the group of athletes into strength (SG) and endurance (EG) athletes. Here, the initial learning rates did not differ between the groups. Similar results were found regarding the average response times on both learning days, as neither sequence-specific nor non-sequence-specific improvements were observed between SG and EG. In addition, learning rates showed no significant differences between the two groups, indicating similar improvements in CWB-SRTT acquisition and performance. Finally, when retention was assessed, response times were significantly higher on day 2 compared with day 1. However, our results showed neither a significant effect for GROUP factor nor a significant interaction between GROUP and SEQUENCE factors. This is similar to the results for NAG vs AG, as retention rates also were not significantly different between SG and EG. All findings and their implications are discussed in detail below.

The lack of differences in initial performance between NAG and AG was expected since all participants were task naïve. Furthermore, CWB-SRTT does not contain specific movement patterns related to common practice routines of endurance or strength athletes. Although athletes of various disciplines generally have lower visual and auditory reaction times compared to non-athletes (Atan and Akyol, 2014; Barrett et al., 2020), several studies indicate that these differences are highly sport- and task-specific (Dogan, 2009; Kida et al., 2005). Furthermore, CWB-SRTT represents an extension of the simple, choice, and serial reaction time tasks. In CWB-SRTT, comparatively higher processing demands are placed on visuomotor information integration as well as motor coordination and postural stability (Mizuguchi et al., 2019). For this reason, it is unlikely that a significant group-specific difference in initial performance is related to overall athletic competence. It is therefore not surprising that the initial performances between SG and EG did not differ between groups. Although both groups theoretically differ in terms of their general motor adaptations related to different long-term training regimens (Hughes et al., 2018), a specific transfer effect on the initial execution of a new motor sequence pattern is rather unlikely to occur. Interestingly, the effects of motor skill transfer have been shown to be closely related to the variability of training schedules (Mussgens and Ullen, 2015). Therefore, monitoring athletes' training regimens and separating groups according to the degree of variability within their training is an important aspect that should be considered in future studies. Although initial performance did not differ, we observed a general effect between groups on response times. On average, AG was ~50 ms faster compared to NAG. This was expected as many studies show that athlete reaction times, a component of response time, are generally better compared to non-athletes (Atan and Akyol, 2014; Dogan, 2009; Verburgh et al., 2016). Reaction times reflect basic sensorimotor skills. As such, reaction time can positively influence concentration, attention, and effective motor responses (Ali et al., 2018), thus plays a role in athletic performance and mainly accounts for the observed results of different response times between NAG and AG in our study.

We observed sequence-specific improvements in response times for NAG and AG. A decrease in response time across sequence learning blocks along with an increase in response time during a subsequent random sequence block is a common finding for SRTT paradigms (Moisello et al., 2009). However, no significant differences in sequence-specific improvements were observed when comparing both groups on either day. These findings thus indicate that sequence-specific improvements in response times were similar between groups. Although sequence-specific learning is straightforward in the sense that practice of a constant sequence leads to an improvement within this sequence over time (Dayan and Cohen, 2011), the underlying strategies are still not entirely known. In the context of serial reaction time adaptation, several acute adaptations are being discussed as possible mechanisms. Among those are the acquisition of the sequence of stimuli (Haider et al., 2014), knowledge concerning response locations (Willingham et al., 2000), as well as knowledge concerning sequence latency between response and subsequent stimuli (Shin, 2008). One such adaptation or a combination of multiple adaptations may result in the observed sequence-specific improvement (Zhao et al., 2019). The lack of difference between sequence-specific improvements may be related to the sport- and exercise-independent nature of the CWB-SRTT. Recent findings support this assumption, as it was demonstrated that non-sport-specific training in a visuomotor task improved cognitive but not sport-specific motor performance within such tasks (Formenti et al., 2019). Further, compared to sport-specific training, non-sport-specific training of general motor abilities was shown to be superior in improving complex motor performance in football players (Trecroci et al., 2016). Consequently, although gross motor skills are necessary for the development of sport-specific skills (Beamer et al., 1999; Oliver et al., 2011), the environment in which novel skills are performed and learned plays a crucial role in the development of adaptation strategies concerning task-specific perception and action (Formenti et al., 2019, 2021). It is therefore reasonable to assume that the specificity of the task, rather than the athletic background, is mainly responsible for learning outcomes in CWB-SRTT.

Learning rates also did not differ between (1) NAG and AG or (2) SG and EG. In the cognitive domain, higher learning rates are often reported for athletes of various disciplines compared to non-athletes (Alves et al., 2013; Florkiewicz et al., 2014; Mann et al., 2007; Savelsbergh et al., 2005). Better extraction, encodement, and retrieval of task-relevant information are commonly cited as reasons for better learning rates of athletes in cognitive tasks. Since many cognitive abilities are also necessary for sports, e.g., sustained attention, perceptual and visual skills

(Savelsbergh et al., 2005), it is tempting to speculate that there may be an overlap between superior cognitive and motor learning abilities in athletes. However, these improved cognitive learning rates in athletes are again related to task specificity. That is, many athletes show better learning rates on cognitive tasks in the sport context, but these superior learning rates are not evident for general non-specific cognitive skills (Kida et al., 2005). Therefore, the CWB-SRTT may be as nonspecific for NAG as it is for AG, SG, and EG, and thus, although all groups are physiologically distinct, they are equivalent in terms of task-specific neurocognitive and executive abilities, resulting in similar learning rates. Retention rates also did not differ between (1) NAG and AG or (2) SG and EG. Although exercise has been shown to improve retention rates in a number of motor skills (Song et al., 2015), these effects were only noticeable after acute training, in contrast to the long-term effects of exercise (Roig et al., 2012). Therefore, compared to long-term effects, acute effects of exercise might be more beneficial with regard to retention rates in a motor sequence learning paradigm (Taubert et al., 2015).

4.1. Limitations

The first limitation of our paradigm is that both groups of athletes may not be sufficiently specific considering the demands of CWB-SRTT. The rationale for selecting endurance and strength athletes was to examine athletes with pronounced fundamental motor abilities, i.e., strength and endurance athletes in order to provide a general reference point for future studies. Secondly, long-term strength and endurance training induces differential global adaptations i.e., predominantly cardiovascular (endurance) and neuromuscular (strength) improvements while also enabling complex whole-body movement pattern acquisition in both strength and endurance athletes. However, our findings demonstrate that neither form of exercise is significantly affecting key parameters related to CWB-SRTT performance. Two solutions to these problems can be proposed. First, the CWB-SRTT can be tailored to a specific sport or exercise regime. Second, more specific groups of athletes can be selected. As the CWB-SRTT poses demands on postural control, and rapid shifting of attentional resources (participants must quickly step in one of four directions), athletes that fit the profile, such as football or parcours athletes could be recruited in future studies. Additionally, the level of expertise of our athlete groups might not be distinctive enough. Since previous studies have shown that cognitive abilities differ between high-level and low-level athletes (Scharfen and Memmert, 2019) future studies should include athletes of one sport at different levels of expertise to test this influence. Another limitation is the fact that we cannot separate the implicit and explicit learning components. The SRTT is not considered a strictly implicit task (Robertson, 2007). However, it would be helpful to gain an understanding of the time course of explicit and implicit motor learning within this task. To approach this, future studies should monitor training background in terms of variability as well as ask participants about knowledge of sequences. Further, an additional limitation is related to the main parameter of the CWB-SRTT, the mean response times. Due to technical restraints of the experimental design in the present study, the mean response times cannot be separated into reaction times (time from stimulus to onset of motor action) and motor times (time from onset of motor action to touching the plate). Future studies should consider enabling the separation between reaction and motor times within the design of novel SRTT's. A final limitation of our study is that retention was not evaluated at a later time point. Retention rates differ greatly between motor skills (Dayan and Cohen, 2011), thus additional time points are needed to fully capture retention rates following CWB-SRTT training.

5. Conclusion

Our findings show that strength and endurance athletes and non-athletes do not differ in their ability to learn a novel CWB-SRTT. Although we found lower mean response times in our athlete group, neither sequence-specific nor non-sequence-specific learning rates differed between NAG and AG. We argue that this is due to the fact that there is no motor transfer between general athletic abilities and specific motor sequence learning within this task. The study of motor skill acquisition within complex whole-body movements is important for both amateur and competitive sports. Especially in the training of young athletes, the balancing act between general physical education and early skill specialization is one without a clear, and correct strategy. In this sense, the stepwise uncovering of differentiated motor learning behavior of different sports seems to be a promising starting point to address this issue. Future studies should attempt to increase task specificity by either tailoring the task to a specific athletic domain or including more narrowly recruited athletes that fit the kinematic profile of the CWB-SRTT.

Declarations

Author contribution statement

Caroline Schempp and Eric Noack: Conceived and designed the experiments; Performed the experiments.

Patrick Ragert: Conceived and designed the experiments.

Tom Maudrich and Rouven Kenville: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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