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Does the inverted-U function disappear in expert athletes? An analysis of the attentional behavior under physical exercise of athletes and non-athletes

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HIGHLIGHTS

- Two experiments compare athletes' and non-athletes' attentional behavior.
- Completion of the attention-window paradigm under different exercise intensities.
- Non-athletes' attentional performance level represents an inverted-U relationship.
- Athletes show a linear increase of attentional performance level.

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ABSTRACT

A number of studies document that physical exercise influences cognitive performance in a variety of ways. Some of these studies present the relationship between the workload of exercise and the activation level of the central nervous system as an inverted-U relationship. Among the factors that could be responsible for diverging results are the participants' individual fitness level and the athletic status. While athletes and non-athletes do not differ in general cognitive skills, athletes are better able to maintain these during physical exercise especially under high exercise intensities. Hence, we hypothesized that the inverted-U function applies for non-athletes but disappears in team sports experts. We compared athletes' and non-athletes' cognitive performance on a measure of attentional behavior under three different physical exercise intensities. Results showed an increase of non-athletes' attentional breadth right up to a certain level of maximal aerobic power before decreasing, as expected according to an inverted-U curve. In contrast, athletes' attentional breadth continued to increase with higher physical exercise intensities. We concluded that physical exercise influences participants' attentional behavior and that individual fitness acts as a moderator of this relationship.

1. Introduction

It is well-known that, particularly during fast team ball sports, athletes are required to deal with a multitude of attentional processes under physical exercise ranging from moderate to intensive effort. They have to simultaneously perceive the positions and movements of teammates, opponents, and the ball, and consciously decide on the best possible action [1]. In order to be successful, team sports players should have and maintain a high fitness level as well as a high cognitive skill level irrespective of physical exercise bouts. Among the factors that might be responsible for performance differences between expert athletes and novices in team sports, for example at the end of a game or during intensive physical effort, might be the relationship between individuals' athletic status and cognitive skill level.

A large number of studies have focused on the influence of physical exercise on the efficiency of cognitive processes. Several studies were able to show that moderate physical exercise improves cognitive performance (e.g., [2,3]). Among other things, authors provided evidence of positive effects of exercise on simple reaction time (e.g., [4]), choice reaction time (e.g., [5,6]), as well as stimulus detection, and coincidence-timing (e.g., [7]). Relatively few studies have attempted to examine the effects of physical exercise on attentional processes (e.g., [8–12]) assuming that an increase in arousal and activation levels allows for higher involvement of attentional resources to the performed cognitive task [13,14]. Pesce and colleagues focused on acute exercise effects on attention as a function of physical fitness and sports-related expertise but without manipulation of exercise intensity. Huertas, Sanabria, and colleagues concentrated on visual attention during bouts of exercise, giving further information about how visual attention

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changes under physical effort; however, they did not address the expertise/fitness issue.

In total, the beneficial relationship between exercise and cognition seems to be caused by enhanced arousal and the amount of allocatable resources [13,15]. However, several research works do not only show a positive effect of exercise on cognitive behavior but they also document that performance increases until a certain optimal point which seems to be close to the *anaerobic (lactate) threshold*. As a result, exercises at high intensity above the optimal point or the anaerobic threshold worsen cognitive performance [2]. This indicates that the intensity acts as a moderator of the acute exercise–cognition relationship. The improved effects of moderate physical exercise on cognitive performance are generated by an improvement in the cerebral blood circulation and an alteration of the neurotransmitters' action [16]. A facilitated regional cerebral blood flow positively affects cognitive task performance. The blood lactate concentration increases rapidly as soon as the anaerobic threshold is reached while, at the same time, human production of hormones and catecholamines is activated [17,18] resulting in a decrease of cognitive performance. There is a mismatch between lactate production and uptake at exercise intensities above the anaerobic threshold since the rate of lactate removal is lagging behind the rate of lactate production [19]. The relationship between exercise workload and the activation level of the central nervous system [20] is illustrated as an *inverted-U curve* [21].

However, in contrast to studies that found a positive effect of physical exercise until a certain exercise intensity, providing support for the approach of an inverted-U function, there are also a number of other studies showing that the physical exercise intensity does not have any influence on the cognitive performance (for a review, see [22,23]). Among others, McMorris, Collard, Corbett, Dicks, and Swain [24] did not find a direct effect of increments in plasma catecholamine concentrations induced by increasing exercise intensity on cognition. As a consequence, McMorris [25] proposed a neuroendocrinological explanation to conciliate the inconsistent findings related to the acute exercise–cognition interaction.

Recent meta-analyses addressed the failure to unequivocally demonstrate an inverted-U effect [22,23]. One of the major contributing factors for the contradictory results is the difference in the methods used by the different researchers. Some examples of factors that are responsible for the methods' inconsistency among several studies are cognitive and physical task characteristics (type, intensity, duration) as well as cognitive task demands [22,23,26]. Considering the cognitive performances athletes still attain under higher physical exercise compared to non-athletes, it is possible that different levels of expertise or athletic status might also have an influence on the presence or absence of an inverted-U function.

In the present study, we examined whether there is an inverted-U relationship between the intensity of an acute bout of physical exercise and visual attentional performance as well as whether physical exercise effects on attentional performance are moderated by the individual athletic status. Following the evidence that highlights a superior cognitive performance of athletes compared to non-athletes during physical exercise of high intensity, we hypothesized that team sports experts would be able to maintain attentional performance for a longer period in comparison to non-athletes during high-intensity physical exercise. We assumed that both athletes' and non-athletes' attentional performance would increase when starting with low up to moderate physical exercise because of an enhanced arousal and amount of allocatable resources [13,15]. As soon as the anaerobic threshold is reached, non-athletes' attentional performance would decrease, as opposed to athletes' performance where it would remain constant (e.g., [27]). In other words we assumed that expert athletes, in contrast to non-athletes, would maintain their attentional performance also during physical exercise above the anaerobic threshold. We measured individuals' attentional performance under physical exercise when simultaneously focusing on two peripheral targets with systematically varying positions [28,29]. An attention-demanding conjunction task was used to exclude pre-attentive and automated responses [30,31]. Since a significant number of studies dealing with physical exercise induced increased heart rates during cycling on an ergometer, we have also decided to employ this approach. We compared the performance of non-athletes to that of expert athletes and defined the physical exercise intensity at 50%, 60%, and 70% of the individual maximum heart rate.

2. Method

2.1. Participants

A total of 17 university students (6 females) between 20 and 32 years of age ($M_{\text{age}} = 25.47$, $SD = 3.76$ years) participated voluntarily in the study. All participants reported normal vision without need for corrective lenses. All of them provided informed consent before being involved in the study.

Following the procedure of Ericsson [32], participants with more than ten years of intensive training in a team sports and regular exercise (at least three times per week) were categorized as expert team sports athletes ($n = 8$, 2 females; $M_{\text{age}} = 24.88$, $SD = 3.27$ years; $M_{\text{team sports experience}} = 11.02$, $SD = 5.72$ years). Primary team sports included basketball ($n = 1$), handball ($n = 2$), soccer ($n = 3$), and volleyball ($n = 2$). Participants without any team sports experiences and no regular physical exercise (two times per week or less) were classified as non-athletes ($n = 8$, 4 females; $M_{\text{age}} = 26.00$, $SD = 4.27$ years).

According to Shvartz and Reibold [33], a fitness category was individually calculated for each participant: *1 = excellent*, *2 = very good*, *3 = good*, *4 = average*, *5 = fair*, *6 = poor*, and *7 = very poor*. We found a significant difference between team sports athletes' (2.00 ± 0.53) and non-athletes' values (4.56 ± 0.53), $t = -9.913$, $p < .001$.

2.2. Materials and procedure

Participants were tested in a laboratory room where they were required to sit on a bicycle ergometer (Lode OEM®) at a distance of 60 cm from a PC-driven video screen with a visual angle of about 73° in the horizontal and 45° in the vertical direction. They also wore a heart rate monitor (Polar S810®) and heart rates as well as the pedal frequency were continuously monitored during the whole testing period.

Eye position was monitored by using a head-mounted eye tracking system (Eye Mobile®, Applied Science Laboratories, Bedford, U.S.A.). The system mapped the fixation position onto a video image of the surroundings, with a sampling rate of 30 Hz and a resolution of 1°. Participants were instructed to keep their head still and maintain fixation throughout the trials. Trials in which they failed to maintain fixation were deleted (4% of the trials of athletes, 2% of the trials of non-athletes).

Before participating in the primary experiment, participants performed a perimetry test (visual field test) to verify that stimuli were visible in the periphery and that any limitations in perception were due to attention and not limited peripheral acuity. While fixating straight ahead, a single visual stimulus was moved from the participants' visual periphery toward the center until they could recognize it. Both eyes were tested separately; the eye not being tested was covered until completion of the test. Participants were able to identify the stimuli at eccentricities up to $M = 58.24°$ ($SD = 2.31°$). Consistent with the findings from previous studies that athletes generally do not differ from non-athletes in basic measures of visual perception such as acuity [34−37], the measured values of the expert athletes ($M = 57.63°$, $SD = 2.20°$) and non-athletes ($M = 58.78°$, $SD = 2.39°$) were not significantly different ($t = -1.031$, $p = .319$).

2.2.1. Physical exercise

Target heart rates for each participant were computed for physical exercise intensities of 50%, 60%, and 70% of individual maximum heart rates. (As opposed to VO_{2max}, the heart rate is considered to be a simple alternative index to measure exercise intensity during physical exercise [38]). In order to assess the maximum heart rate, two formulas were employed based on participants' age and gender: (220 − age) beats min^{-1} for male and (226 − age) beats min^{-1} for female participants [39]. Analysis indicated no significant differences ($t = -0.301$, $p = .767$) of maximum heart rate values between athletes ($M = 195.88$ bpm, $SD = 4.09$ bpm) and non-athletes ($M = 196.67$ bpm, $SD = 6.34$ bpm). The physical exercise intensities were increased by increments in resistance strength to be applied for pedaling. Each exercise load intensity was determined as required target heart rate, respectively 50%, 60%, and 70% of the maximum heart rate. Fifty percent of the maximum heart rate conformed to $M = 98.15$ bpm, $SD = 2.63$ bpm, 60% to $M = 117.78$ bpm, $SD = 3.15$ bpm, and 70% to $M = 137.41$ bpm, $SD = 3.68$ bpm across all participants. They warmed up for a period of 5 min. Starting with a 50 W exercise, the wattage was increased stepwise until participants reached their individual required target heart rates. Subsequently, the attentional breadth measure task was initiated and exercise continued with simultaneous heart rate monitoring. Whenever the actual heart rate deviated from the required target heart rate more than ±5 beats min^{-1}, adjustments were made to the individual exercise by altering the wattage. Participants performed the three test conditions with different exercise intensities in random order for approximately 10 min each, depending on their speed of responses. They had to pedal on the bicycle ergometer at 60 rpm to be in accordance with physiological optimal rates reported by Gregor, Broker, and Ryan [40]. They were also instructed to strictly maintain the imposed pedal rate.

For evaluation of the subjective exercise sensibility, participants had to state their perceived exertion on a Borg-scale after completing each of the exercise intensities. Although this can be considered as a subjective measure, a person's exertion rating may provide a fairly good estimation of the actual heart rate during physical activity [41]. The scale reflects how heavy and strenuous the exercise feels to participants, combining all sensations and feelings of physical stress, effort, and fatigue. The scale rates physical exertion on a range that varies from 6 (no exertion at all) to 20 (maximal exertion).

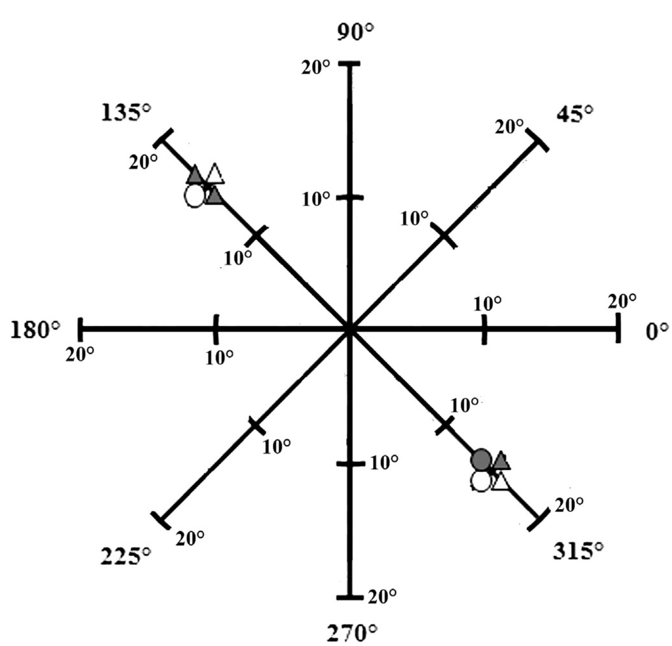

Fig. 1. Stimuli were located at one of 16 possible distances from the center of the screen along one of four meridians (0°/180°, 45°/225°, 90°/270°, or 135°/315°). The figure shows a stimulus pair separated by 30° along the 135°/315° meridian. Note that the meridians and distance marks were not visible to participants and are included here only for illustration purposes (adapted from [28]).

2.2.2. Attentional task

In the attentional breadth measuring task (see [28]), participants had to judge the number of light gray triangles in different stimulus pairs presented on the PC-driven video screen while pedaling on the bicycle ergometer at the three above described physical exercise intensities. The members of each stimulus pair appeared equidistant from and on opposite sides from the central fixation cross along one of four meridians (horizontal: 0°/180°, vertical: 90°/270°, diagonal 1: 45°/225°, diagonal 2: 135°/315°; see Fig. 1). Stimulus pairs generated with E-Prime® were presented on the screen in 16 possible locations along each of the meridians, and for analyses, we combined data from the two diagonal meridians. The members of a pair were separated by a visual angle that ranged from 10° to 40° (in 2° increments). Fig. 2 illustrates a stimulus pair on one of the diagonal meridians. The meridian and stimulus separation were fully crossed, with each combination tested twice (16 separations × 3 meridians × 2 repetitions), giving a total of 96 experimental trials for each of the exercise intensities.

Each stimulus consisted of four elements (2.8 cm × 2.8 cm) arranged in a square. Each of the elements was assigned a shape (circle or triangle) and a color (light or dark gray). A stimulus included 0, 1, 2, 3, or 4 light gray triangles with equal probability (i.e., on 20% of trials). Both, form and shading of all elements of a stimulus varied randomly. On each trial, participants had to verbally state the number of light gray triangles without time pressure for both stimulus configurations. Only if participants reported the correct number of light gray triangles for both stimuli, responses were treated as correct. Due to the fact that participants had to detect the conjunction of both, form and shading of stimuli elements, this was considered an attention-demanding task ([30,31]; see [28], for a complete description of this task).

During the warm-up phase on the bicycle ergometer, participants completed 16 practice trials. The primary experiment included 288 trials separated into three blocks of 96 trials for each of the exercise intensities with 30 s breaks in between blocks. A trial consisted of a sequence made of six displays (see Fig. 2). Participants were required to fixate between the two presented stimuli and process both peripherally. Each trial started with a 1000 ms central fixation cross, equidistant from each stimulus location. Subsequently, a 200 ms pre-cue (black outline circle with 2.5 cm diameter) appeared on one of the 16 possible stimulus locations. Following a 200 ms blank interval, the stimulus pair appeared at the pre-cued locations for 300 ms—a time interval too short to saccade between the stimuli. Then, participants verbally reported the number of light gray triangles (0–4) in each target stimulus, and the experimenter recorded their responses.

3. Results

The subjective Borg rating was not significantly different between groups for 50% exercise intensity ($M = 10.38$, $SD = 0.92$ for athletes; $M = 11.00$, $SD = 0.71$ for non-athletes; $t = -1.585$, $p = .134$) and 60% ($M = 13.25$, $SD = 0.89$ for athletes; $M = 13.89$, $SD = 0.60$ for non-athletes; $t = -1.758$, $p = .099$) but for 70% exercise intensity of maximum heart rate ($M = 15.75$, $SD = 1.28$ for athletes; $M = 17.00$, $SD = 0.71$ for non-athletes; $t = -2.531$, $p < .05$).

The individual and joint effects of athletic status and physical exercise intensity on attentional performance were analyzed as a function of the attentional breadth by a 2 (athletic status: athletes, non-athletes) x 3 (exercise intensity: 50%, 60%, 70% of maximum heart rate) × 4 (stimulus separation: 10°, 20°, 30°, 40°) analysis of variance (ANOVA), with repeated measures on the last two factors. Since Mauchly's test revealed violations of the sphericity assumption for the factor stimulus separation, $\chi^2(5) = 12.883$, $p = .025$, we used adjusted degrees of freedom based on the Greenhouse–Geisser correction. For these analyses in

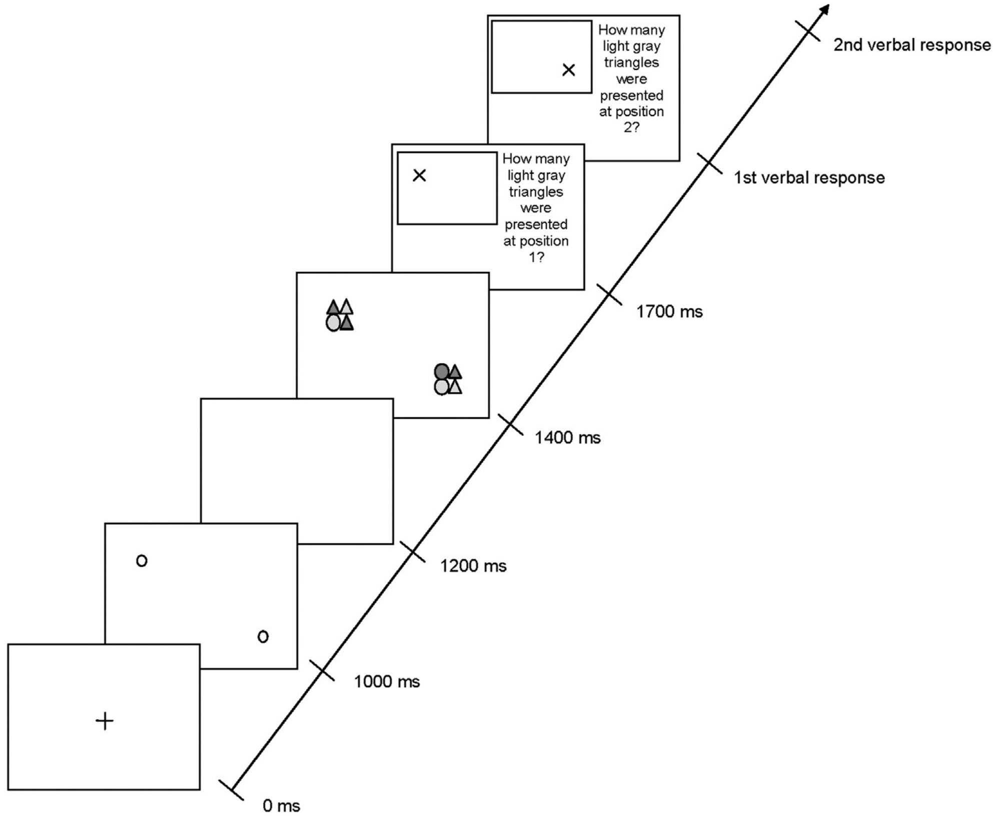

Fig. 2. Sequence of events in a trial from the attentional breadth measurement task with the stimuli presented along the diagonal meridian (135°/315°; adapted from [29]).

which the sphericity assumption was violated, we reported the value of ε from the Greenhouse–Geisser correction. The ANOVA revealed significantly higher success rates for athletes ($M = 73.80\%$, $SD = 3.81\%$) as compared to non-athletes ($M = 60.55\%$, $SD = 6.92\%$), $F(1, 15) = 23.009$, $p < .001$, $\eta^2 = .605$. There was a significant main effect for exercise intensity, $F(2, 30) = 3.643$, $p = .038$, $\eta^2 = .195$, and stimulus separation, $F(1.928, 28.924) = 178.292$, $p < .001$, $\eta^2 = .922$, $\varepsilon = .643$.

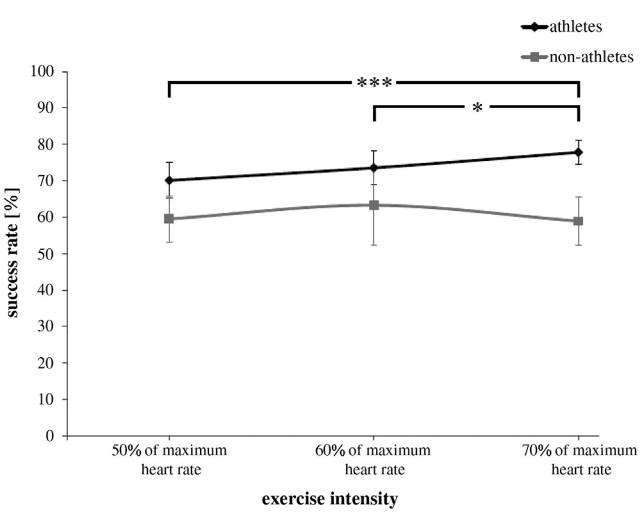

Fig. 3. Attentional differences between athletes and non-athletes as a function of exercise intensity. Symbols represent across-subject means, error bars the standard deviations, and asterisks indicate significance (* p<.017, *** p<.001 with an adjusted alpha of 0.017 of the Bonferroni corrected post-hoc comparisons).

Expert athletes outperformed non-athletes in the attentional breadth task during 50% (expert athletes: $M = 70.07\%$, $SD = 4.91\%$; non-athletes: $M = 59.50\%$, $SD = 6.32\%$; $t(15) = 3.814$, $p = .002$), 60% (expert athletes: $M = 73.52\%$, $SD = 4.59\%$; non-athletes: $M = 63.26\%$, $SD = 11.10$; $t(15) = 2.430$, $p = .028$), and 70% (expert athletes: $M = 77.79\%$, $SD = 3.33\%$; non-athletes: $M = 58.90\%$, $SD = 6.62\%$; $t(15) = 7.281$, $p < .001$) workload intensity of maximum heart rate. Overall, participants attained highest success rates at 60% ($M = 68.09\%$, $SD = 9.93\%$) compared to the 50% ($M = 64.48\%$, $SD = 7.75\%$), and 70% ($M = 67.79\%$, $SD = 11.01\%$) physical exercise intensity of maximum heart rate. Attentional performance decreased with increasing stimulus separation (10° stimulus separation: $M = 86.58\%$, $SD = 10.03\%$; 20° stimulus separation: $M = 75.44\%$, $SD = 9.71\%$; 30° stimulus separation: $M = 59.69\%$, $SD = 10.15\%$; 40° stimulus separation: $M = 45.42\%$, $SD = 10.05\%$).The effect of exercise intensity also varied as a function of athletic status, as indicated by a significant interaction, $F(2, 30) = 5.107$, $p = .012$, $\eta^2 = .254$. Athletes attained highest success rates at 70% ($M = 77.79\%$, $SD = 1.89\%$) compared to the 60% ($M = 73.52\%$, $SD = 3.07\%$; 70% vs. 60%: $t(7) = 3.374$, $p = .012$), and 50% ($M = 70.07\%$, $SD = 2.02\%$; 70% vs. 50%: $t(7) = 5.735$, $p = .001$) physical exercise intensity of maximum heart rate (60% vs. 50%: $t(7) = 2.942$, $p = .022$). Accuracy was comparable for the 50% ($M = 59.50\%$, $SD = 1.90\%$), 60% ($M = 63.26\%$, $SD = 2.90\%$), and 70% ($M = 58.90\%$, $SD = 1.78\%$) physical exercise intensity of non-athletes' maximum heart rate (50% vs. 60%: $t(8) = -1.293$, $p = .232$; 50% vs. 70%: $t(8) = 0.323$, $p = .755$; 60% vs. 70%: $t(8) = 1.438$, $p = .188$; Bonferroni corrected post-hoc comparisons had an adjusted alpha of 0.017). Fig. 3 shows the athletes' and non-athletes' attentional performance as a function of exercise intensity.While the three-way interaction (athletic status x exercise intensity x stimulus separation) was also significant, $F(4.252, 63.773) = 2.229$, $p = .047$, $\eta^2 = .129$, the other two-way interactions did not show any significant effect (athletic status x stimulus separation,

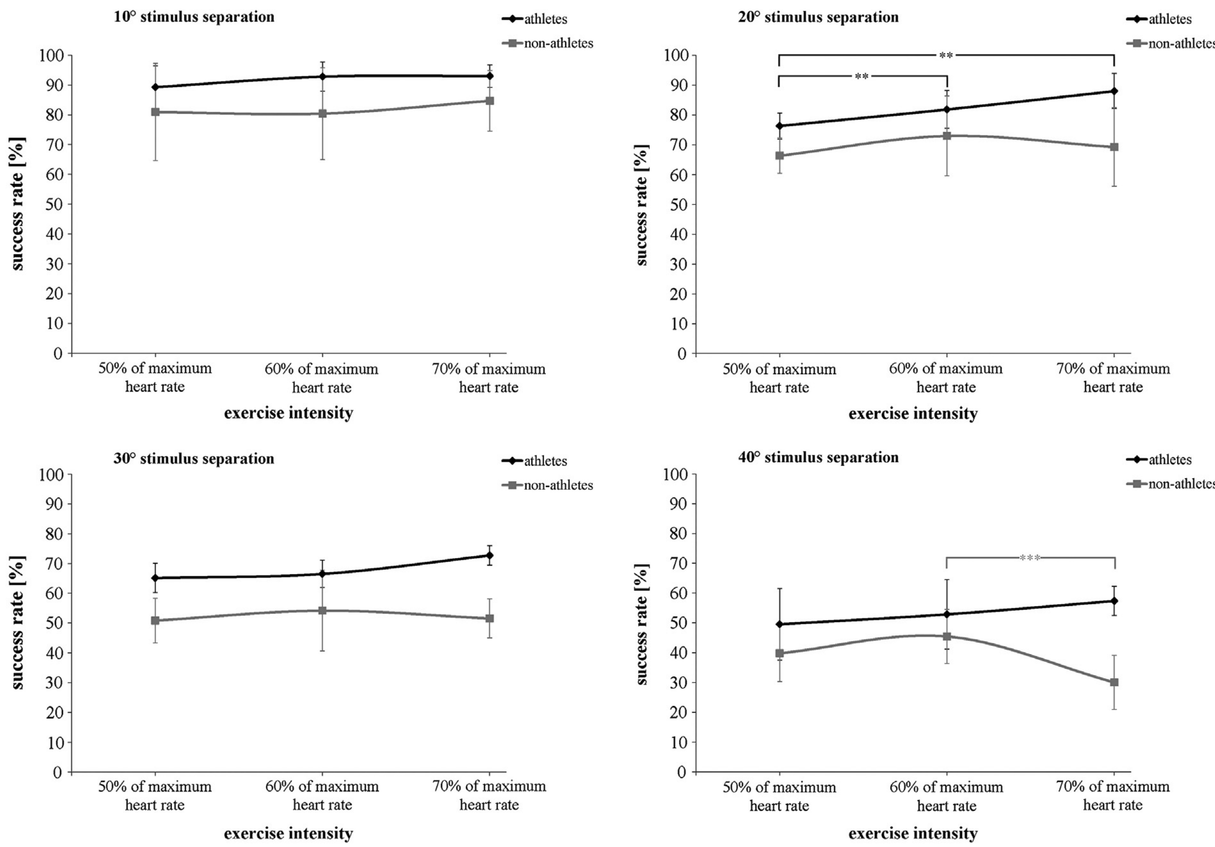

Fig. 4. Attentional differences between exercise intensities as a function of athletic status for 10° (top, left), 20° (top, right), 30° (bottom, left), and 40° (bottom, right) stimulus separation. Symbols represent across-subject means, error bars the standard deviations, and asterisks indicate significance (** $p<.01$, *** $p<.001$ with an adjusted alpha of 0.017 of the Bonferroni corrected post-hoc comparisons).

$F(1.928, 28.924) = 1.041$, $p = .384$, $\eta^2 = .065$; exercise intensity x stimulus separation, $F(4.252, 63.773) = 1.635$, $p = .147$, $\eta^2 = .098$). Fig. 4 represents attentional differences between exercise intensities as a function of athletic status and stimulus separation.

4. Discussion

In the last decades, different studies have focused on the exercise–cognition relationship (e.g., [42,43]) and its potential mediators and moderators [44,45]. Among the features that can play a moderating role in acute exercise–cognition relationships (e.g., the features of the physical exercise task and the type of cognitive performance) there are not only the characteristics of the physical exercise task and the type of cognitive task but also the participants' physical characteristics [43]. Both, the physical fitness level [22] and the sports-related expertise [26] belong to the individual characteristics acting as moderators on the acute exercise–cognition relationship. The aim in the current paper was to verify the validity of the inverted-U relationship between exercise and cognitive performance for expert team sports athletes and non-athletes through the analysis of attentional performance under different exercise intensities (50%, 60%, and 70% of individual maximum heart rate).

The new finding of the present study is that expert athletes are able to maintain their attentional performance level during physical exercise independently of workload intensity while for non-athletes, cognitive performance increases until a certain point of exercise capacity (more precisely to 60% of individual maximum heart rate) after which it starts to decrease. The results confirmed the inverted-U hypothesis [22,23] of physical exercise effects on cognition only in non-athletes and documented a linear increase in attentional performance up to the highest tested exercise intensity in the present study (70% of individual maximum heart rates) in expert athletes. The observed effect of physical exercise on attentional performance in non-athletes is consistent with previous results reported in different research works during basic cognitive tasks (for a review, see [46,47]) that show a cognitive performance improvement with exercise-induced activation of the central nervous system and deterioration after exceeding a certain work intensity (e.g., [2]). Following previous research studies, there is an indication that physical exercise benefits cognitive performance due to enhanced arousal and a freed amount of allocatable resources [13,15] until the anaerobic threshold is reached. Any effort above this level would cause the production of lactate which is associated with the decrease of cognitive performance. Now, one might speculate that athletes were able to maintain their attentional performance level since their anaerobic threshold was not reached, first because non-athletes slightly rated the workload intensity during 70% workload intensity of maximum heart rate higher than athletes did; and second, because previous research found higher values of athletes' anaerobic threshold compared to non-athletes [48–50]. Nevertheless, our results are consistent with those of previous studies showing an enhancement of cognitive performance through improvements in physical fitness levels [26,47,51]. In total, athletes characterized as team sports experts with a high fitness level performed better in the attentional breadth measure task across all exercise intensities. Consequently, we can now give evidence that athletic status has a positive impact on the attentional response to higher exercise doses.

From the practical point of view, it is important that expert team sports athletes are able to appropriately adjust their attentional focus even under high physical workload since they should make an optimal decision under these conditions during a match. Besides the playing skills as well as further individual circumstances, the maintenance of the attentional performance will be one of the reasons why high-class teams mostly win against bush-league teams in cup matches. Future research might attempt to focus on the time interval in which expert athletes are able to maintain their cognitive performance level. In the present study, participants had to keep up their focus in each of the exercise intensities for approximately 10 min. In their meta-analysis, Lambourne and Tomporowski [23] concluded that steady-state exercise has a positive effect on cognitive performance and a negative effect for incremental and fatiguing exercise. Hence, it would be interesting to examine how long athletes are able to maintain their cognitive performance level under physical exercise of high intensity. That would particularly be interesting for the estimation of athletes' possible performance decline at the end of a game in different team sports.

5. Conclusions

A number of past investigations have documented that athletes and non-athletes do not differ in general cognitive skills, although physically-fit individuals are able to reach better cognitive performance under physical exercise of high intensity than individuals with lower fitness level. We compared team sports athletes' and non-athletes' attentional performances under physical exercise across three different workload intensities. Athletes did not show an inverted-U relationship between physical exercise and cognitive performance, at least not for physical exercises up to 70% workload intensity of their maximum heart rate. In contrast, non-athletes revealed an inverted-U function between cognitive performance and physical exercise with a reversal point at approximately 60% workload of their individual maximum heart rate. Results are indicative that team sports athletes, as opposed to non-athletes, are capable of maintaining their attentional performance also during high physical exercise. In summary, the findings suggest that different physical exercise intensities can momentarily alter the attentional performance of non-athletes as opposed to expert team sports athletes, meaning that individual athletic status acts as a moderator of this relationship.

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