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# Executive functions in elite athletes – Comparing open-skill and closed-skill sports and considering the role of athletes' past involvement in both sport categories

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ABSTRACT

Previous research documented differences in executive functions between elite athletes in different sports. It was argued that athletes in sport disciplines with higher cognitive demands (i.e., open-skill) show better executive functions than athletes in less cognitively challenging sport disciplines (i.e., closed-skill). In the current study, we aimed at detecting differences in executive functions between elite athletes in open-skill versus closed-skill sports and questioned the role of their total involvement in these sports until the age of 18 on executive functions.

Seventy-five elite athletes (45 males and 30 females; $M_{age} = 23.03 \pm 4.41$ years) from various sports were classified as open- or closed-skill athletes based on the sport they currently competed in. The athletes conducted a series of neuro-psychological tests measuring working memory, inhibition, and cognitive flexibility (Design Fluency test, Trail Making test, Flanker task, and a 2-back task). Retrospective interviews assessed athletes' sport involvement in open-skill and closed-skill sports until the age of 18.

MANCOVAs revealed that athletes in open-skill sports performed better on measures of working memory and cognitive flexibility. Generalized Linear Models displayed that elite athletes in closed-skill sports, with greater involvement in open-skill sports until the age of 18, performed better during working memory and cognitive flexibility tasks.

The results indicate that extensive time spent in open- and closed-skill sports can affect executive functions in elite athletes. A high involvement in open-skill sports proved to be beneficial for executive functions, in particular for elite athletes in closed-skill sports. These findings suggest that experiences in cognitively demanding sports may cause benefits for the development of executive functions.

Promising evidence from past research has shown the cognitive benefits of physical activity (McMorris, 2016; Warburton & Bredin, 2017). In particular, chronic participation in physical activity has been associated with improved cognitive functions (Etnier & Chang, 2009; Kramer & Erickson, 2007) and this association has been commonly demonstrated in young adults and children (Best, 2010; Chaddock, Pontifex, Hillman, & Kramer, 2011; Khan & Hillman, 2014; Marchetti et al., 2015). Physiological effects of chronic physical activity, such as high cardiovascular fitness, coordinative ability, and motor fitness, have also been positively associated with structural and functional changes in brain anatomy (Chaddock et al., 2011; Voelcker-Rehage & Niemann, 2013). Further support for the positive impact of long-term participation in physical activity and sport comes from studies reporting that athletes scored higher than non-athletes or population norms on certain cognitive tests (Lundgren, Högman, Näslund, & Parling, 2016; Moratal, Lupiáñez, Ballester, & Huertas, 2020; Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012). However, when scrutinizing the benefits of physical activity, Diamond and Ling (2016) emphasized that physical exercise with low cognitive demand, such as resistance training or aerobic exercise, yields little or no improvement in cognitive abilities, whereas cognitively demanding physical activity shows the strongest effects (Diamond & Ling, 2016, 2019; Gu, Zou, Loprinzi, Quan, & Huang, 2019). Prolonged participation in cognitively demanding physical exercise had a positive impact on cognitive functions and cognitive vitality across the lifespan (Best, 2010; Diamond & Ling, 2016; Etnier & Chang, 2009; Marchetti et al., 2015).

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The beneficial effects of physical activity on cognitive functions have been most visible when assessing "higher-level" cognitive functions, also known as executive functions (EF; Chaddock et al., 2011; Khan & Hillman, 2014; Scharfen & Memmert, 2019). EF are involved in the control and regulation of behavior and "lower-level" cognitive processes that are necessary for basic information processing (Alvarez & Emory, 2006; Diamond, 2013). As theoretically discussed by Diamond (2013) and Miyake et al. (2000) the three core EF: working memory, inhibition, and cognitive flexibility aid us to select, monitor and control emotions, thoughts and actions, while processing information from the environment. They enable thought before action, promote mastery of new challenges, and help us maintain focus during periods of sensory overload. By updating and monitoring working memory, EF allow us to process information and dynamically manipulate it, rather than passively storing it. Working memory is the foundation of most EF constructs and brings conceptual knowledge to our decisions (Diamond, 2013; Miyake et al., 2000). Inhibition supports us to screen and select our attention, emotions, thoughts, and behaviors to override or resist internal impulses and react with controlled and appropriate actions (Diamond, 2013; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). Cognitive flexibility is the ability for us to "think outside the box", change perspectives spatially or interpersonally, and deliberately switch between different tasks or foci of attention (Diamond, 2013; Miyake et al., 2000). These core EF contribute to goal-directed behavior, reasoning, problem-solving, and planning, which are known as higher-order EF.

Previous research has emphasized the significance of core EF in different sports (Lundgren et al., 2016; Vestberg et al., 2012). Basketball players, for example, have to memorize the blocking habits of their opponents and use that information to plan their attacks (working memory). These players also have to filter out distractions, including stadium noise or nonproductive thoughts (inhibition), while quickly adjusting their pass options based on changes in the positions of their opponents and teammates (cognitive flexibility). Overall, athletes must rely on both their core and higher-order EF to master sport-specific challenges.

Following the "cognitive component skills approach" which examines the relationship between sport expertise and measures of cognition that are beneficial for the fundamental cognitive demands of competitive sports (Nougier, Stein, & Bonnel, 1991), research questioned if sport experts in general show better cognitive skills than non-sport experts (Scharfen & Memmert, 2019; Voss, Kramer, Basak, Prakash, & Roberts, 2010). In this regard, research focusing on EF in sport revealed that elite athletes exhibited better core EF performance when compared to sub-elite athletes and non-sport experts (Huijgen et al., 2015; Moratal et al., 2020; Verburgh, Scherder, van Lange, & Oosterlaan, 2014; Vestberg et al., 2012; Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017). Moreover, past studies displayed the prognostic validity of EF in sports by predicting seasonal performance indicators amongst adult elite-athletes (Lundgren et al., 2016; Vestberg et al., 2012) and youth elite-athletes (Vestberg et al., 2017). These studies suggest that an athletes' EF have an impact on their performance. Thus, athletes with higher EF may be more likely to reach the highest performance levels in their sports, whereas athletes with lower EF may be more likely to drop out or not to reach elite status (Voss et al., 2010). Different explanatory approaches currently exist to interpret these findings and understand how nature and nurture are involved in this process. In this regard, an athlete's EF may, amongst other factors, reflect their potential to achieve elite performance, and act as a selection criterion for athletic experts. This self-selection bias could be supported by the "neuroselection effect", where adults with better physical fitness scored higher on cognitive tests but already had greater cognitive functioning during childhood (Belsky et al., 2015). Hence, proposing that children with better cognitive functions choose more active and healthier behaviors and could engage more frequently in sports. Reviews of intervention studies on the other hand, reported improvements in EF through physical exercise and sport (Diamond & Ling, 2016; Gu et al., 2019). Studies that linked high sport experience to superior EF scores (Ishihara, Sugasawa, Matsuda, & Mizuno, 2017, 2018; Supinski, Obminski, Kubacki, Kosa, & Moska, 2014; Yongtawee & Woo, 2017) may therefore indicate that extensive and long-term involvement in sports contributes to the enhanced EF observed in elite athletes. Especially a diverse sport involvement during the early stages of an athlete's career, as proposed by the developmental model of sport participation (Côté, 1999; Côté, Lidor, & Hackfort, 2009; Côté & Vierimaa, 2014) could enhance EF that are beneficial for pursuing elite performance. By improving intrinsic motivation and fostering a wide range of cognitive experiences, a diverse sport environment that includes deliberate play (i.e., informal and voluntary sport participation) can ultimately affect future performance outcomes (Côté et al., 2009; Côté & Vierimaa, 2014; Ericsson, 2018; Rees et al., 2016). This is further supported by examples of athletes who engaged in numerous sport activities during childhood and required less domain-specific practice to acquire expertise within their main sport (Baker, Côté, & Abernethy, 2003; Côté, Baker, & Abernethy, 2007). For brain development, childhood and adolescence represent significant periods in particular, as core EF mature gradually, often reaching their full capacity before early adolescence, although each construct follows their own distinct developmental trajectory and can continue to develop into late adolescence and young adulthood (Diamond, 2013; Huizinga, Dolan, & van der Molen, 2006; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

Indeed, several studies suggested that the various cognitive demands of certain types of sports generate different effects on EF when athletes participate regularly over long periods (Becker, McClelland, Geldhof, Gunter, & MacDonald, 2018; Chang et al., 2017; Jacobson & Matthaeus, 2014; Krenn, Finkenzeller, Würth, & Amesberger, 2018; Voss et al., 2010). To categorize sports based on their cognitive demands, most studies have applied the approaches of Poulton (1957) and Knapp (1963), who differentiated between open-skill and closed-skill movements. Accordingly, sports can be classified as open-skill or closed-skill sports (Singer, 2000). In open-skill sports like basketball or tennis which are of an external paced nature, athletes need to react and adapt to a dynamic and continuously changing environment (Allard & Burnett, 1985). In contrast, closed-skill sports like running or swimming are mostly self-paced, follow predetermined movement patterns and take place in a predictable and stable environment (Allard & Burnett, 1985). In this regard, studies have shown that athletes in open-skill sports outperformed those in closed-skill sports on problem solving (Jacobson & Matthaeus, 2014) and inhibition tasks (Ballester, Huertas, Pablos-Abella, Llorens, & Pesce, 2019). Investigations of elite athletes showed differences on EF between open- and closed-skill sports. For example, varsity tennis players performed better on inhibition tasks compared to swimmers (Wang et al., 2013), and varsity badminton players performed better on tasks of cognitive flexibility compared to varsity track and field athletes (Yu, Chan, Chau, & Fu, 2017). Additionally, elite athletes from strategic sports (open-skill) showed better performance on measures of mean reaction time, cognitive flexibility, and working memory when compared to elite athletes from static sports (closed-skill; Krenn et al., 2018). Moreover, a longer training experience in open-skill sports in childhood and adolescence was positively associated with inhibition (Supinski et al., 2014), cognitive flexibility (Ishihara et al., 2017, 2018), and processing speed (Yongtawee & Woo, 2017). These findings support the argument that open-skill sports are superior to closed-skill sports for improving certain aspects of EF (Gu et al., 2019). While adaptions to the specific environments of open- and closed-skill sports may affect EF, it remains unclear whether athletes develop stronger EF through sport participation, and/or if they already possess strong EF before excelling in their respective sports. Hence, long-term tracking or retrospective assessment of athletes' physical activity, sport involvement, training hours and EF scores might provide additional insights into this matter. Thus, the purpose of this study was a) to corroborate findings of previous research and detect differences in

EF between elite athletes in open-skill versus closed-skill sports, and b) to clarify the role of athletes' past involvement in open-skill and closed-skill sports during childhood and adolescence. We focused on the three core EF and further considered the cognitive component skills approach in our investigation of sport involvement and measures of cognition. It was hypothesized that open-skill athletes would score better on core EF tasks than closed-skill athletes and that more time spent on cognitively demanding sport activities would lead to stronger performance in core EF.

## 1. Method

### 1.1. Participants

Seventy-five Austrian elite athletes (45 males and 30 females; $M_{age} = 23.03 \pm 4.41$ years) from various sports participated in the present study. To ensure the elite status of the participants, athletes were only included if they were either part of the active national team or competed in the highest Austrian league in their respective sports during the year that they participated in data collection. In accordance with Singer (2000) athletes were either classified as open- or closed-skill athletes. Thirty-one athletes (19 males and 12 females; $M_{age} = 23.23 \pm 4.71$ years) competed in closed-skill sports (archery, cross-country skiing, marathon, sport shooting, swimming, track-bike, track & field, and triathlon). These athletes self-reported qualification for a collective total of 77 European championships, 35 world championships and 11 Olympic Games. In contrast, forty-four athletes (26 males and 18 females; $M_{age} = 22.89 \pm 4.23$ years) competed in open-skill sports (basketball, canoe slalom, handball, Olympic sailing, and American football). These athletes self-reported qualification for a collective total of 72 European championships, 58 world championships and 9 Olympic Games. Due to the required elite status of athletes, sample size was restricted in the current study. However, the number of selected athletes still outranged previous studies from the field assessing elite athletes (a. o. Lundgren et al., 2016; Vestberg et al., 2012; Yu et al., 2017).

### 1.2. Materials

To assess athletes' executive functions, four different neuropsychological tests were used to cover the concepts of working memory, inhibition, and cognitive flexibility. These were the Design Fluency and Trail Making subtests from the D-KEFS test battery for measuring cognitive flexibility (Delis, Kaplan, & Kramer, 2001), a modified Eriksen flanker task to measure inhibition and cognitive flexibility (Krenn et al., 2018), and a 2-back task to measure working memory (Krenn et al., 2018).

#### 1.2.1. Design Fluency Test

The Design Fluency test (DFT) is a non-verbal psychomotor test that measures response inhibition and cognitive flexibility (Delis et al., 2001; Homack, Lee, & Riccio, 2005; Swanson, 2005). In the DFT, the participants were asked to connect dots, which were framed in a square, with four lines using a pen. Across three different conditions, the goal was to create as many new combinations or designs as possible, within 60 s. In Condition 1, filled dots were connected to create designs. In Condition 2, empty dots were connected to create designs, while filled dots were present and had to be inhibited. During Condition 3, the same rules as Condition 1 and 2 applied regarding the design, but each line had to connect one empty and one filled dot. The total number of correct designs drawn in Conditions 1, 2 and 3 was the main metric used for this test (Delis et al., 2001).

#### 1.2.2. Trail Making Test

Three subtests (Conditions 2, 3 and 4) from the Trail Making Test (TMT) were used in this study. Condition 2 measures basic numerical processing, while Condition 3 measures alphabetical sequencing (Delis et al., 2001). Condition 2 and 3 both require visual scanning, and engage attentional ability and motor function (Delis et al., 2001). Condition 4, the number-letter switching subtest of the TMT, measures cognitive flexibility, visual scanning, and split attention. Due to the focus on core EF, Condition 1 and 5, which measure visual scanning and motor speed, were excluded. Using pen and paper, the participants connected circles containing numbers in ascending order (Condition 2) or circles containing letters in alphabetical order (Condition 3) with a line, as quickly as possible. During Condition 4, the participants had to switch back and forth between connecting circles with numbers in ascending order, and connecting circles with letters in alphabetical order, always alternating between a number and a letter. Condition 4 was the primary measure of executive functioning in this test (Delis et al., 2001), as it placed the highest demand on task switching. Using a handheld stopwatch, the times of completion in milliseconds for each condition were used for statistical analyses.

#### 1.3.1. Flanker Task

Analogue to Krenn et al. (2018), a modified Eriksen flanker task (FT) was used to measure inhibition. In the FT, 108 images of five white arrows against a black background were shown on a computer screen. Participants were asked to press the C key with their left forefinger if the arrow in the middle was directed to the left, and to press the M key with their right forefinger if the arrow in the middle was directed to the right. They were required to react as quickly and as accurately as possible. In congruent trials ($k = 72$), all arrows pointed in the same direction, and in incongruent trials ($k = 36$), the middle arrow pointed in one direction and all other 4 arrows pointed in a different direction. The four flanking arrows had to be ignored by the participants. Stimuli were presented for 1000 ms each; inter-trial interval was randomized for 500, 750 or 1000 ms and counterbalanced. Since images with incongruent stimuli require more inhibitory control then images with congruent stimuli (Diamond, 2013; Eriksen & Eriksen, 1974) the main metrics used for analysis were mean reaction time (RT) of correct responses on congruent trials, mean RT of correct responses on incongruent trials, difference between RT of correct responses on congruent and incongruent trials, and the number of conducted errors on incongruent trials (cf. Krenn et al., 2018).

Furthermore, the flanker task shifting (FT-S) was used to assess cognitive flexibility using a task-switching paradigm (Kiesel et al., 2010; Krenn et al., 2018). As in the FT, participants had to respond to the arrow in the middle by pressing a key (C when arrow pointed to the left; M when the arrow pointed to the right) when they were shown five white arrows that represented congruent ($k = 18$) or incongruent trials ($k = 18$). However, if the arrow in the middle was red ($k = 18$), participants had to respond by pressing the opposite key (M when arrow pointed to the left; C when the arrow pointed to the right). When the arrow in the middle was shown in green ($k = 18$), participants had to follow the same rules as if the arrow was white. Participants therefore had to switch their response in accordance with the predetermined rules (Diamond, 2013; Yu et al., 2017). In addition, 36 neutral trials were used, displaying a middle arrow that pointed up or down, where no reaction was required. 108 stimuli were presented in total for 1000 ms each; inter-trial interval was randomized for 500, 750 or 1000 ms and counterbalanced. The main metrics used for the FT-S were the number of conducted errors on red arrow trials, mean RT on red arrow trials, and the difference in RT between red arrow and congruent white arrow trials as an indicator of switch costs (c.f. Kiesel et al., 2010).

#### 1.3.2. 2-back Task

The 2-back task, was administered analogue to Krenn et al. (2018), and requires on-line monitoring, updating and manipulation of remembered information, which places great demand on working memory (Chan, Shum, Toulopoulou, & Chen, 2008; Owen, McMillan, Laird, & Bullmore, 2005). During the 2-back task, participants were shown three conditions: dots on a dice, numbers, and geometrical forms on a computer screen. If the image on the screen was identical to the image that was presented two images earlier, participants had to press the spacebar. 48 stimuli were presented for 1000 ms in each condition, (in total 144) and inter-trial interval was set at 500 ms. For further analysis, the number of correct and false responses in all three conditions, and the mean RT on correct responses were used.

### 1.3.3. Retrospective Interview

A retrospective interview was used to identify the participants' sport histories and trace their development pathways. To fit the purpose of the study, a questionnaire was adapted and simplified from the retrospective interview guide of Côté, Ericsson, and Law (2005). Demographic variables such as sex and age were also assessed during the interview. To measure the participants' involvement in various sport activities, they provided information on all the sports they practiced for every year until the age of 18. Only sports with continued engagement of at least three months were included, but this also included sports with an intensive yearly involvement (e.g., weeklong ski trips every year). To better recall episodic memory, participants were asked to report training hours per week and training months per year for every age. Questions such as: "When was the first time you engaged in this sport?" and "How did your involvement in this sport change in the next year?" helped the participants to provide more comprehensive information. Based on their given statements, training hours per week and training months per year were used to calculate the total hours of involvement per year for every sport at every age (Côté et al., 2005). All sports were then categorized into either open-skill and closed-skill sports, and participants' hours of sport engagement were summed to determine their total involvement until the age of 18 in open- or closed-skill sports, which was used as a main metric.

### 1.4. Procedure

The interviews and assessments were conducted at the participants' training facilities or in the laboratory of the University. The assessment procedure was standardized and kept chronologically constant. After giving informed consent, the participants conducted the DFT, then the FT, followed by the FT-S and the 2-back task. Eight practice trials were performed before each FT, FT-S, and 2-back task, that included immediate feedback on the correctness of each response to familiarize with the task. The TMT was then administered in a one-on-one setting. Afterwards, trained interviewers conducted the retrospective interview with the participants in a one-on-one setting. Pen and paper were used for the DFT test and the TMT. All other tests were conducted via notebook on a 17-inch screen, using the software QDesigner (© amescon). The study was approved by the University of Vienna ethics committee.

### 1.5. Statistical analysis

At first, we were interested in replicating and corroborating previous findings to reveal differences in EF between elite athletes in open-skill and closed-skill sports. Thus, MANCOVAs for each test were calculated. Age was incorporated as a covariate to take care of any developmental age-related effects within our sample (Huizinga et al., 2006; Luna et al., 2004; Vestberg et al., 2017).

Second, we were interested in clarifying the role of athletes' total involvement in open-skill sports as well as closed-skill sports until the age of 18 on measures of EF. To generate a first overview, the Pearson correlations coefficients of athletes' involvement in open-skill and closed-skill sports with all EF measures were calculated. The assumptions of normal distribution, linearity and homoscedasticity were acceptable. To enable a more profound analysis, Generalized Linear Models (GLM) were conducted including age, sport type (closed-skill versus open-skill sports), total number of hours spent in open-skill sports and total number of hours spent in closed-skill sports as predictors. Due to the high risk of Type I error, we did not prove the model for each single test measure. Instead, we selected the major test scores from each of the five assessments as dependent variables, which were particularly considered and reported in former studies. These included the sum of correct designs in the DFT (Lundgren et al., 2016; Vestberg et al., 2012, 2017), the difference of the mean RT on incongruent trials and the mean RT on congruent trials in the FT (Krenn et al., 2018), and the difference between the mean RT on red arrow and congruent white arrow trials (switch costs; Kiesel et al., 2010) in the FT-S. In the 2-back task, we calculated the difference between correct and false responses to consider their interdependence and generate a single measure for the test. In the TMT, the time spent in Condition 4 was considered the only dependent variable, as this condition involves the highest cognitive demand in comparison to Condition 2 and Condition 3 (Lundgren et al., 2016; Vestberg et al., 2017). Multicollinearity posed a severe limitation due to the high correlation between athletes' involvement in open- or closed-skill sports and the sport type in which they reached elite status (r (75) = 0.82, $p = < .001$, and r (75) = 0.78, $p = < .001$, respectively). Thus, athletes' total involvement in open-skill and closed-skill sports was nested in the variable of sport type. To enable a more concise and easier interpretation of the B-values in the GLM, athletes' hours of involvement were divided by 100 (1 = 100 hours) before they were incorporated into the models. Due to our directed hypotheses alpha level was set one-sided at 0.05. Taking multiple testing and the inflated risk of error 1 into consideration, alpha level was adjusted using a Bonferroni correction based on the number of tested scores, and thus was set at $p < .003$ for the correlational analyses ($k = 16$) and $p < .01$ for the GLM ($k = 5$). Due to misunderstandings in the test instructions and irregular test performances, the results of one athlete in the FT-S and three athletes in the DFT were excluded from further data analysis. All statistical analyses were carried out using SPSS 21.0 for Windows (SPSS Inc., Chicago, IL, USA).

## 2. Results

The MANCOVA for the TMT Conditions 2, 3 and 4 revealed a significant main impact of sport type ($F$ (3, 70) = 2.55, $p = .03$, $\eta^2 = 0.10$), and a significant impact of athletes' age ($F$ (3, 70) = 2.49, $p = .04$, $\eta^2 = 0.10$). Elite athletes in open-skill sports showed faster performances than elite athletes in closed-skill sports. In addition, the older the athletes were, the more time they spent for the task and vice versa. The univariate analyses detected a significant difference in TMT Condition 2, but not in Condition 3 and 4. The means, standard deviations and univariate findings for each condition are displayed in Table 1.

The conducted MANCOVA for the DFT revealed a non-significant effect for sport type ($F$ (3, 67) = 1.73, $p = .09$, $\eta^2 = 0.07$), as well as age ($F$ (3, 67) = 0.09, $p = .49$, $\eta^2 = 0.00$). The univariate analyses also did not find any significant differences between athletes in open-skill and closed-skill sports.

For the FT, the MANCOVA did not detect a significant impact of sport type ($F$ (3, 70) = 0.79, $p = .25$, $\eta^2 = 0.03$), but detected a significant impact of the covariate age ($F$ (3, 70) = 3.53, $p = .01$, $\eta^2 = 0.13$): Younger athletes showed faster RT scores on congruent and incongruent trials relative to older athletes, whereas the error rate on incongruent trials also revealed higher for younger athletes. The univariate findings did not detect any significant differences between athletes in open-skill and closed-skill sports. For the FT-S, the MANCOVA revealed a significant impact of sport type ($F$ (3, 69) = 3.04, $p = .02$, $\eta^2 = 0.12$) whereas the impact of age was not significant ($F$ (3, 69) = 0.87, $p = .23$, $\eta^2 = 0.04$). The univariate analyses clarified that athletes in open-skill sports recorded faster RTs on trials showing red arrows, fewer errors, as well as smaller RT differences between RT on red arrows and congruent trials compared to athletes in closed-skill sports.

In the 2-back task, the MANCOVA detected a significant main effect of sport type ($F$ (3, 70) = 3.05, $p = .02$, $\eta^2 = 0.11$), but not of age ($F$ (3, 70) = 0.46, $p = .36$, $\eta^2 = 0.02$). The univariate analyses showed a higher number of correct responses and fewer false responses for athletes in open-skill sports versus closed-skill sports. However, the difference

**Table 1**
Means, standard deviations and univariate findings of the conducted MANCOVAs for all test scores.

| | Open-skill sports ($n = 44$) | | Closed-skill sports ($n = 31$) | | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | | | |
| TMT | | | | | | | |
| Condition 2 | 20.47 | 5.61 | 25.32 | 9.19 | 7.78 | .01 | .10 |
| Condition 3 | 20.92 | 8.93 | 24.66 | 11.75 | 2.31 | .07 | .03 |
| Condition 4 | 49.20 | 12.04 | 53.39 | 19.05 | 1.19 | .14 | .02 |
| DFT | | | | | | | |
| Condition 1 | 14.32 | 4.47 | 14.00 | 3.65 | .10 | .38 | .00 |
| Condition 2 | 16.24 | 3.99 | 14.71 | 3.64 | 2.77 | .05 | .04 |
| Condition 3 | 11.12 | 2.69 | 10.65 | 3.41 | .45 | .26 | .01 |
| FT | | | | | | | |
| RT congruent | 449.59 | 52.80 | 461.74 | 42.34 | 1.18 | .14 | .02 |
| RT incongruent | 501.00 | 54.78 | 515.10 | 42.46 | 1.63 | .11 | .02 |
| RT diff | 51.41 | 22.00 | 53.35 | 17.63 | .26 | .31 | .00 |
| Errors incongruent | 3.23 | 1.87 | 3.42 | 2.72 | .22 | .32 | .00 |
| FT-S | | | | | | | |
| RT red arrow | 663.09 | 62.15 | 693.45 | 65.98 | 4.39 | .02 | .06 |
| Errors | 3.49 | 2.10 | 4.74 | 2.77 | 5.21 | .02 | .07 |
| RT diff red-con | 212.74 | 41.84 | 231.71 | 50.87 | 3.34 | .04 | .05 |
| 2-back task | | | | | | | |
| Correct responses | 18.02 | 3.41 | 16.29 | 5.41 | 2.78 | .05 | .04 |
| False responses | 4.64 | 3.24 | 7.52 | 6.67 | 6.02 | .02 | .08 |
| RT correct | 528.76 | 72.56 | 550.68 | 77.43 | 1.76 | .10 | .02 |

*Note.* TMT = Trail making test; DFT = Design Fluency test; FT = flanker task; FT-S = flanker task-shifting; RT = reaction time; diff = difference; diff red-con = difference between red arrow and congruent.

between RT on correct responses did not turn out significant between open-skill and closed-skill sports athletes.

At second, correlational analyses between the total involvement in open-skill and closed-skill sports until the age of 18 and the EF test scores were calculated. The Pearson correlation coefficients are displayed in Table 2. Results revealed that only the correlation between involvement in closed-skill sports and the conducted errors in the FT was statistically significant, meaning the greater an athlete's past involvement in closed-skill sports, the more errors they tended to record in the FT. In general, the size of the correlation coefficients – even without reaching statistical significance – showed more beneficial associations between involvement in open-skill sports and EF scores relative to involvement in closed-skill sports. Particularly in the FT-S and 2-back task, greater involvement in open-skill sports was associated with faster RTs, fewer errors, and also with more correct responses in the 2-back task. In contrast, involvement in closed-skilled sports was positively correlated with the number of errors made in the FT-S and 2-back task.

**Table 2**
Correlational coefficients (Pearson) of all test scores with the total involvement in open-skill and closed-skill sports until the age of 18.

| | Total involvement in … | |
|---|---|---|
| | Open-skill sports | Closed-skill sports |
| TMT | | |
| Condition 2 | −.28 | .11 |
| Condition 3 | −.07 | .20 |
| Condition 4 | −.15 | .10 |
| DFT | | |
| Condition 1 | .11 | .03 |
| Condition 2 | .30 | −.10 |
| Condition 3 | .21 | −.07 |
| FT | | |
| RT congruent | −.16 | −.18 |
| RT incongruent | −.25 | −.11 |
| RT diff | −.23 | .15 |
| Errors incongruent | −.04 | .38* |
| FT-S | | |
| RT red arrow | −.26 | .03 |
| Errors | −.20 | .29 |
| RT diff red-con | −.18 | .19 |
| 2-back task | | |
| Correct responses | .25 | −.15 |
| False responses | −.26 | .28 |
| RT correct | −.15 | −.05 |

*Note.* *$p < .003$; TMT = Trail making test; DFT = Design Fluency test; FT = flanker task; FT-S = flanker task-shifting; RT = reaction time; diff = difference; diff red-con = difference between red arrow and congruent.

The results of the GLMs are displayed in Table 3. The GLM for Condition 4 of the TMT revealed a significant effect of age: the younger the athletes were, the faster they tended to finish the task in Condition 4. However, neither the total involvement in closed-skill sports, nor the total involvement in open-skill sports revealed a significant impact. The GLM for the DFT, FT-S and the 2-back task showed similar findings: a significant effect was found for involvement in open-skill sports for elite athletes in closed-skill sports. To be specific, the more time closed-skill elite athletes spent in open-skill sports until the age of 18, the higher they tended to score in terms of their EF measures: They created more correct designs in the DFT, showed less switch costs in the FT-S (smaller RT differences between trials showing red arrows and trials showing congruent white arrows) and more correct/less incorrect responses in the 2-back task. For elite athletes in open-skill sports their varying investment in open-skill sports showed no significance in all three tests. Nor did involvement in closed-skill sports reveal any significant impact on the test scores in the DFT, FT-S and 2-back task. In the FT, sport type showed a significant main effect. Open-skill athletes showed smaller RT differences between incongruent and congruent trials, and thus scored higher on the FT relative to athletes in closed-skill sports. The consideration of total involvement in open-skill and closed-skill sports nested in both groups of elite athletes, did not show any significant effect.

## 3. Discussion

The aim of the current study was to clarify the differences in EF between elite athletes of open-skill and closed-skill sports and to contribute to the understanding of how past involvement in open- and closed-skill sports affects the EF measures of inhibition, working memory and cognitive flexibility. Elite athletes in open-skill sports showed significantly higher performance in working memory and cognitive flexibility during the FT-S, and the 2-back task in comparison to elite athletes in closed-skill sports. These findings are in line with previous research (Krenn et al., 2018; Yu et al., 2017). In addition, univariate analyses also suggested a significantly better performance in the TMT Condition 2 for open-skill athletes. Concerning inhibition, we did not detect a significant difference between athletes in open-skill and closed skill sports. While our results are in line with findings of Jacobson and Matthaeus (2014), other studies detected superior inhibition performance of athletes in open-skill sports relative to athletes in closed-skill sports (Ballester et al., 2019; Wang et al., 2013). However, these opposing findings might be explained by differences in the measured aspects and the assessment methods of inhibition (Diamond, 2013). Ballester et al. (2019) and Wang et al. (2013) used a task mainly assessing response inhibition (i.e. only suppressing an action during a Go/No-go task), whereas Jacobson and Matthaeus (2014) and the current study applied an inhibitory control task, where participants inhibit a certain response to a stimuli in order to make a more appropriate response. Future research should use a wider array of inhibition measures (e.g. go/no-go tasks, stroop tasks, flanker tasks) to address these varying findings for different aspects of inhibition.

Overall, our findings suggest that elite athletes in open-skill sports display more beneficial EF in comparison to elite athletes in closed-skill sports. However, it seems noteworthy to say that effect sizes were small throughout the analyses restricting the generalizability of the findings. Previous studies have also reported these small effect sizes (Jacobson & Matthaeus, 2014; Krenn et al., 2018; Vestberg et al., 2017), which might

**Table 3**
Coefficients of the conducted Generalized Liner Models (GLM) for the main test scores of all five tests.

| | TMT (Condition 4) | | | | DFT (total sum of correct designs) | | | | FT (diff RT incon – RT con) | | | | FT-S (diff RT red-con) | | | | 2-back (diff correct – false) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Predictors | B | SE | χ2 | p | B | SE | χ2 | p | B | SE | χ2 | p | B | SE | χ2 | p | B | SE | χ2 | p |
| Age | 1.23 | .41 | 9.05 | .002* | .25 | .29 | .74 | .195 | −.70 | .49 | 2.01 | .079 | −1.7 | 1.15 | 1.65 | .100 | −.05 | .13 | .12 | .363 |
| Sport type | 3.87 | 8.06 | .23 | .316 | −9.60 | 6.72 | 2.04 | .153 | 27.10 | 11.45 | 5.61 | .009* | −42.01 | 28.08 | 2.24 | .068 | 2.11 | 3.28 | .41 | .261 |
| INV OSS (CSA) | −.32 | .19 | 2.83 | .047 | .28 | .10 | 8.76 | .002* | −.05 | .20 | .05 | .410 | −1.31 | .53 | 6.08 | .007* | .18 | .07 | 6.31 | .006* |
| INV OSS (OSA) | −.05 | .07 | .47 | .247 | .13 | .09 | 2.38 | .062 | −.33 | .15 | 4.56 | .017 | .15 | .27 | .33 | .284 | −.01 | .03 | .11 | .371 |
| INV CSS (CSA) | .13 | .10 | 1.56 | .106 | −.04 | .05 | .81 | .185 | .25 | .11 | 4.75 | .015 | .08 | .38 | .04 | .419 | −.05 | .04 | 1.37 | .121 |
| INV CSS (OSA) | −.19 | .09 | 4.25 | .020 | .20 | .09 | 4.91 | .014 | −.06 | .17 | .13 | .358 | .44 | .42 | 1.15 | .143 | .04 | .05 | .54 | .231 |

*Note.* *$p < .01$; INV = Involvement; OSS = Open-skill sports; CSS = Closed-skill sports, OSA = open-skill athletes; CSA = closed-skill athletes; TMT = Trail making test; DFT = Design Fluency test; FT = flanker task; FT-S = flanker task-shifting; RT = reaction time; diff = difference; incon = incongruent; con = congruent.

present a consequence of the heterogeneity of sports within the broad categories of open-skill and closed skill sports. Regarding our selected sample, it seems important to consider the difficulty of standardizing the categorization of elite athletes. Although we only recruited athletes who competed at the highest national leagues in their respective sports, the level of expertise can vary between different sports.

To further explore how sport participation can promote the development of EF, the current study explored the influence of time invested in open- and closed-skill sports until the age of 18 on EF. In general, the Pearson correlation coefficients showed a slight but mainly non-significant trend that a high involvement in open-skill sports went along with more beneficial EF measures, whereas the opposite trend was found for closed-skill sports: A high involvement in closed skill sports showed higher associations with errors during the FT, the FT-S, and the 2-back task, but only reached statistical significance for the FT. The GLMs revealed that a high involvement in open-skill sports by closed-skill sports athletes led to higher scores on working memory and cognitive flexibility tasks. This finding seems to be in line with previous research indicating a significant positive effect of training hours and experience in open-skill sports on inhibition, working memory and cognitive flexibility (Huijgen et al., 2015; Ishihara et al., 2017; Yongtawee & Woo, 2017). This effect solely was revealed for closed-skill sports elite athletes in our study, but not for open-skill sports athletes, who did not show any additional benefit by enhanced involvement in open-skill sports. While previous research focused on youth athletes, only adult elite athletes were considered in our sample. Hence, it seems possible that the EF of elite athletes' from closed-skill sports benefitted from higher involvement in open-skill sports, whereas within the sample of open-skill sport elite athletes a ceiling effect of the positive impact of open-skill sport involvement might have been detected. As a consequence, open-skill sports athletes might have superior EF in comparison to closed-skill sport athletes, but within their sample an additional investment in open-skill sports might not bring an additional benefit for their EF development. In this regard, future research should question a minimum and maximum threshold of open-skill sport involvement to better understand its impact. Our findings concerning the impact of closed-skill sports involvement were in line with our assumption: We did not detect a significant impact of closed skilled sports involvement for elite athletes of both sport categories. However, a small trend towards statistical significance became visible at the TMT and DFT: High involvement in closed-skill sports by elite open-skill athletes seemed to be positively associated with cognitive flexibility measures for the TMT and the DFT. Since involvement in closed-skill sport was usually associated with inferior EF results in previous studies (Jacobson & Matthaeus, 2014; Krenn et al., 2018) and throughout our analysis, this tendency was against our expectation. It seems possible that athletes of open-skill sports, who additionally exercised more in closed-skill sports were also exposed to more diverse sport environments. This might have facilitated broader athletic experiences for these individuals, which might have enhanced their cognitive flexibility. However, it has to be noted that this tendency was not revealed in the FT-S. Thus, future research is challenged to shed a light on this potential effect and its underlying mechanism. The open- versus closed-skill sport dichotomy further possesses several limitations, especially for sports including open- and closed-skill elements. Future studies may overcome these limitations by comparing different sports directly, instead of categorizing them into groups.

The present findings make it difficult to confirm whether superior EF of athletes are attributable to genetic influences, (i.e. result of nature) or their sport involvement and deliberate practice (i.e. result of nurture). Applying the cognitive component skills approach, sport involvement is considered as a medium for experience dependent brain plasticity (Voss et al., 2010) and as elite athletes from open- and closed-skill sports have invested extensive time in their respective sports during childhood and adolescence, the cognitive characteristics of their deliberate sport practice have the potential to induce brain alterations (Chaddock et al., 2011; Voelcker-Rehage & Niemann, 2013). A greater increase in production of brain-derived neurotropic factor, which is a biomarker of exercise-induced cognitive benefits (Huang, Larsen, Ried-Larsen, Møller, & Andersen, 2014; Poo, 2001) and near significant improvements in task-switching performance (Hung, Tseng, Chao, Hung, & Wang, 2018) where observed after acute open-skill exercise when compared to closed-skill exercise and may therefore hint at the underlying physiological effect for EF improvement supporting the nurture standpoint. As research already suggested (Best, 2010; Gu et al., 2019; Voss et al., 2010) physical activities with high cognitive demands, complex motor movement, and more frequent social interactions - all elements which are more apparent in open-skilled sports - may have contributed to higher EF scores observed in the present study. Open-skill sports further demand rapid reactions to dynamic stimuli (e.g., to accurately return a tennis serve at 250 km/h) and could explain why open-skill sport involvement was associated with faster RT during EF tasks in this study and better processing speed in previous research (Krenn et al., 2018; Voss et al., 2010; Yongtawee & Woo, 2017). The higher accuracy during EF tasks in our sample and superior cognitive flexibility associated with open-skill sport involvement (Ishihara, Sugasawa, Matsuda, & Mizuno, 2018, 2017; Krenn et al., 2018; Yu et al., 2017) could highlight the flexible, high-speed decision making required in open-skill sports (e.g., to generate a counterattack after a turnover in soccer or basketball). Reacting to an external stimulus is often not relevant in closed-skill sports because environmental changes during competitions do not occur quickly or in unexpected ways and could indicate why high error rates during complex EF tasks were associated with closed-skill sport involvement in our sample. It seems reasonable that cognitive tasks which resemble the cognitive demands of sports more closely allow better distinction between open- and closed-skill sports. Lastly, a significant impact of age was also detected in the GLM and the MANCOVA of the TMT and during the MANCOVA of the FT. It was found that younger athletes displayed faster RT during the FT and faster completion times of the TMT in Condition 4. Recent findings detected slightly better EF in youth athletes ($<18$ years of age) compared to adult athletes ($\geq 18$ years of age; Scharfen & Memmert, 2019) and showed a performance plateau around adulthood (~21 years of age; Beavan et al., 2020). This aligns with trends in research (Diamond, 2013; Huizinga et al., 2006) showing that EF may reach their full capacity around adolescence and may stagnate afterwards, which could be attributable to cognitive decline that was observed around the age of 24 in general populations (Crone, Peters, & Steinbeis, 2017, pp. 58–72). However, the influence of age in our sample was solely detected for reaction- and completion times during two EF measures and should therefore be interpreted with caution.

Our approach enabled us to gain insight into the beneficial influence of open-skill sport involvement, especially during childhood and adolescence, working memory, and cognitive flexibility. Constant adaptation to the cognitive demands of sports during childhood and adolescence may explain why superior EF scores were associated with open-skill sport involvement in our sample. Previous findings indicate that high EF are essential to reach elite status in open-skill sports (Huijgen et al., 2015; Vestberg et al., 2012, 2017), whereas they may not be necessary for success in closed-skill sports. The assumption that only enormous engagement in one single sport at a young age will lead to elite performance is opposed by research that highlights the benefits of deliberate play and diverse sport involvement for elite performance (Côté & Vierimaa, 2014; Rees et al., 2016). It is important to note that our results showing benefits of open-skill sport involvement in elite closed skill athletes, highlights that involvement in multiple sports during childhood and adolescence could provide a strong foundation for the development of EF (Côté et al., 2009; Gu et al., 2019; Voss et al., 2010). Additionally, studies displayed dropout and burnout as the negative consequences of early sport specialization (Fraser-Thomas, Côté, & Deakin, 2008; Gould, Tuffey, Udry, & Loehr, 1996). Both nature and nurture seem to play critical roles in the development of EF in elite athletes but a reinforcing cycle where children with a strong skill set of EF have a stronger chance to become athletes and improve EF further through extensive training seems plausible (Voss et al., 2010).

The following limitations have to be considered regarding the validity of this study's findings. A fixed order of the four tests was necessary to be time efficient and to fit the strict time schedules of elite athletes. Thus, the test procedure was not counterbalanced which might have affected the results. The TMT, the DFT, and the FT-S all aimed to assess specific aspects of cognitive flexibility, but their results were incongruent, and the significant impact of sport type between open-skill and closed-skill sports varied across these tests. It seems that the multifaceted nature of cognitive flexibility and its assessment (Diamond, 2013) may explain these inconsistencies. Further research is needed to clarify the differential roles of each test within the concept of cognitive flexibility. In addition, a more detailed and more comprehensive analysis of participants responses in all test measures (e.g. deficient/repeated designs in the DFT; responses and RT at trials showing green arrows in the FT-S) might help to deepen our understanding of each test's scope and cognitive flexibility in general in the sample of elite athletes. Future studies may consider that intelligence, education, and physical fitness levels could vary between athletes and therefore have an impact on athlete's EF (Ballester et al., 2019; Ishihara et al., 2018; Marchetti et al., 2015). The small sample size further limits the generalizability of our findings. Due to the high level of expertise of our target population the options to increase the sample size, still taking care of our selection criteria, revealed limited. However, future research should consider this aspect and aim for larger sample sizes to increase the validity and generalizability of the results. Another limitation relates to the reporting of exact values during the retrospective interviews. It may have been challenging for athletes to recall the number of hours they invested in different sports over the past ten years. Since the deliberate cognitive involvement can be highly variable to the context, the quality of an athletes' sport involvement provides additional uncertainty. Athletes that grew up watching their parents or siblings practice sport could also be cognitively involved in this sport. Assessing the time spent watching sports deliberately or comparing the statements of athletes with estimations from parents or coaches that were involved in their training would enable even better understanding of this matter. While a longitudinal design—whereby athletes are monitored throughout their sporting career—would be interesting for future research, the retrospective approach we took in this study enabled us to exclusively select athletes who were already heavily involved in sport and performing at an elite level. Finally, several tests were conducted to cover a broad spectrum of core EF, whereas we did not consider higher EF to gain even more insights about their role in the sport context. In this regard, future studies are challenged to additionally focus on higher EF and clarify its interaction with different sport disciplines.

## 4. Conclusions

The current study provided an insight into how involvement in open- and closed-skill sports affects EF amongst athletes in various sports. Elite athletes from open-skill sports displayed superior performance on tasks of working memory and cognitive flexibility when compared to elite athletes from closed-skill sports. When considering athletes' prior sport involvement, the results indicated that extensive time spent in open-skill sports until the age of 18 was beneficial for faster and more accurate performance on working memory, and cognitive flexibility tasks, especially for elite closed-skill sport athletes. These findings suggest that the cognitive demands of a diverse sport environment provided by open-skill sports may benefit athletes' development of EF and contribute to superior EF in elite athletes.

## CRediT authorship contribution statement

**Koch Philipp**: Conceptualization, Methodology, Investigation,

Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Björn Krenn:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing.

## Conflicts of interest statement

We report no conflicts of interest for this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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