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Executive Function Expertise in Sport: A Meta-Analytic Review

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The candidate confirms that the work submitted is their own and that appropriate credit has been given where reference had been made to the work of others.

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Abstract

The previous decade has seen a significant growth in the number of studies investigating the executive function-athletic expertise relationship. Yet the influence of executive function on expertise level requires clarification due to heterogenous results, varied methodologies, and uncertainty regarding the transferability of sport-specific skills into the standardised cognitive domain. **Objective:** We addressed this by meta-analysing the relationship between executive function and athletic expertise and investigated if specific executive function constructs have differential relationships with athletic expertise. We also tested whether there are expert-novice differences in specific elements of cognitive performance (i.e. cognitive efficiency and cognitive effectiveness). **Method:** Our literature search yielded 31 studies (N = 2133) composed of non-, amateur-, and elite-athletes from various sport types and age groups (age ranged from 14.16 to 28.80 years). **Results:** Meta-analysis using random effects models revealed overall executive function, executive function efficiency, executive function effectiveness, cognitive flexibility, cognitive flexibility efficiency, working memory, working memory efficiency, working memory effectiveness, problem solving, problem solving efficiency, decision-making, decision-making efficiency, and decision-making effectiveness displayed small or moderate positive associations with athletic expertise. Subsequent moderation analyses revealed that these relationships can be influenced by sample characteristics (i.e. age and gender) and operational measures of executive function. **Conclusions:** Results provide further support for the notion that athletes of greater expertise possess superior executive function abilities that potentially aid sports performance. Elite athletes are able to perform standardised cognitive tasks with greater efficiency and effectiveness which then transfer into the sports domain. The present findings also highlight the necessity to implement multi-measure approaches when investigating executive function in future research due to the idiosyncrasies of individual measures.

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1. Introduction

The ability to consistently perform in elite level sport requires incredible physiological ability, fine motor control, and heightened perceptual cognition (Lundgren, Hogman, Naslund, & Parling, 2016). The last 30 years have witnessed a rapid increase in attempts to further understand the factors that influence performance at the highest level, with organisations seeking to find every advantage to be successful in multi-million-pound industries (e.g. The English Football League, National Basketball Association, etc.). With so much at stake, it is no surprise that researchers are being challenged to decipher the most influential variables that impact sports performance (see Chaabene, Hachana, Franchini, Mkaouer, & Chamari, 2012 for a review on elite karate athletes). For years, successful performance has been classified by measuring the physical and technical attributes of an athlete whilst neglecting the complex cognitive processes that facilitate them (Ducrocq, Wilson, Smith, & Derakshan, 2017). It is now widely regarded that sports performance does not solely rely on the physical aspects of an athlete, with greater emphasis being placed on their cognitive abilities.

A variety of cognitive skills such as attentional capacities, perceptual cognition, procedural knowledge, and anticipation are required to participate in sport at an elite level (Lundgren et al., 2016; Scharfen & Memmert, 2019) All of these processes have been studied in some capacity within athlete populations, with those athletes competing at the highest levels demonstrating exemplary abilities (see Mann, Williams, Ward, & Janelle, 2007, for a review). Expert athletes have demonstrated greater efficiency in utilising perceptual cues during performance on tests of general cognition. For example, experts demonstrated a 31% increase in response accuracy and 35% decrease in response time compared to novice athletes

(Mann et al., 2007). Knowing where and when to look for these environmental cues is critical for sports performance, providing the athlete an opportunity to utilise their extensive procedural knowledge to predict future events (McPherson, 2000).

Since the turn of the century, the cognitive factors that impact expert performance have become more widely studied, resulting in publication of two large meta-analyses investigating the influence of perceptual-cognition on sport expertise (i.e. Mann et al., 2007; Voss, Kramer, Basak, Prakash, & Roberts, 2010). Whilst these studies provided a summative evaluation of perceptual-cognition in sport, they fall short of highlighting the complexity of cognitive skills required to be a successful athlete which have come to light through the previous decade of research. Specifically, attention has shifted to a group of cognitive processes known as executive functions (Diamond, 2013). This umbrella term encompasses an array of complex processes that enable flexible goal-directed behaviour in real time (i.e. behaviours that can be adapted rapidly to new demands; Lezak, Howieson, Bigler, & Tranel, 2012). Given that successful performance in sport often requires an athlete to respond flexibly to an ever-changing environment and adapt their behaviour, it is logical to suggest that executive functions are crucial in the execution of technical sporting manoeuvres. This premise has received support in the literature with studies demonstrating the heightened executive function abilities of elite athletes and the predictive ability of executive function on successful future sporting performance (e.g. Brevers et al., 2018; Huijgen et al, 2015; Krenn, Finkenzeller, Wurth, & Amesberger, 2018; Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017). Expert-novice differences in executive function were initially meta-analysed by Scharfen and Memmert (2019) demonstrating they differentially influenced sports expertise compared to visuo-perceptual skills. Furthermore, this was the first study to highlight the moderating influence of athlete skill definition (i.e. expert or elite) and highlighted the necessity to further investigate the role of executive function in athletic expertise.

An updated comprehensive meta-analytic review of the literature is warranted. Given its importance, the present review focused on the association between executive function and athletic expertise. Research to-date may have been misinterpreted due to inconsistent findings, heterogenous methodologies, no consistent taxonomy, and underpowered studies. Subsequently, resulting in difficulty in deducing the true effect of this relationship. Furthermore, the top-down processing capabilities of executive functions can heavily influence an athlete's perceptual-cognition. Given that these were of primary interest in two previous meta-analyses (i.e. Mann et al., 2007 & Voss et al., 2010), the influence of executive functions on an expert/elite athletes performance needs to be investigated, as it may not have been captured previously. This is particularly pertinent given that executive function research far preceded this work and each construct was shown to differentially influence performance on various cognitive tasks (i.e. Wisconsin Card Sorting Task and Tower of Hanoi; Miyake et al., 2000). We sought to bring more clarity to the research area by rigorously conducting a meta-analytic review of the executive function–athlete expertise literature.

Much work in this field fails to differentiate important outcomes associated with cognitive processes such as effectiveness and efficiency (i.e., it is not fully understood if/when expert athletes perform better cognitively). That is, theory postulates that these processes are conceptually different and may indicate unique variability with athletic expertise (e.g., attentional control theory; Eysenck, Derakshan, Santos, & Calvo, 2007; Ducrocq et al., 2017). Therefore, the present study sought to strategically analyse the unique contributions of efficiency and effectiveness by independently measuring cognitive efficiency (i.e. speed of performance) and effectiveness (i.e. accuracy of performance) in the hope of bringing greater understanding to the specific executive function advantages possessed by expert athletes. We utilised the first validated classification criteria for athletic expertise (i.e. Swann, Moran, & Piggott, 2015) in response to the recommendation of Scharfen and Memmert (2019), and to further illuminate any expert-novice differences in executive function abilities. Finally, we aimed to investigate the moderating influence of age, gender, facet of executive function, and operational measure of executive function to shed new light on the relationship and develop a greater understanding of the previous 10 years of extant research.

1.1 Executive Functions

Executive functions are a group of higher-order cognitive processes that facilitate thought and action during non-routine tasks (Friedman et al., 2006). Research divides executive function into specific processes such as inhibition, working-memory, cognitive flexibility, planning, problem-solving, and decision-making (Diamond, 2013). Scenarios that may require executive function typically include elements of error correction, overcoming a strong habitual response, or sequences of events that are not well-rehearsed (Norman & Shallice, 1986). In a sports context, activities such as football and rugby are characterised by highly dynamic environments and the necessity for athletes to respond appropriately whilst experiencing high levels of distraction (Huijgen et al., 2015; Lundgren et al., 2016). Moreover, executive function aids in the regulation of lower-level processes in given situations (Gilbert & Burgess, 2008). This top-down processing allows an athlete to direct their cognitive, perceptual, and motor processes towards achieving their goal and not solely be governed by environmental triggers (Lundgren et al., 2016; Verburgh, Scherder, van Lange, & Oosterlaan, 2014).

There are multiple models of executive function explaining how they facilitate goal achievement (see Chan, Shum, Toulopoulou, & Chen, 2008). However, most models acknowledge that executive function can be divided into two subcategories, lower and higher order. One such model streamlines executive function into three lower-order (working-memory, inhibitory control, & cognitive flexibility) and three higher-order processes (reasoning/decision-making, planning, & problem-solving; see Diamond, 2013 for an in-depth review). Each of these interrelated executive functions are multifaceted and play important roles in completing tasks successfully (e.g. choosing to respond counter to initial tendencies based on information that is held in mind; Diamond, 2013). More complex tasks, such as those encountered in sports, may utilise these processes in tandem in order to be successful.

According to Diamond (2013), working-memory or updating consists of manipulating information that is no longer perceptually present. Inhibitory control or inhibition encompasses the control of attention, emotion, and behaviour to withhold a prepotent response. Cognitive flexibility or attentional shifting includes being able to change perspectives, and flexibly switch between tasks or two components within a task that both require cognitive demands. Regarding the higher-order constructs; reasoning/decision-making refers to the ability to assess the environment for important information, interpret it appropriately, and then select the optimum response based on the individual’s set of generated options (Baker & Cote, 2003). Planning can be defined as the ability to think about the future, anticipate the correct way to achieve a goal, and organise behaviour accordingly (Sorel & Pennequin, 2008). Problem-solving is the process involved when an individual is attempting to overcome difficulty that is diminishing their progress towards a desired goal (VandenBos, 2006).

Executive functions have been measured extensively within athlete populations to deduce their relationship with sports performance and athletic expertise. Research suggests that executive function offers a promising avenue of research for identifying elite athletes from their lesser able counterparts (see Scharfen & Memmert, 2019). However, assessing the downstream application of executive function is difficult due to the complexity of the sports environment and ecological validity may be confounded by the elite athletes' superior procedural knowledge (Voss et al., 2010). On the other hand, utilising standardised measures is deemed to over-simplify the complex cognitive processes performed by elite athletes (Ericsson, 2003). Studies have provided contradictory findings, that is, statistically significant differences in executive function between varying expertise levels were only reported consistently in certain sports (e.g. football; Huijgen et al., 2015) and not for others (e.g. ice hockey; Lundgren et al., 2016, & volleyball; Alves et al., 2013). Ultimately, forming conclusions from the research findings in the literature is difficult, hindered by the various methodologies, sampling methods, and operational measures of executive function (Krenn et al., 2018; see Table 1 for a detailed description of each study).

1.2 Executive Function in Sport

Although sport provides optimal environment to measure athletes of differing classification (Moran, 2009, 2012), previous research investigating differences in cognition has provided contradictory findings (Voss et al., 2010). This is in part due to the use of two contrasting methodologies, the expert performance approach and the cognitive component skills approach. To date, there is more substantial evidence supporting the near transfer hypothesis whereby extensive experience in an activity only facilitates improvement within the individual's domain (i.e. participating in sport does not improve basic cognition; Furley & Memmert, 2011). The expert performance approach examines athletes in a sport-specific context (Starkes & Ericsson, 2003). The focus of these studies is to examine the interaction of the athlete with their specific environment, whether this be through sport-specific displays or through simulating sporting actions (Scharfen & Memmert, 2019; Voss et al., 2010). Generally, studies following the expert performance approach report that expert athletes outperform non-experts on tasks measuring gaze behaviour, anticipation, decision-making, and attentional capacities (e.g. Mann et al., 2007; van Maarseveen, Oudejans, Mann, & Savelsbergh, 2016).

More recently, researchers have been using in-situ performance and dynamic game video sequences to measure a higher-order executive function (i.e. decision-making; Causer & Ford, 2014). In a study assessing the relationship between decision-making and technical ability in volleyball players, athletes with higher in-play decision-making ability (e.g. measured using a game performance assessment index by qualified coaches) were also noted as having superior service and set action skill; two essential manoeuvres in volleyball (Lopes, Magalhaes, Diniz, Moreira, & Albuquerque, 2016). Given the nature of the sport (i.e. there is a limited number of touches allowed in possession & the ball can not touch the floor), the need for accurate decision-making is critical to providing the best opportunity for sufficient technical skill performance (Lima, Martins-Costa, & Greco, 2011).

Comparable findings were reported in a sample of expert hockey players and non-athlete controls when responding to a series of perceptual cognitive dynamic video sequences (Wimhurst, Sowden, & Wright, 2016). As anticipated, expert hockey players were more accurate in choosing an appropriate action to their "opponent's" movements, with the biggest difference being found in the most cognitively demanding condition. Specifically, the video sequence was stopped 160 milliseconds before a response was required, in comparison to 60 milliseconds (i.e. less cognitively demanding condition). Research has noted that differences in executive control are clearer between groups when more substantial levels are required (Diamond & Lee, 2011). Furthermore, this finding has been frequently reported throughout the literature (Hillman et al., 2014; Houlston & Lowes, 1993). Of particular interest, performance between the experts and non-athlete controls was similar when responding to a neutral sports stimulus (i.e. badminton, where neither group possessed expertise; Wimhurst et al., 2016). This finding supports the notion of the expert performance approach that cognitive abilities in athletes are sports specific (Starkes & Ericsson, 2003; Wimhurst et al., 2016). While studies from the expert performance approach demonstrate the near-transfer effects from the sports arena to the laboratory, the validity of reported expert-novice differences in cognitive abilities is questionable. Namely, the confounding influence of the superior declarative and procedural knowledge possessed by high-performing athletes is thought to impact the salience of stimuli and task maintenance capabilities (Voss et al., 2010). Furthermore, the expert novice approach suggests that an individual's cognitive abilities are genetically predisposed and non-malleable to the supposed benefits of sports participation or cognitive training. However, there is much contradictory evidence against this notion (e.g. Ishihara, Sugasawa, Matsuda, & Mizuno, 2017; Schmidt, Jager, Egger, Roebers, & Conzelmann, 2015).

In contrast, the cognitive component skills approach investigates the relationship between athletic expertise and standardised cognitive abilities that are thought to be requirements for successful sports performance (Nougier, Stein, & Bonnel, 1991). This approach is distinctly different from the expert performance approach as it removes the inherent complexity of the sporting environment and specifically focuses on the basic cognitive skills of the athlete. Research within the cognitive component skills paradigm predominantly investigates the far transfer abilities of sports participation, highlighting expert-novice differences in cognitive abilities irrespective of the expert's domain (Voss et al., 2010). However, it is within this approach that the studies report inconclusive findings regarding the influence of executive functions on athletic expertise. Several studies have reported heightened executive function in elite athletes (e.g. Vaughan, Laborde, & McConville, 2018; Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012). It should be noted that many of these studies are limited methodologically. For example, they contain small sample sizes (e.g. Kasahara, Mashiko, & Niwa, 2008), fail to control for key confounding variables (e.g. moderate-to-vigorous physical activity; (e.g. Jacobson & Matthaeus, 2014), or inappropriate classification criteria to deduce the expertise level of the athletes (e.g. Pacesova, Smela, Kracek, Kukurova, & Plevkova, 2018). Furthermore, some studies report no significant differences in executive function between levels of athlete (e.g. Furley & Memmert, 2010).

Although the discrepancy in findings is not fully understood, it is heavily debated as to what level cognitive skills can be demonstrated in various domains. Cognitive skills transfer is the process in which expertise in one area of cognition may be transferred to an untrained task (Taatgen, 2013). The lack of any expert-novice differences in non-specific cognition (e.g. Furley & Memmert, 2010) suggests that the level of transfer is too broad to elicit a significant difference in cognitive performance. Several studies have reported differences in domain-specific cognition (i.e. sport-specific) whilst failing to differentiate between classification of athletes using standardised cognitive measures (Helson & Starkes, 1999; Lum, Enns, & Pratt, 2002). On the other hand, evidence remains that demonstrates heightened executive function abilities in elite athletes (e.g. Brevers et al., 2018), and the topic remains prevalent in contemporary research (Jacobson & Matthaeus, 2014). At the time of publication of Voss and colleague's meta-analysis, research on the transfer of executive skills was sparse. With almost a decade of new research to consider, it seems appropriate to readdress this issue incorporating state-of-the-art methodologies.

1.3 Expertise in Sport

A commonly utilised method of investigating the role of cognitive factors in sports performance is to measure differences in cognitive domains between levels of athlete (e.g. Brevers et al., 2018; Elferink-Gemser et al., 2018). Studies following the expert-novice paradigm are aplenty within the skill acquisition and sports psychology literature, with an array of evidence supporting the notion that athletes with greater expertise demonstrate heightened cognitive performance (e.g. Vaughan et al., 2018; Zhang, Ding, Wang, Qi, & Luo, 2015). Given the growing nature of sports psychology, particularly in reference to expert-novice differences of cognitive domains, there appears to be substantial evidence supporting the heightened cognitive abilities of elite/expert athletes. However, as was recently highlighted in a systematic review, the research evidence is flawed due to vast inconsistency in how researchers are classifying athletes (see Swann et al., 2015 for an in-depth review). Ultimately, the lack of an appropriate classification tool for athletic expertise makes it difficult to deduce the true effect of the reported expert-novice differences to which so many conclusions are drawn from.

A common inconsistency noted within the literature is the interchangeable use of the term's "expert" and "elite". An "expert" often refers to an individual who has participated in a prolonged period of deliberate practice to improve their performance in a task. This term was popularised by Ericsson, Krampe, and Tesch-Romer (1993), concluding that it takes over 10 years of maximal effort in practice to become an expert performer. In contrast, "elite" athletes are typically characterised by their current level of competition within their sport (e.g. regional/county, national, or international), and where that sits in comparison to other sports globally (Swann et al., 2015). Those athletes who are performing at the highest level within their sport are deemed to be "elite" performers.

Further highlighting this inconsistency in definition, Scharfen and Memmert (2019) reported significant moderation between studies using the two contrasting definitions of "high-performing athletes". It was noted that using the "expert" definition predominantly based on accumulated hours of practice may not be precise enough to distinguish between athletes who are performing at the elite and sub-elite levels. Comparable findings were reported in a meta-analysis investigating the relationship between deliberate practice hours and sports performance, highlighting that practice hours lost its predictive power of performance beyond a sub-elite skill level (Macnamara, Moreau, & Hambrick, 2016). Focusing on one of the included studies, there was a non-significant difference in practice-hours between Olympic level field hockey players and other players competing in the top four divisions in that country (i.e. athletes who compete at a super-elite and elite level; Gullich, 2014). This becomes problematic as athletes of different performance levels can be mistakenly classified together, bringing into question the validity of studies investigating expert-novice differences of cognitive skills.

It is now widely considered that following the “elite” definition for athlete classification is more valid for studies of this nature. Given its detailed list of classification criteria and wider use within the literature (e.g. Vaughan, Madigan, Carter, & Nicholls, 2019), the present study followed the protocol outlined by Swann et al. (2015) to classify the athlete samples of the included studies. The classification criteria were produced following a rigorous systematic review of empirical evidence from various fields (e.g. sport psychology, cognitive psychology, & neuroscience), and represents the first evaluation of the validity of the operational definitions of sport expertise and indeed the framework itself (see Swann et al., 2015 for an in-depth review). Specifically, the athlete’s status was based on their highest level of competition (e.g. regional - international level), level of success at their highest level (e.g. some success – sustained success), years spent competing at current level (e.g. fewer than two – more than eight years), and the global representation of the sport (e.g. non-Olympic – Olympic sport). Non-athletes were classified as those who did not compete in any sport and therefore failed to score using the predetermined criteria of Swann and colleagues. Adoption of this taxonomy in a meta-analytic framework will further illuminate the executive function-athletic expertise association.

1.4 Executive Function and Athletic Expertise

Various methodologies have been deployed to investigate this relationship; whether that be through choice of cognitive task (i.e. sport-specific or standardised), following the expert-novice paradigm (e.g. Pacesova et al. 2018), or a cognitive domains ability to predict a performance outcome (e.g. Vestberg et al., 2017).

Ultimately, findings have been largely contradictory, and the true nature of the relationship has been difficult to decipher.

Research indicates that elite athletes typically score higher on measures of executive function compared to their less-elite counterparts (e.g. Alves et al., 2013; Verburgh et al., 2014). In a study measuring response accuracy to a series of 11v11 football video sequences, skilled athletes (i.e. elite) demonstrated superior decision-making ability (*M* response accuracy = 82.8%) compared to lesser-skilled athletes (i.e. amateur; *M* response accuracy = 50.5%; Roca, Ford, McRobert, & Williams, 2013). It was hypothesised that the higher-skilled athletes also possessed greater working-memory ability, as demonstrated through qualitative statements of their cognitive processes during the task. This ability to mentally represent the environment in greater detail provided better opportunity to utilise visual search behaviours to aid their future decision-making (Roca et al., 2013). Furthermore, working-memory capacity has been linked to having an external focus of attention and a heightened ability to resolve response conflict (i.e. choose an appropriate behavioural response when multiple options are available; see Furley & Wood, 2016, for a review). However, this hypothesis would have been further substantiated by taking a quantitative measure of working-memory (e.g. n-back task or corsi block test).

Nonetheless, similar findings were reported in junior football players whereby players with superior defensive tactical behaviour performed better on a standardised decision-making task (i.e. Iowa gambling task; Gonzaga, Albuquerque, Malloy-Diniz, Greco, & Teoldo da Costa, 2014). Although decision-making is a higher-order executive function (Diamond, 2013), it also relies heavily on the input of various other components (e.g. planning, shifting, and categorisation; Brand et al., 2005). Given that sports participation is laden with decision-making opportunities, it is essential to have the ability to make efficient decisions irrespective of the speed of play often exceeding an athlete's processing capacity (Roca & Williams, 2017; Williams, Ford, Eccles, & Ward, 2010).

Studies of the cognitive component skills approach have looked at multiple facets of executive function in athlete populations (e.g. inhibitory control, problem solving, etc.), suggesting that athletes of higher expertise possess superior general cognitive abilities that are particularly useful in a sports context (Jacobson & Matthaeus, 2014; Vestberg et al., 2012). Completing a battery of tests measuring inhibitory control and cognitive flexibility, elite athletes outperformed their sub-elite counterparts (Huijgen et al., 2015). Of particular note, expert-novice differences were only reported for measures of executive function and were non-significant for measures of processing speed and visuo-perceptual abilities. Emphasising the more complex processes where an athlete would typically rely on their executive function skills. Specifically, elite athletes demonstrated superior response inhibition (i.e. inhibition at the level of motor behaviour; Diamond, 2013), and an ability to switch between two tasks seamlessly (i.e. cognitive flexibility). Both of these abilities were likely to have exercised their working-memory-capacity to hold their goal in mind and inhibit the influence of distractors. Furthermore, performance on these tasks provided accurate classification of an athlete's expertise level in 62.5% of cases, supporting the predictive ability of executive function on athletic performance (Verburgh et al., 2014).

Comparable evidence of the executive function-athletic expertise relationship has been reported with elite athletes from various sports including; volleyball (Alves et al., 2013), fencing (Brevers et al., 2018), table tennis (Elferink-Gemser et al., 2018), gymnastics (Schmidt, Egger, Kieliger, Rubeli, & Schuler, 2016), and tennis (Pacesova et al., 2018), demonstrating better executive function abilities than amateur and novice counterparts. It would appear that superior working-memory is particularly prevalent in expert athletes and plays a pivotal role in influencing the other executive functions. This is further substantiated by studies investigating the premise of attentional control theory, in that other executive function performance (i.e. inhibitory control) became impaired as the demands on working-memory capacity increased (Eysenck et al., 2007; Graydon & Eysenck, 1989; Lavie, Hirst, de Fockert, & Viding, 2004). For example, reasoning/decision-making would not be possible without the input of working-memory. In a sports context, working-memory allows an athlete to utilise conceptual knowledge to influence what they perceive in a game situation and make appropriate decisions on the best course of action to achieve their goal (Diamond, 2013; Furley & Wood, 2016). Despite this plethora of evidence, studies of this nature predominantly focus on the lower-order executive function constructs (i.e. inhibitory control, working-memory, & cognitive flexibility) neglecting the more complex higher-order processes that may be utilised more frequently in a sporting environment.

Interest in the higher-order components of executive function (i.e. reasoning/decision-making, planning, & problem solving) has increased furthering our understanding of their impact on performance. In line with the lower-order constructs, findings suggest a substantial link between athletic expertise and subcategories of executive function (Jacobson & Matthaeus, 2014; Kasahara et al., 2008). Examining the effect of specific sport participation on executive function, Jacobson and Matthaeus (2014) reported significant differences in problem-solving favouring athletes over non-athletes. Specifically, external-paced athletes (i.e. those that participate in sports that require adaptability and rapid decision-making in an everchanging environment; Singer, 2000) demonstrated the greatest problem-solving ability. Further insight would have been possible if multiple outcome measures had been utilised to measure the participant's cognitive effectiveness and efficiency, highlighting in more detail where the cognitive improvements of elite athletes are present. Regardless, these results indicate that different aspects of sports participation may differentially facilitate executive function improvement in athletes (Jacobson & Matthaeus, 2014). Even when controlling for key confounding variables (i.e. physical activity & cardiovascular fitness) the observed advantage on executive function of external-paced sport participation remained, highlighting the impact of sport-specific training on cognitive functioning through cognitive skills transfer (Wang et al., 2013).

Furthermore, sports such as football and basketball require the athlete to generate rapid visual representations of their environment and respond according to their goal, particularly when their opponent attempts to hinder their progress (i.e. they utilise planning and problem-solving skills). Given that high performing athletes demonstrate these skills in a general cognitive domain (e.g. Jacobson & Matthaeus, 2014), it suggests that planning and problem-solving ability may be a significant indicator of sporting ability.

Furthering the notion that executive function can influence sporting ability, studies have utilised longitudinal methodologies to decipher if executive function can predict sporting outcomes (e.g. Lundgren et al., 2016; Vestberg et al., 2012). This would be particularly useful for talent identification purposes as youth development coaches could use cognitive performance data during the recruitment process. Examining whether executive function could predict post hoc performance in football players, the number of goals and assists achieved by a player was significantly correlated to performance on a measure of problem-solving, cognitive flexibility, and inhibitory control (i.e. D-KEFS design fluency; Vestberg et al., 2012). Additionally, cognitive flexibility (as measured using D-KEFS trail making test) was correlated (r = .41) with ice hockey performance the following season (Lundgren et al., 2016). Significantly, both studies utilised a measure of executive function with previously validated robust psychometric properties (Schmidt, 2003). These findings suggest that executive function performance has some predictive value to sports performance (i.e. number of goals & assists or plus/minus goals statistic).

Not all cognitive measures utilised within these studies, however, significantly predicted performance (e.g. design fluency did not predict ice hockey performance; Lundgren et al., 2016). Therefore, these findings should be interpreted with caution as the literature has not provided conclusive evidence. Equally, capturing the complexity of these sports with performance indicators is difficult and the validity of these measures has been questioned (Macdonald, 2011). For example, the plus/minus statistic in ice hockey is heavily influenced by variables outside of the players control (e.g. performance of their teammates, performance of their opponents, tactical decisions of the coach, etc.). That being said, it is the objective of all the players to contribute to their team’s success, alluding to a degree of face validity for these measures (Awad, 2009).

Given the extensive body of literature investigating executive function and athletic expertise that has reported significant findings, clarification of the phenomena is of importance and of interest to researchers and practitioners alike, thus worth investigating further. General consensus is that the heterogeneity of previous findings depicts the complexity of high-level competitive sport, as opposed to suggesting that executive function plays no role in impacting an athlete’s performance (Mann et al., 2007; Scharfen & Memmert, 2019; Voss et al., 2010). Numerous variables have been highlighted as impacting the executive function and athletic expertise relationship, including age of the athletes (Alves et al., 2013) gender (Voss et al., 2010), and level of expertise (Vaughan et al., 2018).

1.5 Potential Moderators

The array of research methodologies implemented over the past decade has provided a rich source of data on the link between executive function and athletic expertise. With 27.7 million people participating in sport in England (approximately 62% of the adult population; Sport England), samples within the sport psychology literature can vary widely. Toga and colleagues (2006) argue that the age of the athlete needs to be considered due to the developmental aspects of executive function continuing into the mid-twenties. Executive function development is closely correlated to the maturation of the prefrontal cortex and other mediating brain regions. Neuroimaging research has shown that both make significant developments in the first year of life and continue to do so into early adulthood (Diamond, 2002; Fiske & Holmboe, 2019).

Two studies have previously highlighted the superior executive function ability in elite football players compared to an age matched (non-athlete) control group (Vestberg et al., 2012, 2017). Using measures of both lower-order (working-memory; CogStateSports Demanding Working Memory) and higher-order executive function (planning; D-KEFS Design Fluency), members of an elite youth academy and senior players from the highest national league in Sweden scored highest on executive function measures. Performance was correlated to the number of goals and assists achieved by the player the following season. It was concluded that the lower-order functions were more crucial to football performance in youth players and higher-order functions more critical for senior level players based on the correlation coefficients for the two studies (Vestberg et al., 2017).

Sport-specific findings are in line with the cognitive development of these processes (Crone & Dahl, 2012; Huizinga, Dolen, & van der Molen, 2006). Skills associated with lower-order executive function such as inhibition, and working-memory typically develop during adolescence and the period of accelerated executive function maturation (Crone & Dahl, 2012; Luna, Garver, Urban, Lazar, & Sweeney, 2004). The ability to complete more demanding tasks involving strategy, planning, and reasoning is thought to continue developing throughout early adulthood (De Luca et al., 2003). Although executive functions are considered to be more critical for external-paced sports like football (Jacobson & Matthaeus, 2014), it is important to consider age as a factor in all studies as each sport requires a different cognitive profile to perform successfully (Singer, 2000).

Voss et al. (2010) found gender to be a significant moderating variable in the cognition and athletic expertise relationship. Specifically, male athletes performed significantly better on standardised measures of attentional capacities and processing speed. Several studies have reported gender specific findings for the relationship between cardiorespiratory fitness and executive function (e.g. Booth et al., 2013; Drollette et al., 2016). Taken together, these results suggest that male athletes executive function abilities may be more susceptible to the improvements associated with physical activity/improved physical fitness (Pindus et al., 2016). On the other hand, a recent review of human and animal research on gender differences in executive function concluded that there was little support for significant differences in executive function capacities (Grissom & Reyes, 2019). We argue that meta-analytic procedures using a large sample size will provide significant insight into the queried moderating role of gender on the executive function and athletic expertise relationship.

The specific requirements, paradigms, and stimuli of the cognitive measure may influence performance outcomes. The variety of test batteries that are designed to measure the executive function constructs (e.g. CANTAB & D-KEFS) is an interesting avenue of research to explain the apparent heterogeneity in findings, which to date has yet to be meta-analysed. Firstly, the difficulty of the cognitive measure can significantly influence its ability to demonstrate heightened performance in experts, or those with superior cognitive ability. Research has noted that differences in executive function are clearer between groups when task difficulty is greater (Diamond & Lee, 2011). Additionally, if the tasks are not challenging, they may become vulnerable to ceiling effects and would not elicit any expert-novice differences. For example, Ishihara and Mizuno (2018) examined between-subject improvements in executive function following two 12-month tennis intervention programs. It was cited that the high baseline executive function performance of both groups was a marker for ceiling effects and did not provide adequate opportunity for participants to improve over the training period. Therefore, any between study variance highlighted in the meta-analysis may be due to differing levels of complexity on the standardised tasks or the specific requirements may be more aligned to those utilised by athletes.

Research has provided support for the notion that participating in cognitively engaging physical activity (i.e. activities that require both high physical and cognitive demands) develops executive function to a greater degree than simple physical activity/physical activity alone (e.g. running; Schmidt et al., 2015). Predominantly, this is due to increased brain activity in regions associated with executive function (Diamond & Lee, 2011). It is apparent that participating in sports such as football, rugby, and hockey will simultaneously develop executive function and other neural mechanisms associated with motor skills (Cremen & Carson, 2017). Therefore, it is crucial that clear distinctions can be made between improved executive function ability and other cognitive skills when assessing the impact of participating in these sports. A recent review on the use of cognitive tests to measure intervention benefits for older adults highlighted the use of a single cognitive measure (e.g. Eriksen Flanker Task; Eriksen & Eriksen, 1974) to operationalise an executive function (e.g. inhibitory control) as a flawed methodology (Cremen & Carson, 2017). Specifically, the idiosyncrasies of the tasks require various cognitive functions to be completed successfully (Nose, Spies, & Motyl, 2012), and cannot be solely attributed to improvements in a single function without multiple measures of the construct being utilised. The operational measures of a specific executive function may utilise several cognitive skills which are also required for successful athletic performance. Therefore, measuring the effect of numerous cognitive skills on an athlete’s expertise level rather than the specific construct in question. An advantage of meta-analytic procedures is that they allow for comparison of studies with wide methodologies. Completing moderation analyses provides the opportunity to highlight any discrepancy in findings that are a result of the deployed executive function measure within the included studies.

1.6 Attentional Control Theory

Although it is widely regarded that executive function impacts athletic performance, the mechanisms that induce these deviations remain unclear.

Heightened anxiety or stress can influence an individual's cognition and behaviour on several levels, leading to increased distractibility and decreased performance (Nieuwenhuys & Oudejans, 2017). The nature of sport means that athletes are required to perform under heightened situational stress and with unexpected distractor stimuli more frequently (Coombes, Higgins, Gamble, Cauraugh, & Janelle, 2009). Recent research has called for further investigation into the impact of executive function in the anxiety-performance relationship, citing a breakdown in the top-down regulation of attention during pressurised sporting situations (Ducrocq, Wilson, Vine, & Derakshan, 2016).

According to attentional control theory (Eysenck et al., 2007), anxiety impacts the efficient functioning of the goal-directed attentional system and increases the extent to which processing is influenced by the stimulus-driven system. Increased interference from the stimulus-driven attentional system can cause an anxious individual (i.e., an athlete performing under pressure) to perceive ambiguous stimuli as threatening, diminish the efficiency of their attentional and executive function skills, and cause a breakdown in motor functioning (Coombes et al., 2009; Nieuwenhuys & Oudejans, 2017).

Attentional control theory highlights the importance of two outcome measures; the efficiency of performance (i.e. the time it takes to complete a task), and the effectiveness of performance (i.e. the accuracy with which it is done). This theory suggests that a breakdown in attentional control results in poorer cognitive performance, particularly hindering the efficiency with which a task is completed. This is further emphasised when the cognitive task demands are greater. Attentional control theory emphasises the impact of situational stress on an individual's cognitive efficiency, namely that more anxious individuals can complete cognitive tasks with a similar degree of effectiveness, but it takes them longer to do so (Coombes et al., 2009; Santos & Eysenck, 2006). Attentional control theory has received much support when examining it's influence on lower-order executive function constructs, such as inhibitory control (e.g. Pallak, Pittman, Heller, & Munson, 1975) and cognitive flexibility (e.g. Santos & Eysenck, 2006). Application across different executive functions is not fully understood, nor has the theory been applied in relation to athletic expertise. We addressed this gap.

1.7 The Current Meta-Analysis

Research into executive function and sport performance has simultaneously answered and asked many questions of the cognition and performance relationship. Numerous studies highlight the difference in executive function between athletes of varying expertise (e.g. Alves et al., 2013; Brevers et al., 2018; Vestberg et al., 2017). However, considerable inconsistencies remain. Several studies report non-significant results displaying minimal impact of executive function on an athlete's sporting ability (e.g. Furley & Memmert, 2010), and athletes competing in certain sports don't appear to possess superior cognitive abilities (e.g. swimmers; Wang et al., 2013). Ultimately, a quantitative synthesis will allow for greater clarity, overcome the limitation of small sample sizes that hinder studies in this area (Borenstein, Hedges, Higgins, & Rothstein, 2009), and allow for moderation analyses to be completed on key variables (e.g. age, gender, executive function measure). The ability to bring greater clarity to this relationship will be a significant contribution to knowledge, especially given that executive function was highlighted as a promising avenue of research for distinguishing top-level athletes from their lesser-able counterparts (Scharfen & Memmert, 2019).

Given the rapid growth in executive function research within the sporting domain, it was deemed pertinent to re-evaluate the most up to date literature. In sum, executive functions not only impact athletic performance in their own right (e.g. by allowing a football player to hold a mental representation of the game situation in their mind), but influence a plethora of other cognitive abilities through its top-down processing abilities, something that the previous meta-analyses were unable to account for and didn't conceptually consider. The present study benefits from following an up-to-date and previously validated classification criteria for athletic expertise (i.e. Swann et al., 2015). This is a novel contribution given that two previous meta-analyses utilised their own criteria for expert/elite athletes, and follows the recommendation of Scharfen and Memmert (2019) to focus on the elite definition of expertise (i.e. the current competitive level of the athlete, level of success at that level, etc.). To our knowledge, this is the first meta-analysis to systematically evaluate the impact of the operational measure on the executive function and athletic expertise relationship. This finding will provide new insight for future research to follow when investigating this relationship using the cognitive component skills approach.

Finally, a significant inclusion of the present meta-analysis is its basis on a psychological theory known to explain decreased cognitive performance during periods of high pressure such as those experienced in sport (i.e. attentional control theory; Eysenck et al., 2007). Premised on attentional control theory, the outcome scores from the executive function measures used within the included studies were categorised as measures of effectiveness or efficiency providing a more refined assessment of cognitive processes which may have been blurred in existing meta-analyses. Subsequently, they were analysed independently to investigate if expert athletes typically complete the tasks quicker (i.e. greater efficiency), or with more accuracy (i.e. greater effectiveness).

1.8 Objectives and Hypotheses

The primary aim of the present review was to bring greater understanding to the executive function and athletic expertise relationship by using meta-analytic procedures to synthesise the previous 10 years of research in this area. To date, there is no meta-analysis specifically focusing on executive function in this context despite its popularity as a research topic. Therefore, we have responded to the growing body of published literature and the recommendation of Scharfen and Memmert (2019) to explore this avenue in more detail to fully decipher the input of executive function on an athlete's level of expertise. Secondly, we aimed to gain insight into some of the key moderating variables of the executive function and athletic expertise relationship (e.g. age, gender, etc.), with particular emphasis on the operational measure of executive function (e.g. stop signal task or go/no go task for inhibitory control). Given the heterogeneity of findings to date, and the variety of measures used, this is a novel contribution that will bring significant knowledge to our understanding of measuring executive function following the cognitive component skills approach. A final aim was to investigate if elite/expert athletes typically outperform their lesser-able counterparts in a particular area of executive function, based on the premise of attentional control theory (i.e. effectiveness or efficiency on a cognitive task; Eysenck et al., 2007). Attentional control theory has particular relevance in sport as it explains the breakdown in cognitive performance when under pressure, and athletes often have to use multiple executive function elements in critical game situations (Coombes et al., 2009).

Building on previous research (e.g. Alves et al., 2013; Lundgren et al., 2016; Verburgh et al., 2014), we hypothesised that executive function ability (i.e. inhibitory control, working-memory, cognitive flexibility, decision-making, planning, & problem solving; Diamond, 2013) would display a positive association with athletic expertise. Such that, heightened executive functioning will be linked to greater levels of expertise. We also hypothesised that athletes with more expertise (i.e. super elite) would predominantly outperform athletes with lower expertise (i.e., novice) and non-athlete controls on outcome measures categorised by attentional control theory (e.g., effectiveness and efficiency). Finally, given the plethora of measures used and the inconsistency of findings reported, our investigation into the moderating role of executive function measures was considered to be exploratory.

2. Method

2.1 Search Strategy

In 2018, we completed a literature search using Web of Science, Scopus, Embase, Medline, PsychInfo, and CINAHL Plus was conducted. The search included three groups of search terms, following a similar protocol to Scharfen and Memmert (2019). Specifically, the keywords and Boolean search terms related to (a) the outcome (executive function OR higher-order cognition OR cognition); (b) it's sporting context (athlete OR sport OR sports performance OR athletic performance); and (c) the exclusion criteria concerning the population (NOT concussion NOT disability NOT clinical). The periodic searches of the online databases started in November 2018 and were completed by the end of December 2018. Upon completion of the screening process, we examined the reference lists of the included studies to locate additional relevant literature. However, no further studies were identified for inclusion in the present meta-analysis.

2.2 Selection Criteria

Full-text articles with English versions were eligible for inclusion in the meta-analysis. Studies were included that (a) had a publication date between January 2008 and the date of the search; (b) examined differences between at least two groups of athletes (non-athletes included); (c) used a non-sport specific measure of executive function (d) employed at least one test of executive function; (e) stated an expertise level for the athletes, or provided evidence with which we could classify the athletes (see Swann et al., 2015, for full criteria); (f) the average age of the participants was between 13 and 65 years; and (g) the outcome measure for executive function had to be classified as measuring either efficiency or effectiveness (Eysenck et al., 2007).

Studies were excluded that (a) used participants from a clinical population or those with a disability; (b) didn't report any behavioural performance data for the cognitive tests (e.g. used EEG or fMRI data); (c) the cognitive measure was sport specific in its stimuli or response action; (d) the cognitive measure was inappropriate as a test of executive function; (e) the athletes had suffered from a concussion; (f) used a median split method to classify athletic expertise; and (g) measured the impact of an acute bout of physical activity on executive function.

This literature search yielded 12,318 potential articles for inclusion. Eighty-nine of these articles were considered for eligibility in the meta-analysis. We excluded 58 articles during the eligibility process (see Supplemental Material B). The screening of the studies was conducted by the first and second authors. Disagreement was resolved by revisiting the articles with the fourth author and coming to a consensus. A PRISMA flow diagram of the screening process is provided in Figure 1. After screening these articles and excluding those deemed irrelevant, 31 articles met all the inclusion criteria.

2.3 Meta-Analytic Procedures

Random effects analyses were conducted using Comprehensive Meta-Analysis software (Borenstein, Hedges, Higgins, & Rothstein, 2005). We utilised random effects models, rather than fixed effects models, as the 31 included studies varied in design (see Table 1). Mean effects were weighted following the protocol outlined by Hunter and Schmidt (1990). This procedure allowed us to estimate mean effect sizes and variance in observed scores after considering sampling error (Card, 2012). For studies assessing more than one executive function, the subgroup of executive function was used as the unit of analysis. Each function outlined within the model (Diamond, 2013) is deemed an independent construct and was therefore analysed independently for its effect on athletic expertise. Overall mean effects were calculated for a composite executive function measure (i.e. the influence of all the executive functions combined), the individual executive function (i.e. inhibitory control, working-memory, cognitive flexibility, reasoning/decision-making, planning, & problem solving; Diamond, 2013), and based on the outcome measures provided within the included studies (i.e. a measure of cognitive effectiveness, or cognitive efficiency; Eysenck et al., 2007).

Prior to moderation analyses, we assessed the total heterogeneity of weighted mean effect sizes (Q_T). A significant Q_T indicates the variance in the weighted mean effect sizes exceeds what would be expected by sampling error, and therefore warrants inclusion during moderation analyses (Card, 2012). We also computed the inconsistency in observed effects (I^2) across studies for each analysis. I^2 is a statistic indicating the percentage of total variance across studies due to heterogeneity. A low

PRISMA Flow Diagram

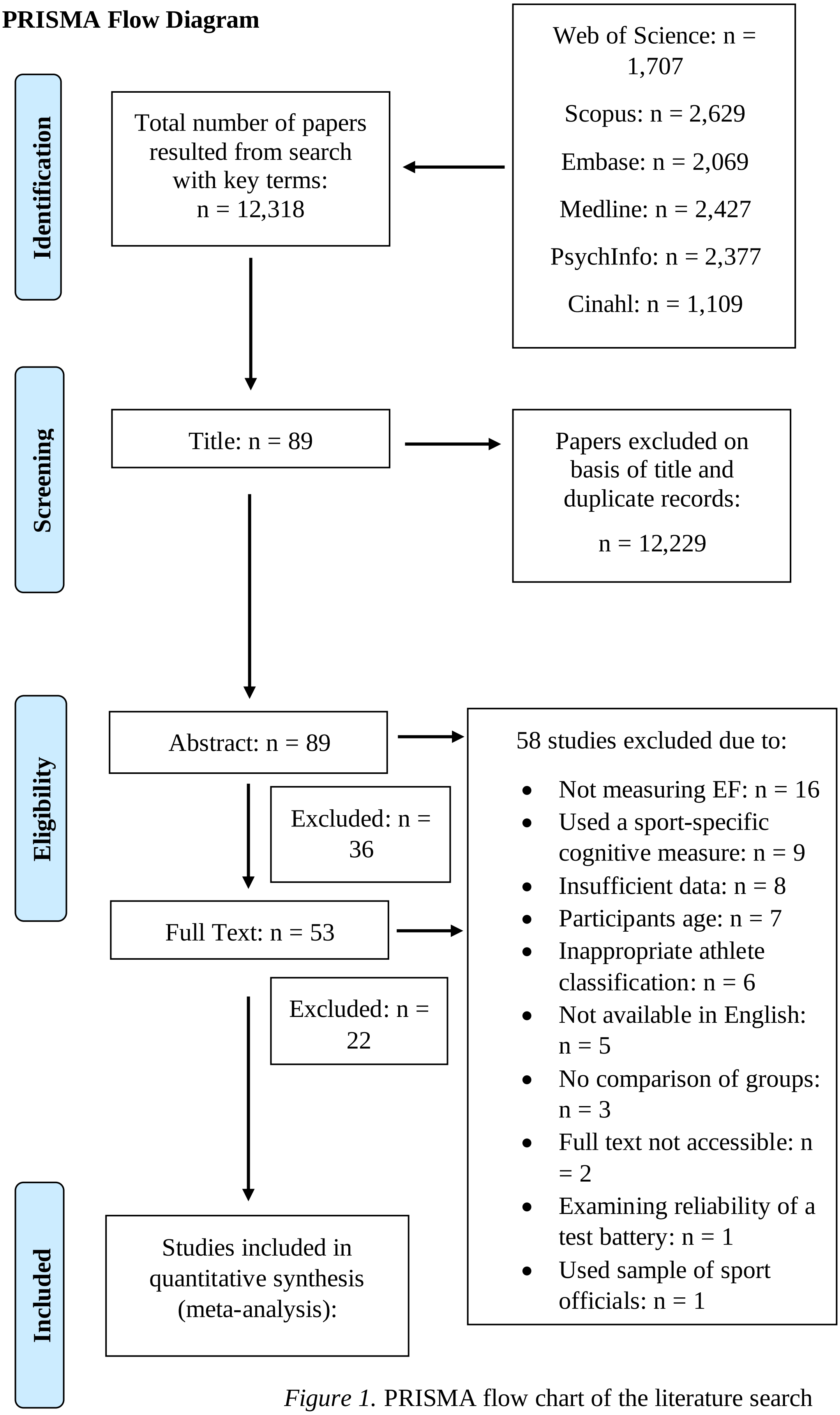

Figure 1. PRISMA flow chart of the literature search

level of heterogeneity is represented by a value of 25%, medium a value of 50%, and high a value of 75% (Card, 2012).

When Q_T was significant, we performed random-effects meta-regression with restricted maximum likelihood estimation to test the moderating effect of two continuous covariates and one categorical covariate: age (mean age of the sample), gender (percentage of female participants in the sample), and the specific executive function. Therefore, for each observed relationship, we tested four models: a model with age entered as a predictor, a model with gender entered as a predictor, a model with specific executive functions entered as a predictor, and a model with age, gender, and the specific executive functions entered simultaneously as predictors.

When testing models for age and gender, we utilised the mean outcome for each executive function from the relevant studies (i.e. we used the average of the weighted effect sizes from each executive function measured within a given study). When the model included a categorical variable (i.e. specific executive function), each outcome measure was treated independently to ensure a meaningful assessment of moderation. We selected subgroup within the study as the unit of analysis as numerous studies measured several aspects of executive function and we wanted to analyse their effects independently.

The same procedure was followed when conducting moderation analyses on the weighted mean effects for the individual executive functions. Again, we tested the moderating effect of two continuous covariates and one categorical covariate: age (mean age of the sample), gender (percentage of female participants in the sample), and the measure of executive function (e.g. stop signal task or go/no go task for inhibitory control).

Finally, we assessed publication bias using the trim and fill procedure (Duval & Tweedie, 2000) and by computing Egger's test of regression to the intercept (Egger, Smith, Schneider, & Minder, 1997). We inspected the funnel plots produced from the trim and fill procedure. When publication bias is absent, effects should be symmetrically distributed around the mean. Alternatively, in the presence of publication bias, there will be symmetry at the top of the funnel plot and asymmetry at the bottom of the funnel plot (Borenstein et al., 2009). Inspecting a plot with both the observed and imputed studies allows for a visual representation of how the effect size shifts when the imputed studies are included in the analyses (Borenstein et al., 2009; Smith et al., 2017). When publication bias is absent, Egger's regression intercept does not differ significantly from zero (Egger et al., 1997).

The present review was registered and updated through Open Science Framework accordingly (see Hagyard, Vaughan, Smith, & Edwards, 2019).

2.4 Description of Studies

Our search identified 31 articles and 73 samples containing relevant effect size data (see Table 1). The total number of participants across the included articles was 2,133. There were 50 samples of athletes (inclusive of all expertise levels) and 23 samples of non-athletes. Sample size varied between 14 and 269, with an average of 68.81 (*SD* = 53.18). The mean age of the samples varied between 14.16 and 28.80, with an average of 21.58 (*SD* = 3.42). The average percentage of female participants was 29.45%. Effect size information for each article is presented in Supplemental Material C.

3. Results

3.1 Overall Effect Sizes

Overall weighted mean effects between overall executive function, executive function efficiency, executive function effectiveness, individual executive function ability (i.e. inhibitory control, working-memory, cognitive flexibility, planning, problem solving, & decision-making), efficiency of the individual executive functions, effectiveness of the individual executive functions, and athletic expertise are presented in Table 2 (see Supplemental Material C for effect size data). Following Cohen's (1992) recommendations for small, medium, and large effects (r= .10, .30, & .50, respectively), overall executive function, executive function efficiency, executive function effectiveness, cognitive flexibility, cognitive flexibility efficiency, working-memory, working-memory efficiency, working-memory effectiveness, problem solving, and problem solving efficiency displayed small-to-medium, positive relationships with athletic expertise (r^+ = .14 - .28; see Table 2). Decision-making, decision-making efficiency, and decision-making effectiveness displayed medium-to-large, positive relationships with athletic expertise (r^+ = .32 - .50). However, we advise caution when interpreting the analyses for problem solving and decision-making as only one study measured these constructs within the present meta-analysis.

Inhibitory control, inhibitory control efficiency, inhibitory control effectiveness, cognitive flexibility effectiveness, planning, planning efficiency, and planning effectiveness' relationships with athletic expertise were non-significant. Further investigation of the inhibitory control and athletic expertise relationship revealed high heterogeneity ($I^2 = 96.53$) which contribute to a non-significant ($p = .051$) r^+ of .29[1].

The test of the total heterogeneity of variance of the weighted mean effect sizes (Q_T) was significant ($p < .05$) for athletic expertise's relationships with overall executive function, executive function efficiency, executive function effectiveness, inhibitory control, inhibitory control efficiency, inhibitory control effectiveness, cognitive flexibility effectiveness, planning, and planning effectiveness (see Table 2). The percentage of total variance owing the heterogeneity (I^2) ranged significantly ($I^2 = 0.00 - 98.10$), suggesting possible moderators.

3.2 Moderator Analyses

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[1] This level of heterogeneity was exacerbated by the inclusion of Alves et al. (2013). After re-assessing the validity of the paper's inclusion, it was concluded that it met all the inclusion criteria. Utilising the one study removed function of comprehensive meta-analysis allows for re-calculation of effect sizes after removal of individual studies. Upon removal of Alves et al. (2013), the magnitude of the effect between inhibitory control and athletic expertise reduced ($r^+ = .23$) whilst reaching a level of significance ($p = .02$). Comparable findings were reported when further investigating the inhibitory control efficiency and athletic expertise relationship. Again, the removal of Alves et al. (2013) produced a reduction of magnitude in the effect size ($r^+ = .35$ & $.24$ respectively) and subsequently reached a level of significance ($p = .03$). This provides evidence that the inclusion of Alves et al. (2013) resulted in a high level of heterogeneity causing difficulty in detecting a significant relationship between inhibitory control and athletic expertise.

Moderator analyses (see Supplemental Material D) investigated whether effect sizes with significant heterogeneity (Q_T) were moderated by age (mean age of the sample), gender (percentage of sample that were female), specific executive function (i.e. inhibitory control, working-memory, cognitive flexibility, planning, problem solving, & decision-making), or executive function measure (e.g. stop signal task or go/no go task for inhibitory control).

Meta-regression revealed the strength of the relationship between athletic expertise and planning was significantly lower than for the other executive functions ($\beta = .191$; $p < .05$;). Also, the strength of the relationship between planning efficiency and athletic expertise was significantly lower than athletic expertise's relationship to the other executive function efficiency abilities ($\beta = -.317$; $p < .05$). Regarding analyses on the individual executive functions and athletic expertise, meta-regression revealed inhibitory controls relationship with athletic expertise was significantly greater for the stop signal task ($\beta = .613$; $p < .01$) compared to the other measures (i.e. flanker task, go/no go task, & stroop/colour-word interference task). Comparable findings were reported for the inhibitory control and athletic expertise relationship when controlling for mean age and female percentage ($\beta = .675$; $p < .01$). Additionally, the strength of the relationship between inhibitory control effectiveness and athletic expertise increased as the mean age of the sample increased when controlling for female percentage and operational measure ($\beta = .099$; $p < .01$). Inhibitory control effectiveness' relationship with athletic expertise was moderated by the measure when controlling for mean age and female percentage, with the relationship being significantly greater for the stroop/colour-word interference task compared to the other measures ($\beta = .294$; $p < .05$).

Table 1: Characteristics of studies included in the meta-analysis

	Sample							
	N	Sample Type	Sport	Mean Age	Female %	Design	Executive Function	Measures
Alves et al. (2013)	154	Athlete Youth Athlete Community	Volleyball	19.20	47.40	Cross-Sectional	Inhibitory Control	SST
Brevers et al. (2018)	52	Athlete Community	Fencing Martial Arts	19.60	13.50	Cross-Sectional	Inhibitory Control	SST
Chan et al. (2011)	60	Athlete Community	Fencing	20.63	50.00	Cross-Sectional	Inhibitory Control	GNG
Chang et al. (2017)	60	Athlete	Endurance Martial Arts	21.32	30.00	Cross-Sectional	Inhibitory Control Cognitive Flexibility Planning	ST WCST ToL
Elferink-Gemser et al. (2018)	60	Youth Athlete	Table Tennis	15.80	60.00	Cross-Sectional	Cognitive Flexibility Inhibitory Control	DKEFS-CWI DKEFS-TMT
Feng et al. (2017)	47	Youth Athlete Community	Diving	14.16	53.19	Cross-Sectional	Working Memory	MRT
Furley & Memmert (2010)	112	Athlete Community	Basketball	24.80	0	Cross-Sectional	Working Memory	CBT
Han et al. (2014)	33	Athlete	Baseball	20.10	0	Cross-Sectional	Cognitive Flexibility	WCST
Huijgen et al. (2015)	88	Youth Athlete	Football	15.35	0	Cross-Sectional	Working Memory Inhibitory Control Cognitive Flexibility	VMS SST DKEFS-TMT

Jacobson & Matthaeus (2014)	54	Athlete	Various	20.13	57.40	Cross-Sectional	Planning Problem Solving Inhibitory Control	ToL DKEFS-CWI
Jansen & Lehmann (2013)	120	Athlete Community	Football Gymnastics	23.47	50.00	Cross-Sectional	Working Memory	MRT
Jansen et al. (2012)	40	Athlete Community	Football	24.48	0	Cross-Sectional	Working Memory	CMR
Kasahara, Mashiko & Niwa (2008)	31	Athlete	Rugby	28.80	0	Cross-Sectional	Planning	WAIS-BD
Krenn et al. (2018)	184	Athlete	Various	23.21	40.20	Cross-Sectional	Inhibitory Control Cognitive Flexibility Working Memory	FT FT-Mod n-BT
Liao et al. (2017)	57	Athlete Community	Badminton	23.55	38.60	Cross-Sectional	Inhibitory Control	SST
Lundgren et al. (2016)	48	Athlete	Ice Hockey	23.70	0	Cross-Sectional	Cognitive Flexibility	DKEFS-TMT
Martin et al. (2016)	20	Athlete	Endurance	24.50	0	Cross-Sectional	Inhibitory Control	ST
Nakamoto & Mori (2008)	18	Athlete	Baseball Athletics Gymnastics	NR	0	Cross-Sectional	Inhibitory Control	GNG
Nakamoto & Mori (2012)	14	Athlete	Baseball	NR	0	Cross-Sectional	Inhibitory Control	CATT
Pacesova et al. (2018)	98	Youth Athlete Community	Tennis	18.07	0	Cross-Sectional	Inhibitory Control	ST
Schmidt et al. (2016)	80	Athlete Community	Endurance Gymnastics Orienteering	25.73	50.00	Cross-Sectional	Working Memory	MRT

Seo et al. (2012)	43	Athlete Community	Archery	27.60	100.00	Cross-Sectional	Working Memory	JLO
Vaughan, Laborde & McConville (2018)	269	Athlete Community	Various	21.80	42.38	Cross-Sectional	Decision-Making	CGT
Vestberg et al. (2012)	57	Athlete	Football	24.05	45.60	Longitudinal	Cognitive Flexibility Inhibitory Control	DKEFS-TMT DKEFS-CWI
Wang et al. (2013)	60	Athlete Community	Tennis Swimming	20.10	0	Cross-Sectional	Inhibitory Control	SST
Wang et al. (2013) 2	42	Athlete Community	Tennis Swimming	20.40	0	Cross-Sectional	Inhibitory Control	GNG
Wang et al. (2014)	25	Athlete Community	Badminton	19.83	100.00	Cross-Sectional	Working Memory	VDT
Wang et al. (2016)	65	Athlete Community	Table Tennis	21.90	38.50	Cross-Sectional	Inhibitory Control	ANT
Wang et al. (2017)	36	Athlete	Badminton Athletics Boat Racing	20.77	0	Cross-Sectional	Inhibitory Control	FT
Yu et al. (2017)	54	Athlete Community	Badminton Athletics	21.30	44.40	Cross-Sectional	Cognitive Flexibility	TS
Zhang et al. (2015)	52	Athlete Community	Fencing	NR	51.90	Cross-Sectional	Inhibitory Control	GNG

Note. **NR** = not reported; ***N*** = total number of participants; **Female %** = percentage female; **SST** = Stop Signal Task; **GNG** = Go No-Go Task; **ST** = Stroop Test; **WCST** = Wisconsin Card Sorting Task; **ToL** = Tower of London Task; **DKEFS-CWI** = Delis-Kaplan Executive Function System Colour Word Interference Test; **DKEFS-TMT** = Delis-Kaplan Executive Function System Trail Making Test; **MRT** = Mental Rotation Task; **CBT** = Corsi Block Test; **VMS** = Visual Memory Span Task; **CMR** = Chronometric Mental Rotation Task; **WAIS-BD** = Wechsler Adult Intelligence Scale Block Design ; **FT** = Flanker Task; **FT-Mod** = Krenn et al.’s (2018) Modified Flanker Task; **n-BT** n-back Task; **CATT** = Coincident Anticipation Timing Task; **JLO** = Judgement of Line Orientation Task; **CGT** = Cambridge Gambling Task; **VDT** = Visual Discrimination Task; **ANT** = Attention Network Test; **TS** = Task Switching Paradigm

Finally, cognitive flexibility effectiveness' relationship with athletic expertise decreased as the proportion of females in the sample increased when controlling for operational measure ($\beta = -.017$; $p < .01$). Again, we advise caution when interpreting these findings due to the small number of studies included in some of the moderator analyses (see Supplemental Material E for scatter plots of significant moderators).

3.3 Publication Bias

Funnel plots (see Supplemental Material F) and Egger's regression intercept (see Table 2) provided mixed evidence for publication bias. Egger's regression intercept was significant for athletic expertise's relationship with executive function, executive function efficiency, executive function effectiveness, inhibitory control, inhibitory control effectiveness, and working-memory (see Table 2). However, after imputing missing studies, adjusted "trim and fill" estimates provided the same substantive findings in terms of effect size and significance for the aforementioned relationships with one exception. Working-memory efficiency's relationship with athletic expertise, where adjusted "trim and fill" estimates reduced the effect size (from .22 to .13) and the relationship became non-significant ($k^{\mathrm{TF}} = 2$).

4. Discussion

The present study aimed to provide a quantitative synthesis of the executive function and athletic expertise literature that falls under the umbrella of the cognitive component skills approach. To date, there is no meta-analysis solely focusing on executive function in this context despite its growing popularity as a research topic. We sought to bring greater clarity by introducing a more detailed framework with which to measure these constructs. Specifically, we utilised the first systematically validated athlete classification criteria from within the athletic expertise literature (i.e. Swann et al., 2015) and implemented the premise of attentional control theory when categorising the cognitive outcome measures (i.e. efficiency and effectiveness; Eysenck et al., 2007). Secondly, we aimed to assess the moderating effects of age, gender, facet of executive function, and operational measure deployed within the included studies. Finally, the present study highlights any gaps in the extant literature from the past 10 years that warrant being addressed by future empirical research.

4.1 The Executive Function-Athletic Expertise Relationship

Our meta-analysis of 31 studies, 73 samples, and 2133 participants constitutes the most comprehensive evaluation of the executive function and athletic expertise relationship to date. Our analysis provided much support for the influence of executive function on athletic expertise. We found an overall small-to-medium effect size for the executive function and athletic expertise relationship despite the heterogeneity of effects found in individual studies. Additionally, the efficiency and effectiveness of executive function task performance was positively related to athletic expertise, demonstrating that athletes participating at higher/more elite levels perform executive function tasks more efficiently (i.e. quicker) and more effectively (i.e. with greater accuracy).

Although we were interested in the overall effect of executive function, within the extant literature these constructs are investigated independently for their influence on an athlete’s level of expertise. We found that higher performing athletes outperformed their lesser-able counterparts on measures of cognitive flexibility, working-memory, problem solving, and decision-making. Furthermore, this finding was stable for composite measures of these constructs (i.e. efficiency and effectiveness combined), standalone efficiency measures, and standalone effectiveness measures (excluding cognitive flexibility effectiveness).

Finally, our moderation analyses highlighted some interesting variables that influence the executive function and athletic expertise relationship. Namely, composite planning ability (i.e. efficiency and effectiveness combined) and planning efficiency display a weaker correlation to athletic expertise than the other executive function constructs, lending to the notion that planning is less crucial to successful athletic performance. Upon further investigation of the individual constructs, the operational measure of inhibitory control significantly influenced the relationship with athletic expertise. Specifically, the stop signal task displayed the greatest effect for overall inhibitory control ability, and the stroop/colour-word interference task displayed the greatest effect for inhibitory control effectiveness, irrespective of age and gender. The link between inhibitory control effectiveness and athletic expertise was significantly influenced age, with the magnitude of the effect increasing as the participants age increased. Regarding cognitive flexibility, the relationship between effectiveness and expertise level was moderated by the proportion of females in the sample, with more females subsequently reducing the strength of the effect.

Our findings support much of the research evidence highlighting that executive function skills are greater in athletes of higher expertise/competing at more elite levels (e.g. Verburgh et al., 2014; Vestberg et al., 2017). Irrespective of heterogeneity in individual studies, the average overall effect substantiates the relationship that has been demonstrated in multiple sports (e.g. fencing, Brevers et al., 2018 and tennis, Pacesova et al., 2018). Participating in elite level sport requires an array of skills including motor control, supreme physiological capacity, and heightened cognitive abilities (Lundgren et al., 2016). The present analyses further

Table 2: Summary of overall effects for the relationship between executive function and athletic expertise

Variable	k	N	r^+	95% CI	Q_T	I^2 (%)	Egger's intercept	95% CI	k^{TF}	"Trim and fill" estimates r^+ [95% CI]
Executive Function	31	2,133	.24**	[.09; .37]	628.44***	93.64	-5.74**	[-9.37; -2.12]	0	.24 [.09; .37]
Efficiency	22	1,630	.28*	[.05; .47]	866.58***	96.77	-10.07**	[-15.76; -4.37]	0	.28 [.05; .47]
Effectiveness	25	1,770	.20*	[.04; .36]	424.59***	93.17	-4.85*	[-8.79; -0.90]	0	.20 [.04; .35]
Inhibitory Control	19	1,231	.29	[-.00; .54]	518.94***	96.53	-9.71**	[-16.10; -3.33]	0	.29 [-.00; .54]
Efficiency	15	1,104	.35	[-.07; .66]	734.92***	98.10	-15.23	[-24.55; -5.90]	0	.35 [-.07; .66]
Effectiveness	12	754	.29	[-.10; .59]	315.89***	96.52	-7.88*	[-15.66; -.10]	0	.28 [-.10; .59]
Cognitive Flexibility	8	584	.16**	[.05; .27]	10.61	34.01	0.75	[-4.74; 6.24]	0	.16 [.05; .27]
Efficiency	5	434	.18**	[.05; .31]	6.58	39.22	0.12	[-10.25; 10.49]	0	.18 [.05; .31]
Effectiveness	6	448	.12	[-.06; .29]	13.23*	62.21	3.71	[-5.46; 12.87]	0	.12 [-.06; .29]
Working Memory	9	739	.16***	[.08; .23]	2.58	0.00	1.74*	[0.41; 3.06]	3	.13 [.06; .20]
Efficiency	5	339	.22**	[.08; .35]	5.54	27.81	3.02	[.2.26; 8.30]	2	.13 [-.03; .29]
Effectiveness	8	699	.14**	[.06; .22]	3.89	0.00	0.12	[-2.81; 3.06]	0	.14 [.06; .22]
Planning	3	145	.12	[-.25; .45]	13.20**	84.85	-4.89	[-36.15; 26.37]	0	.12 [-.25; .45]
Efficiency	2	114	-.06	[-.31; .19]	1.39	28.24	—	—	—	—
Effectiveness	3	145	.13	[-.24; .46]	13.70**	85.41	-4.70	[-43.10; 33.69]	0	.13 [-.24; .46]
Problem Solving	1	54	.30*	[.00; .55]	—	—	—	—	—	—
Efficiency	1	54	.30*	[.00; .55]	—	—	—	—	—	—
Effectiveness	—	—	—	—	—	—	—	—	—	—
Decision Making	1	269	.42***	[.29; .52]	—	—	—	—	—	—
Efficiency	1	269	.50***	[.39; .60]	—	—	—	—	—	—
Effectiveness	1	269	.32***	[.19; .44]	—	—	—	—	—	—

Note. ***k*** = number of studies; ***N*** = total number of participants in the *k* samples; $\boldsymbol{r^+}$ = observed weighted mean correlation; ***CI*** = confident interval for r^+; $\boldsymbol{Q_T}$ = measure of heterogeneity of effect sizes for r^+; $\boldsymbol{I^2}$ = percentage of heterogeneity for r^+; $\boldsymbol{k^{TF}}$ = number of imputed studies as part of "trim and fill" method for r^+.

* $p < .05$; ** $p < .01$; *** $p < .001$

emphasised the crucial role of cognition in elite sport performance, supporting the notion of executive functions being critical to sporting success (Huijgen et al., 2015). The nature of sports participation requires an athlete to respond appropriately in highly dynamic situations with multiple distractors, providing greater opportunity to elicit goal-oriented behaviour (Lundgren et al., 2016; Unsworth et al., 2009). These behaviours are, at least in part, governed by an athlete's ability to form mental representations of their environment (i.e. working-memory), direct their attention to appropriate environmental cues (i.e. inhibitory control), and to utilise this information to formulate a strategy to be successful (i.e. planning and problem solving).

This overarching finding is in line with previous meta-analyses that showed the link between athletic expertise and perceptual-cognition (e.g. processing speed and attention; Mann et al., 2007; Voss et al., 2010). These prior studies demonstrate that perceptual-cognitive advantages in high performing athletes are found for both sport-specific and standardised tasks, suggesting that some cognitive advantages transfer beyond the sporting environment (Voss et al., 2010). Beyond this, we have provided evidence of the superior executive function abilities of elite athletes and refined this by showing how each facet of executive function is differentially related to athletic expertise. This in turn, extends the finding of Scharfen and Memmert (2019) who were the first to highlight an expert-novice difference in executive function ability through meta-analytic procedures and cited that executive function seems to be the most promising avenue for being able to distinguish between super-elite and elite athletes. Furthermore, executive functions aid in the regulation and control of lower-level cognitive processes, such as perceptual and motor processes (Gilbert & Burgess, 2008; Verburgh et al., 2014). For example, working-memory capacity has been shown to more easily allow for an external focus of attention (i.e. an athlete's attention can be focused on utilising environmental cues for contextual information; Furley & Wood, 2016). The top-down processing ability of executive function may ultimately influence an athlete's perceptual-cognition and explain the expert-novice differences reported in the previous meta-analyses (i.e. Mann et al., 2007; Voss et al., 2010).

The present study focused solely on studies of the cognitive component skills approach, in that they used standardised measures of executive function to operationally measure the constructs. This methodological approach removes the complexity of the sports environment and emphasises the role of cognitive abilities that are deemed to be requirements of successful sports performance (Nougier et al., 1991; Voss et al., 2010). Given the large and varied sample of 2133 participants, the presence of expert-novice differences provides support for the notion of cognitive skills transfer (Taatgen, 2013). Specifically, cognitive skills transfer is the process in which expertise in one area of cognition can be utilised on an untrained task (i.e. sport-specific use of executive function being present on standardised executive function tasks). Regardless of the apparent heterogeneity in individual studies, our findings demonstrate a link between athletic expertise and general cognitive performance by removing the influence of contextual information and heightened procedural knowledge that is possessed in expert athletes. This, along with the findings of numerous studies, suggests that there is an overlap between sport expertise and general executive function abilities (e.g. for inhibitory control; Brevers et al., 2018). Our findings support the notion that high performing athletes may possess superior executive functions as they experience more opportunities where these skills are required (Alves et al., 2013; Lundgren et al., 2016; Vestberg et al., 2012). The athletes in the included studies participated in a variety of sports that required responding to ever-changing environments, aspects of decision-making, and withholding prepotent responses (Singer, 2000; Williams & Ericsson 2005). Athletes who frequently utilise their executive function skills in competitive environments whilst under physiological stress may develop improved general executive function skills (Di Russo et al., 2010; Jacobson & Matthaeus, 2014).

Our results also suggest that high performing athletes develop improved executive function in terms of both efficiency and effectiveness of cognitive performance. It has previously been highlighted that successful sports performance is influenced by both the speed of action, and the accuracy of action. For example, in a sample of youth footballers from a talent development program, those who were selected to continue to the next stage of selection performed a passing performance task with greater accuracy (i.e. effectiveness) and without any reduction in the speed of play (i.e. had better efficiency; Huijgen, Elferink-Gemser, Ali, & Visscher, 2013). Given that cognitive abilities, especially executive function, are being emphasised as elite performance indicators in various sports (e.g. football, Vestberg et al., 2017, and ice hockey; Lundgren et al., 2016), our findings refine this further by separating the influence of cognitive efficiency and cognitive effectiveness. Ultimately, demonstrating that improvements in both measures of cognitive performance are prevalent within elite athlete populations.

It would appear that within high performing athletes, the speed-accuracy trade off of cognitive performance becomes less pronounced, in that standardised executive function tasks were performed at greater speed (i.e. efficiency) and with the same or greater level of accuracy (i.e. efficiency) than their lesser-elite counterparts. In a plethora of sports, particularly those of external-paced nature (e.g.

football, rugby, tennis, and badminton), the environment changes rapidly and often exceed the perceptual capabilities of the athlete (Roca et al., 2011). Irrespective of this, successful performance of an athlete is characterised by their ability to perform the necessary cognitive and motor tasks at this speed, whilst being extremely accurate to remain in control of the game (e.g. in football) or to stop their opponent scoring points (e.g. in table tennis; Elferink-Gemser et al., 2018).

The pooled effect sizes of the present study particularly emphasise the influence of executive function efficiency in elite athletes, demonstrated by the increased magnitude of the effects of efficiency outcomes compared to effectiveness outcomes (see Table 2 for complete findings). This finding corresponds to the wider literature examining the anxiety and cognitive performance relationship based on attentional control theory (Eysenck et al., 2007). Attentional control theory suggests that while cognitive effectiveness performance may remain relatively stable across conditions, cognitive efficiency may be susceptible to performance decreases when greater demands are required, or equally may be prone to improvement when frequently trained in a competitive environment. While attentional control theory highlights the influence of anxiety on the efficiency of lower-order executive functions (i.e. inhibitory control, working-memory, and cognitive flexibility), the present study extends this and demonstrates that there are apparent performance differences in the efficiency of elite athletes higher-order functions as well (e.g. decision-making).

Attentional control theory may have particular prevalence in athlete populations as research has highlighted that an increased influence of the stimulus-driven attentional system can inhibit pre-planned motor efficiency, leading to slow physical movements (Coombes et al., 2009). The stimulus-driven system attends to task irrelevant stimuli that can subsequently inhibit the efficiency of the goal-driven attentional system which is required to complete a task successfully (Eysenck et al., 2007). In a sporting context, these task irrelevant stimuli may be an aggressive opponent, a hostile crowd, or internal feelings of fear and inadequacy. Given the competitiveness and performance levels in elite sport, these performance differences may significantly influence the results of an athlete. However, further investigation is required to empirically test this hypothesis.

More recently, researchers have begun to test the principles of other integrated theories, such as the integrated theory of anxiety and perceptual motor performance (Nieuwenhuys & Oudejans, 2017). This model places greater emphasis on the additional resources required to overcome anxiety and attentional deficiencies. For example, in a driving-simulation task, increased anxiety manipulations resulted in a greater number of collisions and a decreased ability to remain in a predetermined speed zone (Gotardi et al., 2019). However, drivers who were more inexperienced (i.e. covered less distance per week while driving) increased the number of visual fixations on other cars (i.e. threat-related stimuli), whereas experienced drivers had a greater focus on the speedometer (i.e. a goal-relevant stimuli that could aid performance). Although these divergent strategies were not enough to elicit significant performance differences, it does demonstrate that individuals with more experience (i.e. greater expertise) utilise different mechanisms to focus on relevant information and aid task performance. Furthermore, the expertise differences may not have been great enough to allow for group differences to be detected in performance, the inclusion of trained/highly-skilled drivers may have provided greater insight to address this hypothesis. Ultimately, these integrated theories have received much support when investigating the influence of attentional control in applied scenarios, such as in darts performance (Nibbeling, Oudejans, & Daanen, 2012) and karate (Williams & Elliott, 1999), and may be of greater relevance than attentional control theory when investigating athlete populations whose cognitive performance directly impacts motor movement.

4.1.1 Lower-Order Executive Functions

Although assessing the impact of executive function as one construct provides some insight into the expert-novice differences of higher-order cognition, each facet is distinctly unique and utilised in different ways for multiple sports. Therefore, we sought to investigate each facet of executive function outlined by Diamond (2013) to evaluate if they are differentially related to athletic expertise. Working-memory is a lower-order executive function that involves manipulating information that is no longer perceptually present and is critical for making sense of anything that unfolds over time (Baddeley & Hitch, 1994; Diamond, 2013). Our results suggest that athletes with superior expertise possess heightened working-memory abilities and utilise these to facilitate their sports performances. In sports like football, rugby, and basketball, a player's value/effectiveness is based on how successfully they can keep possession, progress their teams attack, or score for their team. Subsequently, the choices a player makes are based on the perceptual information they have held in mind within the context of the game situation (Huijgen et al., 2015).

Moreover, components of working-memory are required to utilise other executive functions or cognitive skills (e.g. reasoning/decision-making and inhibitory control; Diamond; 2013). Working-memory and inhibitory control are often used in tandem to successfully complete a task, each supporting one another to achieve a goal. Research has demonstrated that working-memory capacity can aid in the focus of attention and inhibit the influence of auditory distractor stimuli on a basketball decision-making task (Furley & Memmert, 2012). An athlete is more likely to selectively focus their attention on relevant stimuli (e.g. the position and body shape of an approaching opponent) if they hold their goal in mind (e.g. advancing their teams attack by passing the ball to an unmarked teammate) and use this information to influence their future behaviour. An athlete's working-memory capacity may be particularly pertinent during periods of high situational stress (e.g. in the final period of a cup final) due to the impact of anxiety on an individual's attentional control (i.e. they become more influenced by the stimulus-driven system and focus on irrelevant stimuli such as the time left in the game or the crowd; Eysenck et al., 2007). In a study measuring the influence of working-memory capacity on attentional control and cognitive test performance (i.e. modified stroop task), individuals with superior working-memory capacity suffered no visual search or performance decrements between congruent and incongruent trials (Wood, Vine, & Wilson, 2016). Thus, highlighting that working-memory capacity can allow an individual to maintain task goals and use inhibitory control to focus their attention accordingly (Kane & Engle, 2003). Furthermore, when placed in a high threat condition (i.e. an ego threat condition where a fictional leader board was introduced) performance was not negatively influenced in the high working-memory capacity individuals but was significantly hindered in the low capacity group (Wood et al., 2016). Given that competitive elite sport is laden with pressure situations that need to be overcome and the breakdown of attentional control has particular relevance in these scenarios, an athletes working-memory ability may be crucial in allowing them to perform at these exceptionally high standards under the highest levels of stress.

Athletes who competed at more elite levels also demonstrated superior cognitive flexibility skills. Cognitive flexibility consists of several aspects of cognitive shifting. Specifically, being able to view something from another perspective, changing how we think about something, and being able to adjust to changing demands or priorities (Diamond, 2013). Competitive sport is full of situations where athletes have to flexibly change their course of action because their previous actions have been unsuccessful (Furley & Wood, 2016). This may be with regards to tactical decisions made by the coach being inappropriate on the field of play, or their preferred action tendencies are inadequate for achieving their goal. Several studies have provided behavioural (e.g. Yu, Chan, Chau, & Fu, 2017) and neurological (e.g. Han, Kim, Cheong, Kang, & Renshaw, 2014) evidence of superior cognitive flexibility in high performing athletes. Han and colleagues (2014) reported that higher ranking baseball players produced fewer perseverative errors on a standardised cognitive flexibility measure (i.e. Wisconsin card sorting task) and showed increased activation in the left prefrontal cortex, an area of the brain critical to the mediation of these errors (Pederson et al., 2012). Collectively, executive functions are defined as cognitive processes that facilitate thought and action during non-routine tasks (Friedman et al., 2006). Arguably, cognitive flexibility is the most aligned with this definition given that, at its core, is the ability to adjust thinking and react to new demands that can become apparent at any time.

4.1.2 Higher-Order Executive Functions

The ability to utilise the lower-order executive functions in a sports context appears to be a significant indicator of an athlete’s level of expertise. These three constructs (i.e. inhibitory control, working-memory, and cognitive flexibility) have been more readily investigated within athlete populations. However, knowledge is now beginning to be furthered through the inclusion of the more complex higher-order functions (i.e. reasoning/decision-making, planning, and problem solving). Although the number of included studies for these constructs is too low for meaningful meta-analytic conclusions (see Table 2), the findings from those studies which were included are discussed in relation to athletic expertise.

The analysis of the included studies measuring decision-making showed a significant positive relationship between decision-making ability and athletic expertise. Specifically, those that were competing at more elite levels made more effective and efficient decisions on a general measure of the construct. Decision-making in sport is notoriously complex and a lack of ecological validity is often cited as a limitation within this type of research (e.g. Vaughan et al., 2018). However, there remains a plethora of evidence demonstrating the superior decision-making abilities of elite athletes in their own sport and related sports when compared to less-elite counterparts (Travassos et al., 2013). It has previously been hypothesised that elite athletes may utilise a heuristic-driven strategy to make effective and efficient decisions in the extremely complex sports environment (Raab, 2012). This heuristic approach may help to explain the increased efficiency of decision-making in elite athletes. Namely, they are capable of ignoring a lot of irrelevant stimuli in order to get the most important information quickly and implement it. This, in turn, may utilise the lower-order executive functions through top-down processing to focus attention and ignore task irrelevant information (i.e. inhibitory control), jump between possible options if cue validation or the likelihood of success is too low (i.e. cognitive flexibility), and hold the relevant information in mind throughout the duration of the decision (i.e. working-memory). Given that every sport requires some element of decision-making in a pressurised environment, it is logical that athletes would demonstrate increased proficiency as they have to engage their decision-making processes during competitive play and practice (Jacobson & Matthaeus, 2014; Vaughan et al., 2018; Voss et al., 2010).

The present analysis demonstrated that athletes participating at more elite levels possessed greater problem-solving efficiency on a standardised proxy of the construct. While an athlete or team are trying to implement their skills to be successful during sport performance, their opponents are responding with counter moves to make achieving their goal as difficult as possible (e.g. the opponents may change formation to reduce the amount of space around the playmaker in football). The problem-solving process begins by being able to perceive a situation as a problem, before then utilising compensatory tactics to overcome this difficulty (Demiral, 2019). Participating in elite sport requires regularly competing during play and practice whilst undergoing high quality training regimes aimed to facilitate the development of cognitive skills to help achieve an athlete's goals (Chang et al., 2017; Huijgen et al., 2015). Frequent involvement in these high performance environments, where time pressured decisions need to be made in response to the movements of an opponent, may improve the efficiency with which an athlete can perceive the external cues and cognitively shift from their initial planned movement to a more appropriate one (Jacobson & Matthaeus, 2014). These abilities are particularly pertinent in external-paced sports (e.g. football and rugby) where the influence of the opponent is greater and more apparent.

While the other lower-order executive functions (i.e. working-memory and cognitive flexibility) displayed significant relationships with athletic expertise, the inhibitory control-athletic expertise relationship was non-significant despite the reported small-to-medium effect size (see Table 2). This is a somewhat unique finding given the number of studies investigating this construct and reporting significant expert-novice differences in athletes from various sports (e.g. badminton; Wang, Yang, Moreau, & Muggleton, 2017, and football; Huijgen et al., 2015). However, as highlighted earlier, the inclusion of one particular study (i.e. Alves et al., 2013) resulted in a high level of heterogeneity making it difficult to detect a significant result (as highlighted by the finding from the one study removed analysis). Given this, it is still deemed appropriate to discuss the inhibitory control and athletic expertise relationship in more detail.

Inhibition influences the control of attention, emotion, and behaviour to withhold a prepotent response. Predominantly, studies of athlete populations focus on the aspects of inhibitory control that govern behavioural inhibition (e.g. motor; Wang et al., 2017) and the inhibition of attention (e.g. selectively focused attention; Krenn et al., 2018). These skills are crucial to performance in numerous sports as they facilitate a player's ability to focus on appropriate stimuli. For example, a tennis player's ability to focus on the ball during the return of a serve, or a football defender's ability to focus on the body shape of the attacker to deduce the nature of their next move (e.g. a step over in order to deceive the defender). Not only this, participating in sport requires an athlete to block out the influence of inappropriate or distracting stimuli (e.g. a hostile crowd) so that their attentional capacities can be utilised more efficiently to achieve their goal (Eysenck et al., 2007; Lundgren et al., 2016). Furthermore, athletes of greater expertise typically demonstrate a heightened ability to inhibit prepotent motor movements without significantly hindering their response times (e.g. Pacesova et al., 2018; Wang et al., 2017). These skills are especially useful in interceptive sports such as tennis, badminton, and squash where the target travels at high speed and its direction is directly influenced by the actions of the opponent. While elite athletes will likely anticipate the direction of their opponents shot (i.e. use planning and decision-making skills based on appropriate information), racquet sports involve elements of deception and misdirection, meaning the ability to inhibit the prepotent action and respond to the new environmental cues is paramount (Fuchs, Faude, Wegmann, & Meyer, 2014).

The relationship between planning and athletic expertise was non-significant. This was corroborated by initial moderator analyses highlighting a significantly smaller effect size for the planning and athletic expertise relationship compared to the other executive function constructs. It may be that the deployed measures of planning (e.g. Tower of London task) were not complex enough (compared to those faced during competition) to elicit expert-novice differences that are apparent within a sports environment. Research has noted that differences in executive control are clearer between groups when more substantial levels are required (Diamond & Lee, 2011). Equally, it may be that planning abilities are more context specific compared to other executive functions, meaning the operational measures of planning used within the included studies were too generic to demonstrate the heightened planning skills of the elite athletes. Again, we are unable to reach any concrete conclusions regarding this relationship given that only three studies assessed planning in relation to athletic expertise (Chang et al., 2017; Jacobson & Matthaeus, 2014; Kasahara et al., 2008).

4.2 Moderators of Executive Function-Athletic Expertise Relationship

Meta-regression revealed several significant moderating variables in the executive function-athletic expertise relationship. Firstly, we found that the influence of inhibitory effectiveness on athletic expertise hinges on the age of the sample. Specifically, older athletes’ (aged 22 and over) inhibitory control effectiveness ability had a larger effect on their expertise level compared to adolescent and younger adult athletes. Although executive functions are known to continue developing into adulthood, inhibitory control is a lower-order executive function which is thought to be fully developed during adolescence and after the period of accelerated maturation (Crone & Dahl, 2012; Luna et al., 2004; Toga et al., 2006). Equally, is has been demonstrated that lower-order constructs (e.g. inhibitory control) are more beneficial for distinguishing between youth athletes (Vestberg et al., 2012). Senior athletes, with established inhibition skills, require the input of the more complex higher-order executive functions, such as decision-making and problem solving (Vestberg et al., 2017). A possible explanation for this finding lies in personality traits. Roberts, Walton, and Viechtbauer (2006) suggest that conscientiousness increases with age, as the present study demonstrated for inhibitory effectiveness. Conscientiousness is characterised by persistence and self-disciplined goal-directed behaviour (Pervin, Cervone, & John, 2005). It is possible that older athletes may have been more diligent and driven to perform during the inhibitory control tasks. The nature of these tasks predominantly encourages participants to be as accurate (i.e. effective) as possible when inhibiting their responses, leading older and possibly more conscientious individuals to use a more conservative wait strategy to ensure best possible performance (Verburgh et al., 2014).

In accord with Voss et al. (2010), gender was shown to moderate the association between cognitive flexibility effectiveness and athletic expertise, in that a greater proportion of female participants significantly reduced the magnitude of the effect. However, all studies in the present analysis that measured cognitive flexibility had a higher proportion of males within the sample. Therefore, this finding should be interpreted with caution as it is unknown how this relationship is affected by a higher proportion or all female sample.

Of particular note, the inhibitory control and athletic expertise relationship elicited a significantly greater effect when inhibitory control was measured using the stop signal task and equivalent coincident anticipation timing task. Inhibitory abilities are said to be a key factor in successful cognitive and motor control (Chambers, Garavan, & Bellgrove, 2009). Typical inhibitory control tasks, such as the stroop task and flanker task, require the inhibition of a prepotent or dominant response to a target stimulus. Primarily, studies using these tasks implement a “subtraction logic” to investigate the influence of incongruent stimuli on an individual’s inhibitory control (e.g. the target arrow points left, and the surrounding arrows point right in the flanker task). Tasks of this nature are said to require several executive function skills (i.e. motor inhibition and selective attention) to be performed successfully. Furthermore, numerous brain imaging studies have demonstrated differential brain activation in areas of the cortical motor network during congruent and incongruent trials, and therefore these tasks may not be a process pure measure of inhibitory control (see Cremen & Carson, 2017 for full review). In contrast, the stop signal task requires an individual to withhold a prepotent response (i.e. responding to the target stimulus) following the sound of an auditory tone. Certain sports (e.g. football, rugby, and tennis) require athletes to inhibit their movements based on the opponent’s actions (e.g. a defender marking an open player on your team). Given that the requirements of the stop signal task align with those of numerous external-paced sports, the stop signal task may be a more accurate measure of inhibitory control in athletes (Chen et al., 2019).

Interestingly, when only analysing the effectiveness outcomes for inhibitory control, the relationship with athletic expertise was significantly greater when measured using the stroop task. Again, previous research has reported low inter-correlations between the stroop task and other inhibitory control measures that follow the stop signal paradigm, citing the utilisation of different inhibition stages. Specifically, stop signal paradigms predominantly require inhibitory control at the late response execution phase. Whereas the stroop task, which involves a greater element of conflict resolution (i.e. the ability to inhibit the drive to read the stimulus word and state the ink colour), allows for inhibitory control to accumulate and respond during any stage from stimulus perception to response activation (see Khng & Lee, 2014 for full review). Relating this to the overall inhibitory control finding, research has reported a small-to-moderate relationship between stop signal efficiency and stroop task effectiveness measures, in that individuals who take longer to inhibit a prepotent response are also likely to provide inaccurate (i.e. commission errors) responses on the stroop task (Khng & Lee, 2014). This is comparable to findings of the present analyses showing that composite inhibitory control (i.e. efficiency and effectiveness combined) is more correlated to athletic expertise when measured with the stop signal task, and inhibitory control effectiveness had a stronger correlation when measured using the stroop task. This supports the notion that these two outcomes may measure the same inhibitory control mechanisms that are also requirements of elite level athletic performance.

4.3 Limitations of Overall Literature

This meta-analysis provides greater understanding of the executive function-athletic expertise relationship, and in turn, highlights limitations of the literature. Firstly, the majority of studies deploy only one measure of each executive function to operationalise the construct. Given the apparent idiosyncrasies of the different measures, this approach has several shortcomings. Furthermore, during initial investigation of the lower-order constructs it was noted that common executive tasks lack construct validity and are not process-pure measures of a particular construct. Given the inherent complexity of executive function tasks, utilising a latent variable approach can circumvent these issues by extracting commonalities between numerous tasks and defining these as the operational measures of a specific function (Miyake et al., 2000) A more holistic and valid approach would be to utilise numerous measures for each executive function construct to provide convergent evidence that it does indeed influence athletic expertise (see Cremen & Carson, 2017 for full review). Equally, this approach would provide greater insight into the specific aspects of an executive function that are influencing the expertise level or performance of an athlete (e.g. motor response inhibition, or selective attention abilities).

Also, studies use too broad a range of outcome measures for each executive function (i.e. numerous measures of efficiency, effectiveness, and other possible outcomes) which makes the research findings difficult to navigate. Given the findings of the present analysis that expert-novice differences are reported for both efficiency and effectiveness, and the relevance of attentional control theory in sport and cognition, future studies should focus on providing data that align with these key aspects of cognitive performance (Eysenck et al., 2007). Additionally, there still remains vast inconsistency in the operationalisation of athletic expertise. Where studies did not follow the guidelines of Swann and colleagues (2015), we used appropriate provided information to classify the athletes of the included studies. Given the complexity and variability of professional sport, the classification criteria of Swann and colleagues is the most valid and rigorous available to researchers and should be utilised in its full capacity wherever possible. This would provide greater rigour within individual studies, but also allow for easier comparison between studies, levels of athletes, and sports.

4.4 Limitations of the Present Study

Limitations in the literature result in limitations in our analyses. Only five included studies looked at higher-order executive functions (i.e. reasoning/decision-making, planning, and problem solving) in relation to athletic expertise. As a result, we were unable to provide more conclusive meta-analytic findings on how these constructs may influence an athlete's level of expertise. Given what is now known about the top-down processing capabilities of executive function, future research should investigate these constructs further to gain greater understanding of their influence on athletic expertise, the lower-order executive functions, and other cognitive functions.

Samples were predominantly male, and the age range of the included studies was restricted (i.e. age ranged from 14.16 to 28.80 years). Ultimately, we were unable to evaluate the moderating effect of age across the whole athlete career span and conclusions regarding the role of gender need to be interpreted with caution. Irrespective of this, it is still deemed required to further investigate the role of age and gender on the executive function and athletic expertise relationship. Executive functions continue to develop into adulthood and could be further enhanced by the increased opportunity of brain plasticity and neural adaptation of participating in cognitively engaging physical activity (Churchill et al., 2002). Furthermore, the lack of female athlete samples is still an issue initially highlighted by Voss and colleagues (2010) that has not been addressed. Investigators need to forth come greater effort to investigate female athletes from a variety of sports to provide greater clarification on the influence of gender and also further validate the executive function-athletic expertise literature.

Finally, there is mixed evidence of publication bias for studies measuring working-memory efficiency. This brings into question the validity of the present findings as the included studies may not be truly representative of the relationship. Several explanations may be valid when trying to understand this finding. Firstly, is the possibility of null or negative findings being less likely to be published, sometimes referred to as “the file-drawer problem” (Rosenthal, 1979). This may have led to the published literature not being representative of all the studies investigating working-memory efficiency, resulting in the present analysis producing a larger overall effect size (Card, 2012). Alternatively, these null findings are less likely to be highlighted within research articles, often only being reported within tables, and may have not been detected during our literature search process. Finally, the tasks deployed to measure working-memory within the included studies (e.g. n-back task, corsi block task, etc.) typically emphasise the importance of a participant’s effectiveness (i.e. accuracy of response) and use this as the main outcome measure. Therefore, researchers may be less likely to report the efficiency scores on these tasks, irrespective of the effect size or significance of the finding. However, it cannot be conclusively ruled out that null findings were omitted for working-memory efficiency performance in the included studies as it has previously been captured in cognitive research (e.g. Edwards, Edwards, & Lyvers, 2016).

4.5 Future Recommendations

While significant developments have been made, future research may wish to address certain voids. Firstly, researchers may wish to combine the variables included within the extant meta-analyses (i.e. Mann et al., 2007; Scharfen & Memmert, 2019; Voss et al., 2010) to further investigate if they differentially influence athletic expertise. This endeavour would highlight differences between the expert performance approach and the cognitive component skills approach, a significant addition to the literature to date. Additionally, from an experimental perspective, future research may wish to focus on the impact of cognitive control training through randomised controlled trials, and studies implementing longitudinal designs to assess the development of executive function abilities over time. Previous research has demonstrated that cognitive skills can be developed through dedicated cognitive control training (see Koster, Hoorelbeke, Onraedt, Owens, & Derakshan, 2017) and athletic performance can be benefitted through isolated cognitive training (e.g. Hopwood, Mann, Farrow, & Neilson, 2011; Ryu, Kim, Abernethy, & Mann, 2013), but this needs to be further investigated using the most rigorous scientific methodologies within a sports domain.

4.6 Conclusion

This meta-analytic review represents the most rigorous test of the relationship between executive function and athletic expertise to date. In quantitatively synthesising the literature, we corroborate the research demonstrating the heightened executive function abilities of elite athletes compared to their lesser-elite counterparts (e.g. Scharfen & Memmert, 2019; Vestberg et al., 2017). We added to the literature by bringing greater specificity to our understanding of the executive function-athletic expertise relationship. Specifically, four of the six executive functions outlined by Diamond (2013) had positive relationships with athletic expertise, making this the first meta-analysis to differentially investigate the role of specific executive functions on expertise in sport. Furthermore, the focus on studies following the cognitive component skills approach brings credence to the transferability of executive function skills required for successful sports performance into the general cognitive domain.

Our findings indicate that certain executive function-athletic expertise relationships change meaningfully depending on how the executive function is assessed, the age of the participants, and the proportion of females within the sample. The present study highlights the vital methodological requirements for future work in this area. Particular emphasis should be placed on utilising a multi-measure approach to operationalise executive functions due to the idiosyncrasies of individual measures, bringing greater rigour and reliability to the research evidence and further strengthening the notion of the cognitive component skills approach.

The present analysis represents the first line of inquiry to utilise a theory of cognitive performance (i.e. attentional control theory; Eysenck et al., 2007) to breakdown executive function ability into core components. Specifically, we differentially investigated the efficiency and effectiveness of executive function performance to highlight if one particular facet of cognitive performance has greater emphasis on an athlete's level of performance. In synthesising the literature, we showed that elite athletes performed standardised executive function tasks with greater efficiency, and with the same or a greater level of effectiveness. This highlights that the speed-accuracy trade off in cognitive performance may be less pronounced in elite athletes, allowing them to utilise executive functions to think and respond appropriately to the highly dynamic game situation. These findings therefore build on existing research that has examined expert-novice differences in executive function (e.g. Elferink-Gemser et al., 2018), identifying that athletes participating at more elite levels perform cognitive tasks at greater speed, and with a greater degree of accuracy.

5. References

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6. Supplemental Materials

6.1 Supplemental Material A: Included Studies

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Table 3: Characteristics of studies excluded from the meta-analysis

	Sample							
	N	Sample Type	Sport	Mean Age	Female %	Executive Function	Measures	Reason for Exclusion
Abdullah et al. (2016)	26	Athlete	Football	25.00	0	NR	NR	Executive function not measured
Alarcon et al. (2017)	NR	NR	NR	NR	NR	NR	NR	Not available in English
Alarcon et al. (2017) 2	34	Athlete	Basketball	22.70	0	Problem Solving Inhibitory Control	DKEFS-DF ST	Not available in English
Alesi et al. (2015)	46	Community	NR	9.10	0	NR	NR	Participants age < 13 years
Alesi et al. (2016)	44	Community	Football	8.80	0	Working Memory Inhibitory Control Planning	BDS CBT ToL	Participants age < 13 years
Aviles et al. (2014)	NR	NR	NR	NR	NR	NR	NR	Not available in English
Babiloni et al. (2010)	48	Athlete Community	Martial Arts	23.30	54.17	NR	NR	Executive function not measured
Ballester et al. (2015)	75	Athlete Community	Football	13.69	44.00	NR	NR	Executive function not measured
Barhorst-Cates (2018)	50	Athlete Community	Various	18.20	100.00	Working Memory	CBT	Athletes not classified by appropriate criteria
Barsingerhorn et al. (2013)	8	Athlete	Volleyball	21.00	62.50	NR	NR	Executive function not measured
Bhabhor et al. (2013)	209	Athlete Community	Table Tennis	17.96	0	NR	NR	Executive function not measured

Bianco et al. (2017)	48	Athlete Community	Fencing Table Tennis Volleyball Boxing	29.43	12.50	Inhibitory Control	GNG	Insufficient data
Brick et al. (2018)	10	Athlete	Endurance	40.85	60.00	NR	NR	Executive function not measured
Callan & Naito (2014)	NR	NR	NR	NR	NR	NR	NR	Insufficient data - Commentary
Cascone et al. (2013)	40	Athlete	Climbing	NR	NR	Planning	ToL	Insufficient data
Causer & Ford (2014)	205	Athlete	Various	20.00	26.19	Decision-Making	NR	Used sport-specific cognitive measure
Chiu, Chen & Muggleton (2017)	31	Athlete Community	Volleyball Endurance Swimming	22.20	51.60	Inhibitory Control	FT	Insufficient data – Book chapter
Chueh et al. (2017)	48	Athlete Community	Various	20.55	43.75	NR	NR	Executive function not measured
Claver et al. (2015)	134	Athlete	Volleyball	14.82	48.51	Decision-Making	NR	Used sport-specific cognitive measure
Claver et al. (2015) 2	134	Athlete	Volleyball	NR	NR	Decision-Making	NR	Not available in English
Claver et al. (2017)	164	Athlete	Volleyball	14.82	56.71	Decision-Making	NR	Used sport-specific cognitive measure
Cona et al. (2015)	30	Athlete	Endurance	43.00	0	Inhibitory Control	GNG	Athletes not classified by appropriate criteria
Diaz del Campo et al. (2011)	129	Athlete Community	Football	NR	NR	Decision-Making	NR	Insufficient data
Furley & Memmert (2012)	28	Athlete	Basketball	27.20	42.48	Decision-Making	NR	Used sport-specific cognitive measure

Gonzaga et al. (2014)	153	Athlete	Football	14.35	NR	Decision-Making	IGT	Athletes not classified by appropriate criteria
Guldenpenning et al. (2011)	32	Athlete Community	Athletics	23.2	50.00	NR	NR	Executive function not measured
Guzman, Pablos & Pablos (2008)	39	Athlete	Orienteering	28.20	0	NR	NR	Executive function not measured
Helm, Reiser & Munzert (2016)	30	Athlete	Handball	24.40	0	NR	NR	Executive function not measured
Honer & Feichtinger (2016)	2677	Athlete	Football	11.66	0	NR	NR	Participants age < 13 years
Howard, Uttley & Andrews (2018)	NR	NR	NR	NR	NR	NR	NR	Insufficient data – Book chapter
Ishihara et al. (2017)	106	Athlete	Tennis	9.90	50.94	Inhibitory Control Working Memory Cognitive Flexibility	ST n-BT LGT	Participants age < 13 years
Ishihara et al. (2018)	16	Athlete	Tennis	NR	0	Cognitive Flexibility	LGT	Athletes not classified by appropriate criteria
Isoglu-Alkac et al. (2018)	36	Athlete Community	Various	26.00	50.00	NR	NR	Executive function not measured
Johnstone & Mari-Beffa (2018)	48	Athlete Community	Martial Arts	19.65	77.09	Inhibitory Control	ANT	Athletes not classified by appropriate criteria
Lopes et al. (2016)	80	Athlete	Volleyball	13.85	63.70	Decision-Making	NR	Used sport-specific cognitive measure
Lopez & Postigo (2012)	40	Athlete	Gymnastics	18.10	NR	NR	NR	Executive function not measured

MacDonald & Minahan (2016)	18	Athlete	Rugby	19.00	0	NR	NR	Measuring reliability of cognitive measures
Moreau (2013)	36	Athlete Community	Wrestling	22.50	50.00	NR	NR	Executive function not measured
Moreau et al. (2012)	NR	NR	NR	NR	NR	NR	NR	Full text not accessible
Parkin & Walsh (2017)	17	Athlete	Various	13.19	41.18	Decision-Making	CGT	Not comparing between 2 groups of athletes
Parkin, Warriner & Walsh (2017)	23	Athlete	Various	28.25	47.82	Decision-Making	CGT	Not comparing between 2 groups of athletes
Perez-Lobato, Reigal & Hernandez-Mendo (2016)	149	Community	NR	15.05	NR	NR	NR	Not available in English
Pesce &Audiffren (2011)	100	Athlete Community	Various	NR	NR	Cognitive Flexibility	LGT	Participants age > 65 years
Roca et al. (2013)	24	Athlete	Football	24.05	0	Decision-Making	NR	Used sport-specific cognitive measure
Roca, Williams & Ford (2012)	64	Athlete	Football	21.05	0	Decision-Making	NR	Used sport-specific cognitive measure
Sakamoto et al. (2018)	383	Athlete	Football	9.70	NR	Inhibitory Control Cognitive Flexibility	ST DFT	Participants age < 13 years
Sanchez-Horcajo, Llamas-Alonso & Cimadevilla (2015)	56	Athlete Community	Various	NR	0	NR	NR	Executive function not measured
Schaefer (2014)	NR	NR	NR	NR	NR	NR	NR	Insufficient data - Review
Schumacher et al. (2018)	178	Athlete	Football	26.20	0	NR	NR	Executive function not measured

Taddei et al. (2012)	40	Athlete Community	Fencing	36.50	32.50	Inhibitory Control	DRT	Athletes not classified by appropriate criteria
Van Maarseveen et al. (2016)	22	Athlete	Football	16.30	100.00	Decision-Making	NR	Used sport-specific cognitive measure
Verburgh et al. (2014)	126	Athlete	Football	11.90	0	Inhibitory Control Working Memory	SST ANT BDS	Participants age < 13 years
Vimal, Neelambikai & Shanmugavadivu (2018)	49	Athlete Community	Table Tennis	NR	NR	NR	NR	Full text not accessible
Wimhurst, Sowden & Wright (2016)	30	Athlete Community	Various	25.40	36.67	Decision-Making	NR	Used sport-specific cognitive measure
Woods et al. (2015)	48	NR	NR	31.47	0	Decision-Making	NR	Measuring expertise in officiating
Xu et al. (2015)	40	Athlete	Fencing	NR	NR	Cognitive Flexibility	TMT	Not comparing between 2 groups of athletes
Yarrow, Brown & Krakauer (2009)	NR	NR	NR	NR	NR	NR	NR	Insufficient data – Systematic review
Zhou (2018)	28	Athlete Community	Table Tennis	20.57	0	NR	NR	Executive function not measured

Note. **NR** = not reported; ***N*** = total number of participants; **Female %** = percentage female; **DKEFS-DF** = Delis-Kaplan Executive Function System Design Fluency Test; **ST** = Stroop Test; **BDS** = Backward Digit Span Task; **CBT** = Corsi Block Test; **ToL** = Tower of London Task; **GNG** = Go No-Go Task; **FT** = Flanker Task; **IGT** = Iowa Gambling Task; ; **n-BT** n-back Task; **LGT** = Local Global Task; **ANT** = Attention Network Test; **CGT** = Cambridge Gambling Task; **DFT** = Design Fluency Task; **DRT** = Discriminative Reaction Task; **SST** = Stop Signal Task; **TMT** = Trail Making Test.

6.3 Supplemental Material C: Extracted Data Used to Calculate Effect Sizes

Table 4: Group means, standard deviations, and sample sizes for the included studies

Study	EF	Measure	Outcome	Group A Mean (SD)	Group A Sample Size	Group B Mean (SD)	Group B Sample Size
Alves et al. (2013)	IC	SST	Effectiveness	0.57 (0.009)	87	0.54 (0.01)	67
	IC	SST	Efficiency	192.43 (4.59)	87	224.58 (4.99)	67
Brevers et al. (2018)	IC	SST	Efficiency	174.46 (41.43)	27	205.67 (33.74)	25
Chan et al. (2011)	IC	GNG	Effectiveness	5.025 (3.69)	30	6.63 (4.92)	30
	IC	GNG	Efficiency	450.22 (51.42)	30	430.10 (74.69)	30
Chang et al. (2017)	CF	WCST	Effectiveness	10.55 (6.51)	20	9.05 (6.52)	20
	CF	WCST	Effectiveness	12.95 (10.75)	20	10.55 (6.51)	20
	CF	WCST	Effectiveness	12.95 (10.75)	20	9.05 (6.52)	20
	IC	ST	Efficiency	34.31 (6.26)	20	34.33 (8.25)	20
	IC	ST	Efficiency	36.83 (8.74)	20	34.31 (6.26)	20
	IC	ST	Efficiency	36.83 (8.74)	20	34.33 (8.25)	20
	Pl	ToL	Efficiency	37.55 (16.43)	20	28.45 (12.56)	20
	Pl	ToL	Effectiveness	2.90 (2.27)	20	4.55 (2.04)	20
	Pl	ToL	Efficiency	28.10 (16.08)	20	37.55 (16.43)	20
	Pl	ToL	Effectiveness	4.10 (2.47)	20	2.90 (2.27)	20
	Pl	ToL	Efficiency	28.10 (16.08)	20	28.45 (12.56)	20
	Pl	ToL	Effectiveness	4.10 (2.47)	20	4.55 (2.04)	20
Elferink-Gemser et al. (2018)	CF	TMT	Effectiveness	10.70 (1.70)	30	11.20 (1.10)	30
	CF	TMT	Efficiency	10.10 (1.90)	30	10.40 (1.80)	30
	IC	CWI	Effectiveness	12.10 (1.30)	30	11.00 (1.60)	30
	IC	CWI	Efficiency	11.70 (2.10)	30	11.50 (1.90)	30
Feng et al. (2017)	WM	MRT	Effectiveness	0.07 (0.052)	24	0.07 (0.063)	23
	WM	MRT	Efficiency	1371.33 (272.00)	24	1895.67 (802.33)	23
Furley & Memmert (2010)	WM	CBT	Effectiveness	59.20 (10.00)	54	57.80 (12.00)	58

Han et al. (2014)	CF	WCST	Effectiveness	6.50 (3.70)	13	13.40 (9.20)	20
Huijgen et al. (2015)	CF	TMT	Efficiency	32.10 (17.70)	47	43.80 (25.80)	41
	IC	SST	Efficiency	197.50 (37.10)	47	316.30 (33.60)	41
	WM	VMS	Effectiveness	5.30 (1.20)	47	4.90 (1.10)	41
Jacobson & Matthaeus (2014)	IC	CWI	Efficiency	11.26 (1.55)	39	9.69 (1.65)	15
	IC	CWI	Efficiency	11.14 (1.61)	22	9.69 (1.65)	17
	IC	CWI	Efficiency	11.14 (1.61)	22	11.41 (1.50)	17
	IC	CWI	Efficiency	11.41 (1.50)	17	9.69 (1.65)	17
	Pl	ToL	Effectiveness	9.58 (2.43)	39	8.53 (2.97)	15
	Pl	ToL	Efficiency	10.21 (1.56)	39	9.87 (2.90)	15
	Pl	ToL	Effectiveness	10.05 (2.54)	22	8.53 (2.97)	15
	Pl	ToL	Efficiency	10.29 (1.27)	22	9.87 (2.90)	15
	Pl	ToL	Effectiveness	10.05 (2.54)	22	9.00 (2.24)	17
	Pl	ToL	Efficiency	10.29 (1.27)	22	10.12 (1.90)	17
	Pl	ToL	Effectiveness	9.00 (2.24)	17	8.53 (2.97)	15
	Pl	ToL	Efficiency	10.12 (1.90)	17	9.87 (2.90)	15
	PS	ToL	Efficiency	10.97 (2.28)	39	9.47 (1.60)	15
	PS	ToL	Efficiency	11.43 (2.27)	22	9.47 (1.60)	15
	PS	ToL	Efficiency	11.43 (2.27)	22	10.41 (2.24)	17
	PS	ToL	Efficiency	10.41 (2.24)	17	9.74 (1.60)	15
Jansen & Lehmann (2013)	WM	MRT	Effectiveness	7.44 (2.18)	40	6.43 (2.79)	40
	WM	MRT	Effectiveness	7.44 (2.18)	40	7.56 (2.56)	40
	WM	MRT	Effectiveness	7.56 (2.56)	40	6.43 (2.79)	40
Jansen et al. (2012)	WM	CMR	Efficiency	1478.67 (627.38)	20	1810.67 (713.64)	20
	WM	CMR	Efficiency	2458.91 (1035.51)	20	2401.13 (776.36)	20
	WM	CMR	Efficiency	1476.22 (515.73)	20	1763.51 509.51)	20
Kasahara et al. (2008)	Pl	WAIS-BD	Effectiveness	13.40 (2.40)	27	10.50 (2.60)	163

Krenn et al. (2018)	CF	FT-Mod	Effectiveness	1.90 (1.47)	93	1.87 (1.57)	60
	CF	FT-Mod	Efficiency	98.18 (43.23)	93	86.57 (31.75)	60
	CF	FT-Mod	Effectiveness	1.52 (1.60)	29	1.90 (1.47)	93
	CF	FT-Mod	Efficiency	108.76 (34.13)	29	98.18 (43.23)	93
	CF	FT-Mod	Effectiveness	1.52 (1.06)	29	1.87 (1.57)	60
	CF	FT-Mod	Efficiency	108.76 (34.13)	29	86.57 (31.75)	60
	IC	FT	Effectiveness	3.35 (2.35)	93	2.65 (1.80)	60
	IC	FT	Efficiency	57.97 (22.24)	93	56.30 (19.85)	60
	IC	FT	Effectiveness	2.79 (1.92)	29	3.35 (2.35)	93
	IC	FT	Efficiency	57.93 (20.04)	29	57.97 (22.24)	93
	IC	FT	Effectiveness	2.79 (1.92)	29	2.65 (1.80)	60
	IC	FT	Efficiency	57.93 (20.04)	29	56.30 (19.85)	60
	WM	n-BT	Effectiveness	18.02 (3.65)	93	19.65 (2.93)	60
	WM	n-BT	Efficiency	541.83 (68.81)	93	526.62 (53.76)	60
	WM	n-BT	Effectiveness	17.48 (4.28)	29	18.02 (3.65)	93
	WM	n-BT	Efficiency	540.38 (45.44)	29	541.83 (68.81)	93
	WM	n-BT	Effectiveness	17.48 (4.28)	29	19.65 (2.93)	60
	WM	n-BT	Efficiency	540.38 (45.44)	29	526.62 (53.76)	60
Liao et al. (2017)	IC	SST	Efficiency	304.10 (51.70)	42	279.80 (48.40)	15
	IC	SST	Effectiveness	37.30 (13.80)	42	45.80 (13.10)	15
Lundgren et al. (2016)	CF	TMT	Efficiency	9.86 (2.00)	28	10.06 (2.90)	18
Martin et al. (2016)	IC	ST	Effectiveness	705.00 (68.00)	11	576.00 (74.00)	9
Nakamoto & Mori (2008)	IC	GNG	Effectiveness	0.44 (0.53)	9	0.33 (0.41)	9
	IC	GNG	Effectiveness	0.22 (0.66)	9	0.44 (0.53)	9
	IC	GNG	Effectiveness	1.11 (1.76)	9	1.56 (1.33)	9
	IC	GNG	Efficiency	218.00 (19.00)	9	252.00 (33.00)	9
	IC	GNG	Efficiency	239.00 (13.00)	9	253.00 (27.00)	9
	IC	GNG	Efficiency	244.00 (15.00)	9	262.00 (32.00)	9
Nakamoto & Mori (2012)	IC	CATT	Effectiveness	40.00 (9.00)	7	40.00 (8.00)	7
Pacesova et al. (2018)	IC	ST	Efficiency	24.70 (3.39)	44	26.73 (3.04)	54

Schmidt et al. (2016)	WM	MRT	Effectiveness	13.18 (4.40)	60	9.35 (3.83)	20
	WM	MRT	Effectiveness	13.65 (5.16)	20	12.10 (3.57)	20
	WM	MRT	Effectiveness	13.80 (4.35)	20	13.65 (5.16)	20
	WM	MRT	Effectiveness	13.80 (4.35)	20	9.35 (3.83)	20
	WM	MRT	Effectiveness	13.80 (4.35)	20	12.10 (3.57)	20
	WM	MRT	Effectiveness	13.65 (5.16)	20	9.35 (3.83)	20
	WM	MRT	Effectiveness	12.10 (3.57)	20	9.35 (3.83)	20
Seo et al. (2012)	WM	JLO	Effectiveness	47.91 (19.09)	20	40.62 (18.52)	23
	WM	JLO	Efficiency	8404.69 (1525.50)	20	9128.80 (1686.24)	23
Vaughan et al. (2018)	DM	CGT	Effectiveness	0.90 (0.09)	109	0.85 (0.12)	71
	DM	CGT	Efficiency	2019.50 9412.32)	109	2384.90 (451.33)	71
	DM	CGT	Effectiveness	0.95 (0.08)	89	0.90 (0.09)	109
	DM	CGT	Efficiency	1647.22 (382.64)	89	2019.50 (412.32)	109
	DM	CGT	Effectiveness	0.95 (0.08)	89	0.85 (0.12)	71
	DM	CGT	Efficiency	1647.22 (382.64)	89	2384.90 (451.33)	71
Vestberg et al. (2012)	CF	TMT	Effectiveness	11.69 (1.47)	29	10.68 (1.66)	28
	IC	CWI	Effectiveness	12.48 (1.79)	29	11.68 (1.81)	28
Wang et al. (2013) 2	IC	GNG	Effectiveness	2.75 (3.25)	14	1.75 (2.30)	14
	IC	GNG	Effectiveness	2.40 (3.60)	14	1.15 (1.40)	14
	IC	GNG	Efficiency	345.21 (23.14)	14	368.36 (31.15)	14
	IC	GNG	Effectiveness	2.75 (3.25)	14	1.60 (2.30)	14
	IC	GNG	Effectiveness	2.40 (3.60)	14	2.45 (2.50)	14
	IC	GNG	Efficiency	345.21 (23.14)	14	351.45 (16.48)	14
	IC	GNG	Effectiveness	1.60 (2.30)	14	1.75 (2.30)	14
	IC	GNG	Effectiveness	2.45 (2.50)	14	1.15 (1.40)	14
	IC	GNG	Efficiency	351.45 (16.48)	14	368.36 (31.15)	14
Wang et al. (2013)	IC	SST	Efficiency	201.64 (15.16)	20	227.47 (18.65)	20
	IC	SST	Efficiency	201.64 (15.16)	20	222.99 (19.75)	20

	IC	SST	Efficiency	222.99 (19.75)	20	227.47 (18.65)	20
Wang et al. (2014)	WM	VDT	Effectiveness	89.86 (6.08)	12	88.45 (4.84)	13
	WM	VDT	Efficiency	766.87 (47.17)	12	810.64 (58.23)	13
Wang et al. (2016)	IC	ANT	Efficiency	22.50 (1.30)	31	22.20 (3.80)	34
Wang et al. (2017)	IC	FT	Effectiveness	97.00 (3.00)	18	98.00 (2.00)	18
Yu et al. (2017)	CF	TS	Effectiveness	3.83 (2.72)	18	4.06 (2.78)	18
	CF	TS	Efficiency	46.24 (28.32)	18	94.85 (43.17)	18
	CF	TS	Effectiveness	3.83 (2.72)	18	4.33 (2.95)	18
	CF	TS	Efficiency	46.24 (28.32)	18	78.13 (29.63)	18
	CF	TS	Effectiveness	4.33 (2.95)	18	4.06 (2.78)	18
	CF	TS	Efficiency	78.13 (29.63)	18	94.85 (43.17)	18
Zhang et al. (2015)	IC	GNG	Effectiveness	0.42 (0.033)	26	0.31 (0.033)	26
	IC	GNG	Efficiency	710.00 (20.00)	26	780.00 (20.00)	26

Note. **EF** = Executive Function; **SD** = Standard Deviation; **IC** = Inhibitory Control; **CF** = Cognitive Flexibility; **WM** = Working Memory; **Pl** = Planning; **PS** = Problem Solving; **DM** = Decision Making; **SST** = Stop Signal Task; **GNG** = Go No-Go Task; **ST** = Stroop Test; **WCST** = Wisconsin Card Sorting Task; **ToL** = Tower of London Task; **CWI** = Colour Word Interference Test; **TMT** = Trail Making Test; **MRT** = Mental Rotation Task; **CBT** = Corsi Block Test; **VMS** = Visual Memory Span Task; **CMR** = Chronometric Mental Rotation Task; **WAIS-BD** = Wechsler Adult Intelligence Scale Block Design ; **FT** = Flanker Task; **FT-Mod** = Krenn et al.'s (2018) Modified Flanker Task; **n-BT** n-back Task; **CATT** = Coincident Anticipation Timing Task; **JLO** = Judgement of Line Orientation Task; **CGT** = Cambridge Gambling Task; **VDT** = Visual Discrimination Task; **ANT** = Attention Network Test; **TS** = Task Switching Paradigm.

6.4 Supplemental Material D: Meta-Regression

Table 5: Mean sample age, mean percentage of female participants, and specific executive function as moderators of the relationship between executive function and athletic expertise

Moderator	Point estimate (β)	Standard error	95% *CI*	Z	p-value	R^2_{analog}
Level of Athletic Expertise						
Executive Function						
(Model 1) (k = 38)	—	—	—	—	—	.00
Intercept	0.250	0.328	[-0.393; 0.893]	0.76	.445	—
Mean Age	-0.002	0.015	[-0.032; 0.029]	-0.10	.923	—
(Model 2) (k = 38)	—	—	—	—	—	.00
Intercept	0.220	0.081	[0.061; 0.379]	2.71	.007	—
Female %	-0.000	0.002	[-0.004; 0.004]	-0.02	.984	—
(Model 3) (k = 113)	—	—	—	—	—	.09
Intercept	0.204	0.050	[0.106; 0.302]	4.08	<.001	—
Cognitive Flexibility[a]	-0.071	0.085	[-0.237; 0.095]	-0.84	.399	—
Decision Making[a]	0.239	0.129	[-0.015; 0.492]	1.85	.065	—
Planning[a]	-0.191	0.097	[-0.381; -0.001]	-1.97	.049	—
Problem Solving[a]	0.104	0.169	[-0.227; 0.436]	0.62	.537	
Working Memory[a]	-0.008	0.078	[-0.161; 0.146]	-0.10	.922	—
(Model 4) (k = 113)	—	—	—	—	—	.10
Intercept	0.247	0.249	[-0.241; 0.734]	0.99	.321	—
Mean Age	-0.004	0.012	[-0.026; 0.019]	-0.32	.748	—
Female %	0.001	0.001	[-0.001; 0.004]	0.91	.362	—
Cognitive Flexibility[a]	-0.081	0.085	[-0.248; 0.087]	-0.94	.345	—
Decision Making[a]	0.224	0.131	[-0.032; 0.480]	1.71	.087	—
Planning[a]	-0.207	0.099	[-0.400; -0.014]	-2.10	.036	—
Problem Solving[a]	0.065	0.173	[-0.275; 0.405]	0.37	.708	—
Working Memory[a]	-0.021	0.086	[-0.190; 0.149]	-0.24	.811	—

Executive Function Efficiency						
(Model 1) (k = 27)	—	—	—	—	—	.03
Intercept	0.747	0.518	[-0.269; 1.763]	1.44	.150	—
Mean Age	-0.024	0.025	[-0.074; 0.025]	-0.97	.332	—
(Model 2) (k = 27)	—	—	—	—	—	.00
Intercept	0.225	0.132	[-0.035; 0.484]	1.70	.090	—
Female %	0.001	0.003	[-0.005; 0.006]	0.24	.812	—
(Model 3) (k = 57)	—	—	—	—	—	.14
Intercept	0.267	0.067	[0.135; 0.399]	3.97	<.001	—
Cognitive Flexibility[a]	-0.048	0.123	[-0.288; 0.192]	-0.39	.695	—
Decision Making[a]	0.284	0.190	[-0.089; 0.626]	1.49	.136	—
Planning[a]	-0.311	0.145	[-0.594; -0.027]	-2.15	.032	—
Problem Solving[a]	0.041	0.182	[-0.315; 0.398]	0.23	.821	—
Working Memory[a]	-0.077	0.129	[-0.330; 0.176]	-0.60	.550	—
(Model 4) (k = 57)	—	—	—	—	—	.19
Intercept	0.925	0.384	[0.172; 1.677]	2.41	.016	—
Mean Age	-0.033	0.018	[-0.069; 0.003]	-1.82	.069	—
Female %	0.001	0.002	[-0.003; 0.005]	0.44	.657	—
Cognitive Flexibility[a]	-0.028	0.121	[-0.264; 0.208]	-0.23	.816	—
Decision Making[a]	0.319	0.188	[-0.049; 0.686]	1.70	.090	—
Planning[a]	-0.317	0.144	[-0.600; -0.034]	-2.20	.028	—
Problem Solving[a]	0.008	0.185	[-0.356; 0.371	0.04	.967	—
Working Memory[a]	-0.009	0.135	[-0.273; 0.255]	-0.07	.946	—
Executive Function Effectiveness						
(Model 1) (k = 27)	—	—	—	—	—	.03
Intercept	-0.185	0.390	[-0.950; 0.580]	-0.47	.636	—
Mean Age	0.017	0.018	[-0.018; 0.052]	0.94	.346	—
(Model 2) (k = 27)	—	—	—	—	—	.00
Intercept	0.195	0.110	[-0.021; 0.411]	1.77	.077	—
Female %	-0.000	0.002	[-0.005; 0.004]	-0.19	.852	—

(Model 3) (*k* = 56)	—	—	—	—	—	.08
Intercept	0.110	0.072	[-0.031; 0.250]	1.53	.126	—
Cognitive Flexibility[a]	-0.061	0.112	[-0.281; 0.158]	-0.55	.586	—
Decision Making[a]	0.224	0.165	[-0.099; 0.546]	1.36	.174	—
Planning[a]	-0.0046	0.124	[-0.289; 0.197]	-0.37	.710	—
Working Memory[a]	0.090	0.097	[-0.101; 0.280]	0.92	.357	—
(Model 4) (*k* = 56)	—	—	—	—	—	.13
Intercept	-0.368	0.302	[-0.960; 0.225]	-1.22	.224	—
Mean Age	0.020	0.014	[-0.006; 0.047]	1.49	.136	—
Female %	0.002	0.002	[-0.002; 0.005]	1.03	.305	—
Cognitive Flexibility[a]	-0.085	0.112	[-0.304; 0.134]	-0.76	.448	—
Decision Making[a]	0.182	0.164	[-0.138; 0.503]	1.12	.265	—
Planning[a]	-0.082	0.124	[-0.325; 0.161]	-0.66	.507	—
Working Memory[a]	0.007	0.107	[-0.202; 0.216]	0.07	.946	—

Note. Analyses that warranted meta-regression were conducted only for covariates with 6 or more samples. ***k*** = number of effect sizes included in analysis; **Point estimate (*β*)** = unstandardized regression coefficient; **CI** = confidence interval; ***Z*** = significance test of continuous moderators; ***p*** = statistical significance; **R^2_{analog}**= percentage of total between study variance explained by the model; **Mean Age** = sample mean age; **Female %** = average percentage females. For models including categorical moderators, outcome measures were treated independently to ensure meaningful assessment of moderation. Subgroup within study was used as the unit of analysis.
[a]Reference variable was inhibitory control.

Table 6: Mean sample age, mean percentage of female participants, and executive function measure as moderators of the relationship between executive functions and athletic expertise

Moderator	Point estimate (β)	Standard error	95% CI	Z	p-value	R^2_{analog}
Level of Athletic Expertise						
Inhibitory Control						
(Model 1) ($k = 16$)	—	—	—	—	—	.00
Intercept	0.285	0.889	[-1.457; 2.027]	0.32	.748	—
Mean Age	-0.001	0.043	[-0.086; 0.083]	-0.03	.979	—
(Model 2) ($k = 16$)	—	—	—	—	—	.00
Intercept	0.275	0.171	[-0.060; 0.009]	1.61	.108	—
Female %	-0.001	0.005	[-0.010; 0.009]	-0.10	.919	—
(Model 3) ($k = 39$)	—	—	—	—	—	.31
Intercept	-0.001	0.140	[-0.275; 0.274]	-0.01	.995	—
GNG[a]	0.006	0.184	[-0.355; 0.366]	0.03	.976	—
SST/CATT[a]	0.613	0.188	[0.245; 0.981]	3.26	.001	—
Stroop/CWI[a]	0.182	0.179	[-0.168; 0.532]	1.02	.309	—
(Model 4) ($k = 39$)	—	—	—	—	—	.33
Intercept	-0.320	0.764	[-1.817; 1.176]	-0.42	.675	—
Mean Age	0.010	0.033	[-0.053; 0.074]	0.32	.750	—
Female %	0.002	0.003	[-0.004; 0.008]	0.76	.448	—
GNG[a]	0.090	0.213	[-0.328; 0.507]	0.42	.674	—
SST/CATT[a]	0.675	0.212	[0.260; 1.090]	3.19	.001	—
Stroop/CWI[a]	0.197	0.199	[-0.193; 0.587]	0.99	.322	—
Inhibitory Control Efficiency						
(Model 1) ($k = 13$)	—	—	—	—	—	.05
Intercept	1.276	1.228	[-1.139; 3.673]	1.03	.302	—
Mean Age	-0.049	0.061	[-0.169; 0.071]	-0.80	.421	—
(Model 2) ($k = 13$)	—	—	—	—	—	.00
Intercept	0.307	0.244	[-0.172; 0.786]	1.26	.209	—

Female %	-0.001	0.007	[-0.014; 0.012]	-0.11	.916	—
(Model 3) ($k = 23$)	—	—	—	—	—	.20
Intercept	0.025	0.226	[-0.425; 0.475]	0.11	.913	—
GNG[a]	0.152	0.312	[-0.460; 0.763]	0.49	.627	—
SST/CATT[a]	0.531	0.276	[-0.011; 1.072]	1.92	.055	—
Stroop/CWI[a]	0.152	0.268	[-0.373; 0.676]	0.57	.571	—
(Model 4) ($k = 23$)	—	—	—	—	—	.26
Intercept	0.928	1.192	[-1.408; 3.263]	0.78	.436	—
Mean Age	-0.046	0.051	[-0.146; 0.054]	-0.90	.369	—
Female %	0.004	0.005	[-0.005; 0.013]	0.90	.371	—
GNG[a]	0.133	0.347	[-0.548; 0.813]	0.38	.703	—
SST/CATT[a]	0.473	0.333	[-0.180; 1.125]	1.42	.156	—
Stroop/CWI[a]	-0.013	0.314	[-0.627; 0.602]	-0.04	.968	—
Inhibitory Control Effectiveness						
(Model 1) ($k = 9$)	—	—	—	—	—	.05
Intercept	-0.779	1.308	[-3.342; 1.785]	-0.60	.552	—
Mean Age	0.048	0.061	[-0.072; 0.167]	0.78	.435	—
(Model 2) ($k = 9$)	—	—	—	—	—	.00
Intercept	0.202	0.287	[-0.361; 0.765]	0.70	.482	—
Female %	0.001	0.007	[-0.013; 0.015]	0.14	.890	—
(Model 3) ($k = 14$)	—	—	—	—	—	.09
Intercept	-0.013	0.117	[-0.242; 0.215]	-0.11	.909	—
GNG[a]	-0.075	0.155	[-0.379; 0.230]	-0.48	.631	—
Stroop/CWI[a]	0.172	0.187	[-0.195; 0.539]	0.92	.357	—
(Model 4) ($k = 14$)	—	—	—	—	—	.90
Intercept	-2.292	0.527	[-3.324; -1.261]	-4.35	<.001	—
Mean Age	0.099	0.022	[0.056; 0.142]	4.54	<.001	—
Female %	0.001	0.002	[-0.004; 0.006]	0.45	.656	—
GNG[a]	0.191	0.126	[-0.057; 0.438]	1.51	.131	—
Stroop/CWI[a]	0.294	0.120	[0.058; 0.530]	2.44	.015	—

Cognitive Flexibility Effectiveness						
(Model 1) (*k* = 6)	—	—	—	—	—	.09
Intercept	0.412	0.611	[-0.786; 1.611]	0.67	.500	—
Mean Age	-0.014	0.029	[-0.071; 0.042]	-0.49	.624	—
(Model 2) (*k* = 6)	—	—	—	—	—	.10
Intercept	0.253	0.191	[-0.122; 0.628]	1.32	.186	—
Female %	-0.004	0.005	[-0.013; 0.005]	-0.79	.428	—
(Model 3) (*k* = 7)	—	—	—	—	—	.00
Intercept	0.028	0.114	[-0.195; 0.250]	0.24	.808	—
WCST[b]	0.023	0.148	[-0.268; 0.314]	0.15	.877	—
(Model 4) (*k* = 7)	—	—	—	—	—	1.00
Intercept	0.766	0.297	[0.182; 1.348]	2.58	.001	—
Mean Age*	—	—	—	—	—	—
Female %	-0.017	0.006	[-0.029; -0.004]	-2.63	.009	—
WCST[b]	-0.334	0.184	[-0.693; 0.026]	-1.82	.069	—

Note. Analyses that warranted meta-regression were conducted only for covariates with 6 or more samples. ***k*** = number of effect sizes included in analysis; **Point estimate (β)** = unstandardized regression coefficient; **CI** = confidence interval; ***Z*** = significance test of continuous moderators; ***p*** = statistical significance; **R^2_{analog}**= percentage of total between study variance explained by the model; **Mean Age** = sample mean age; **Female %** = average percentage females; **GNG/CCPT** = go/no go task; **SST/CATT** = stop signal task & coincident anticipation timing task; **Stroop/CWI** = stroop task & colour-word interference task; **WCST** = Wisconsin card sorting task. For models including categorical moderators, outcome measures were treated independently to ensure meaningful assessment of moderation. Subgroup within study was used as the unit of analysis.

* Mean age removed from analysis due to excessive collinearity with female %

[a] Reference variable was flanker task

[b] Reference variable was task switching task

6.5 Supplemental Material E: Scatter Plots

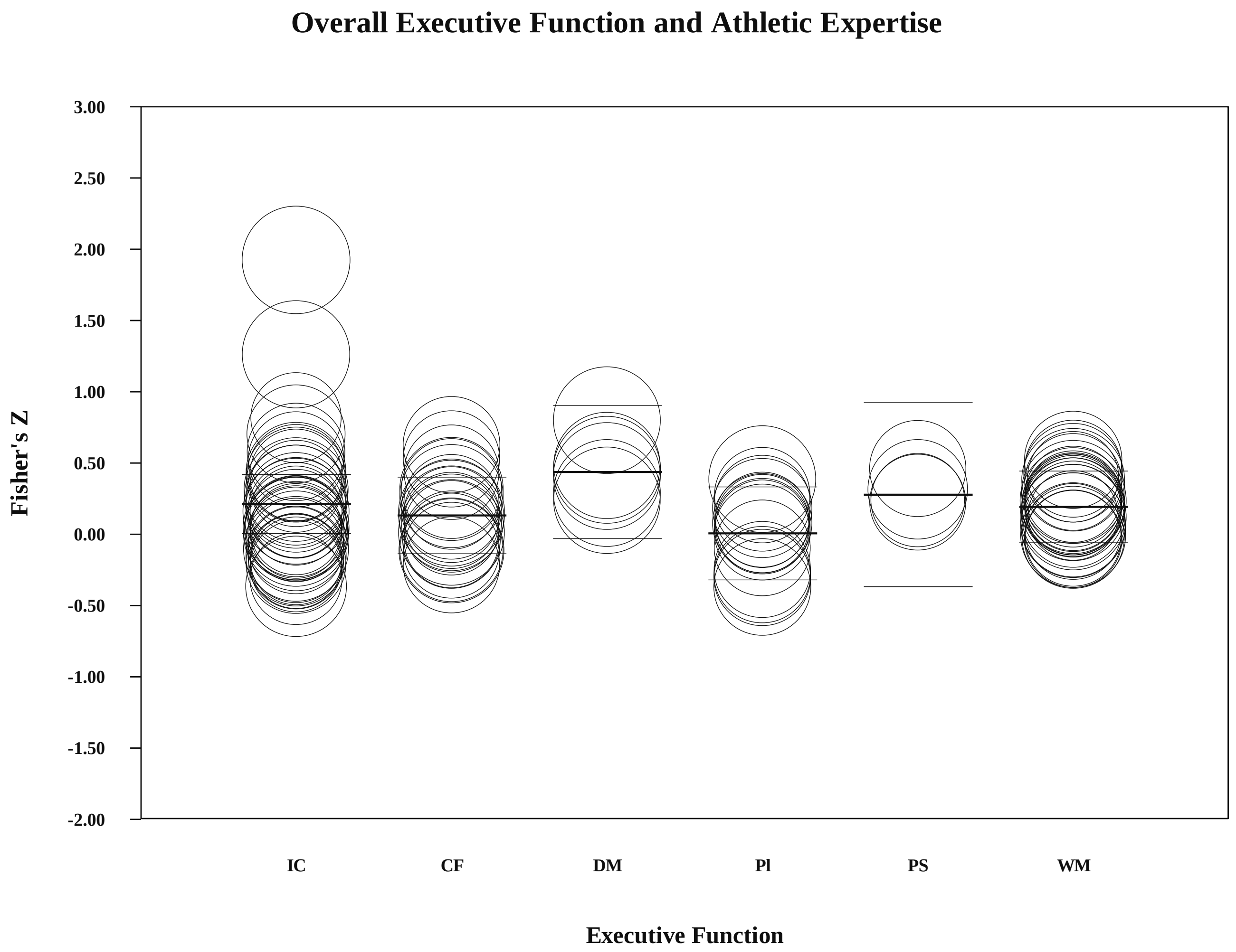

Figure 2. Overall executive function's relationship with athletic expertise regressed on specific executive function

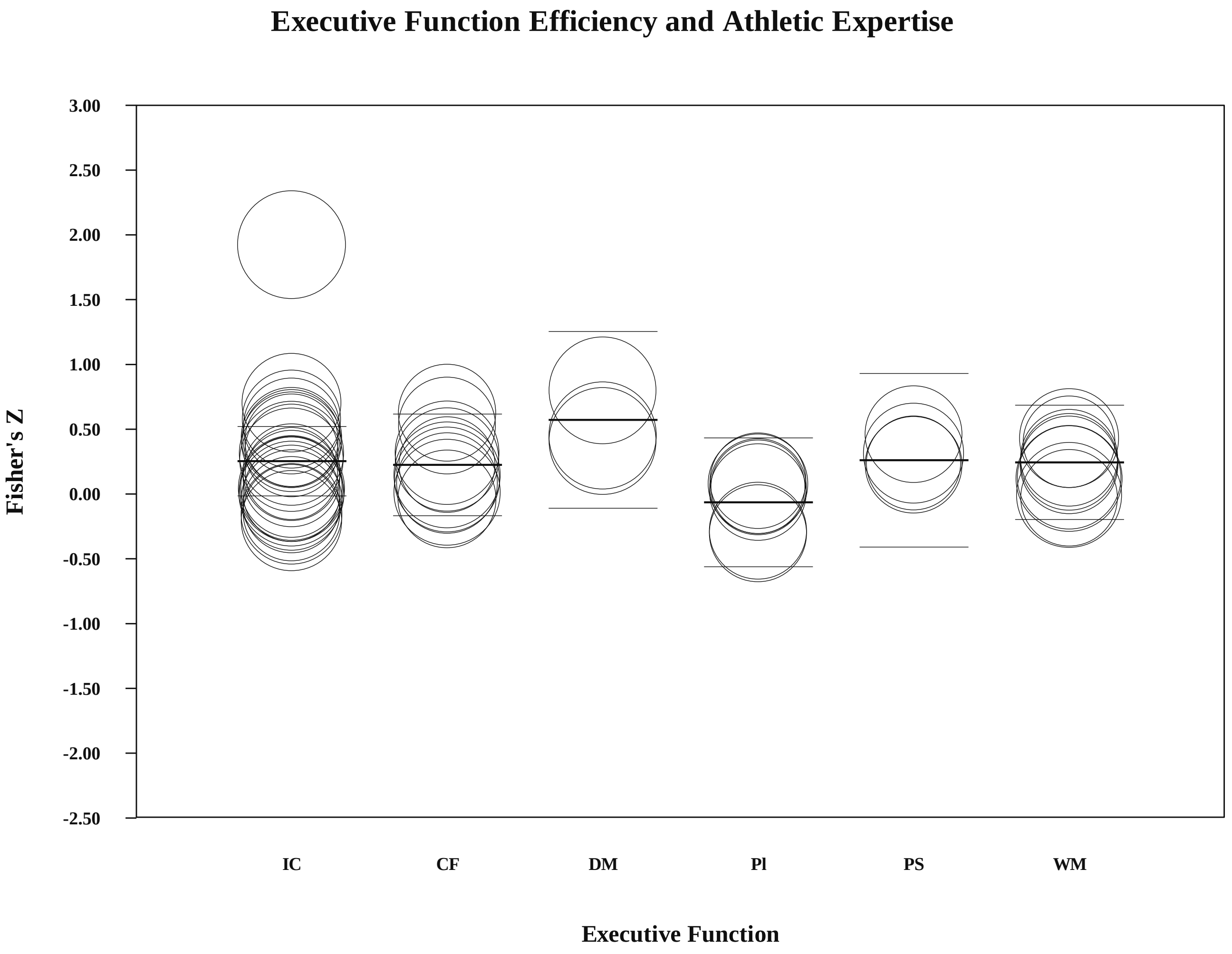

Figure 3. Executive function efficiency's relationship with athletic expertise regressed on specific executive function

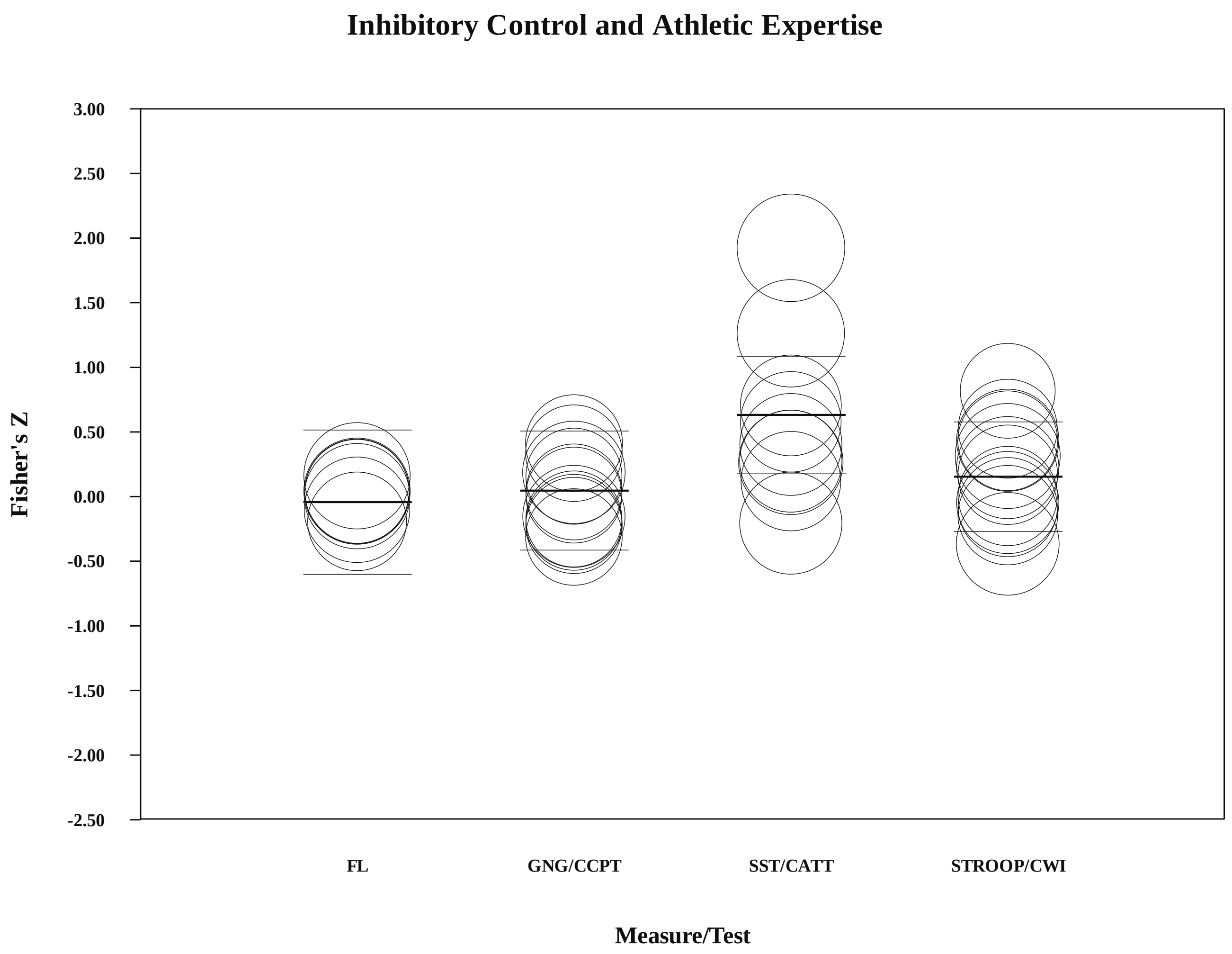

Figure 4. Inhibitory control's relationship with athletic expertise regressed on measure

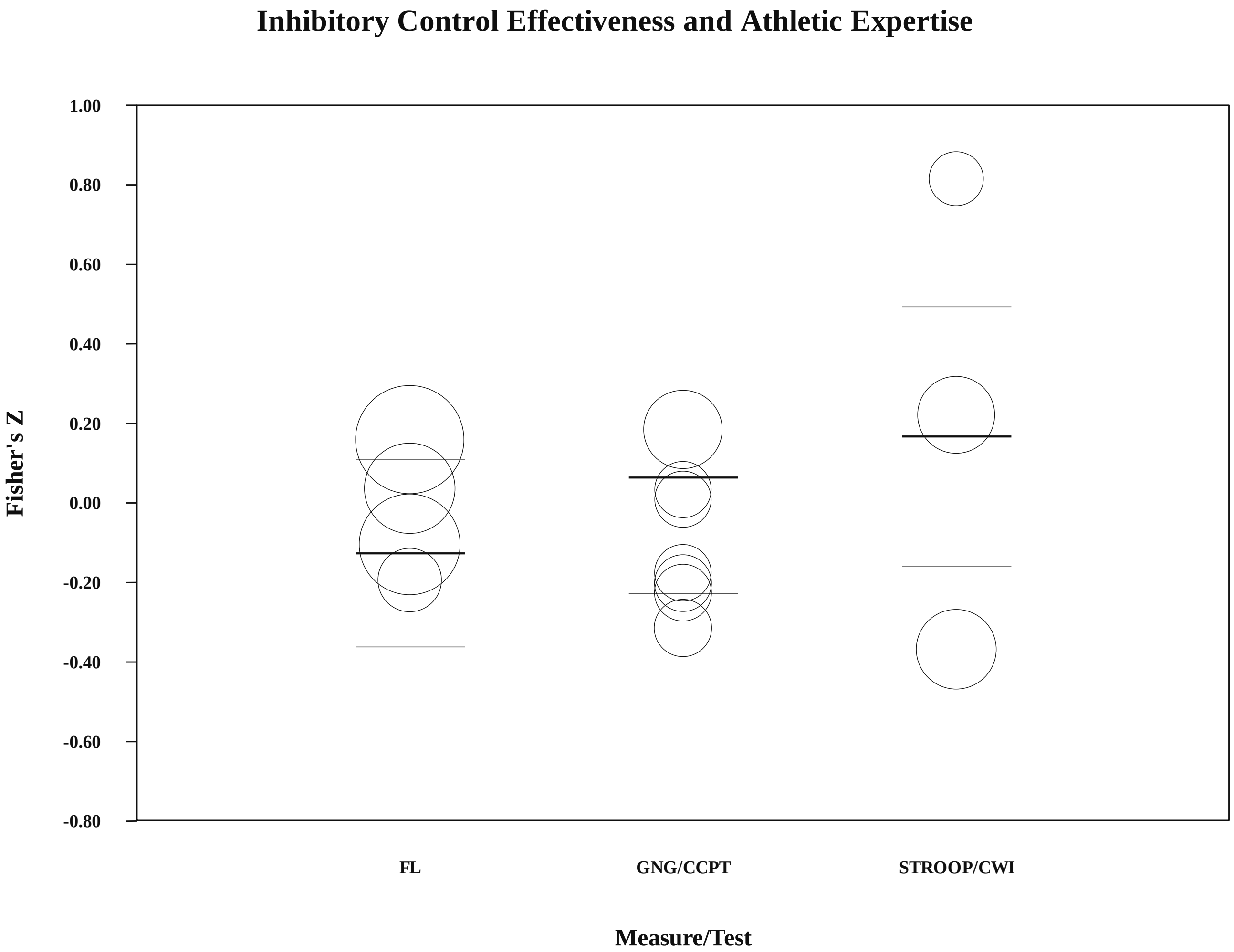

Figure 5. Inhibitory control effectiveness' relationship with athletic expertise regressed on measure

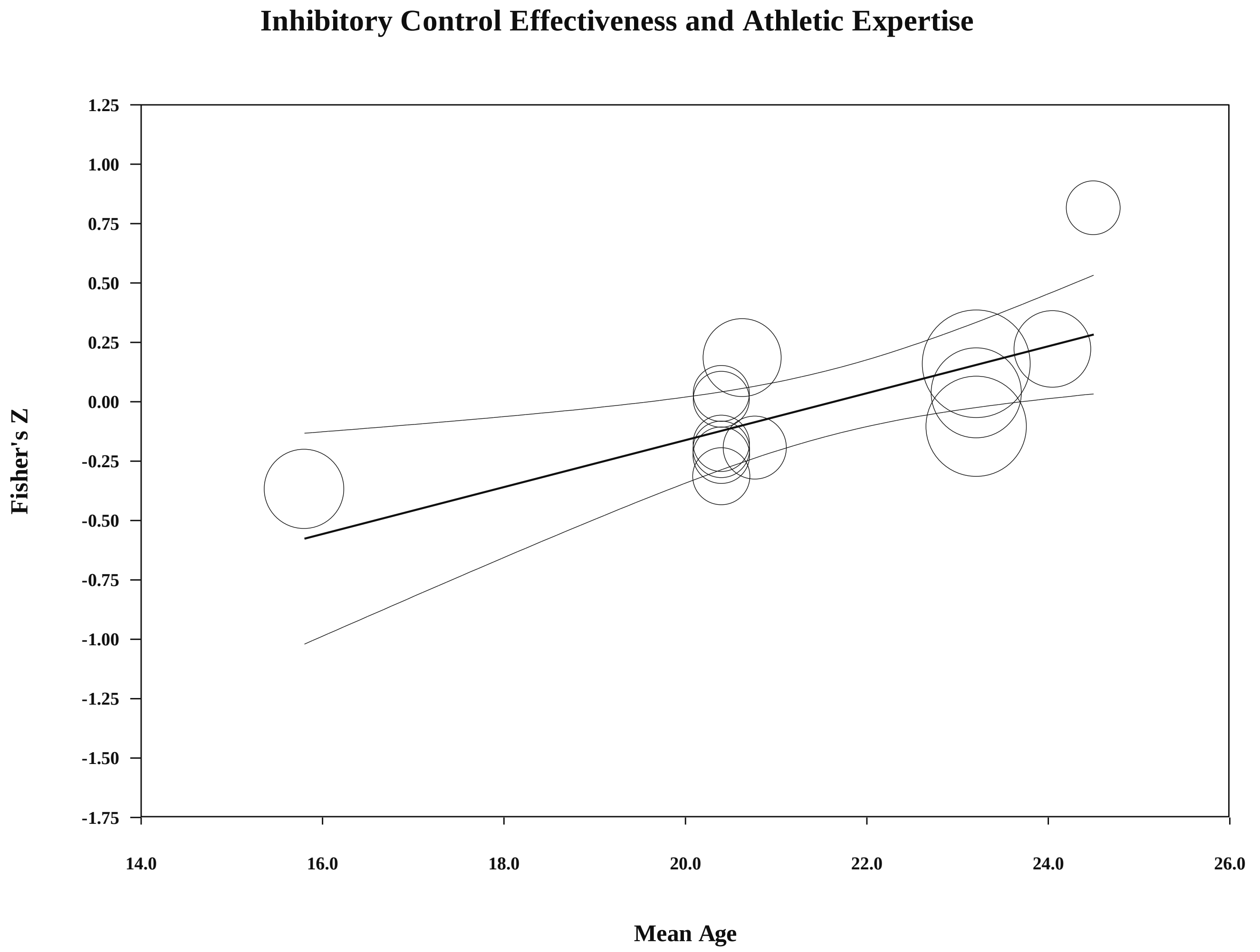

Figure 6. Inhibitory control effectiveness' relationship with athletic expertise regressed on mean age

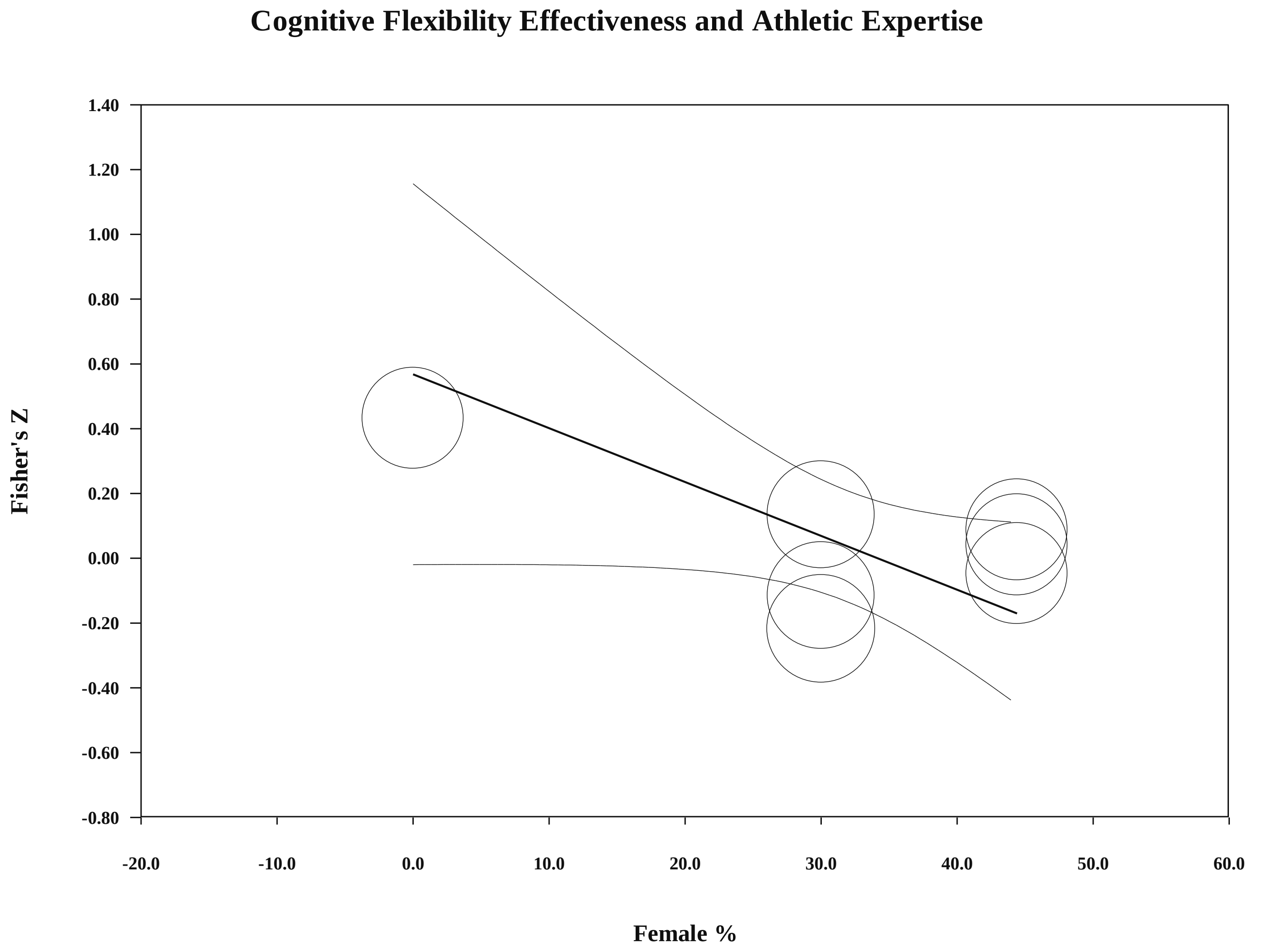

Figure 7. Cognitive flexibility effectiveness' relationship with athletic expertise regressed on female percentage in the sample

6.6 Supplemental Material F: Funnel Plots with Imputed Studies

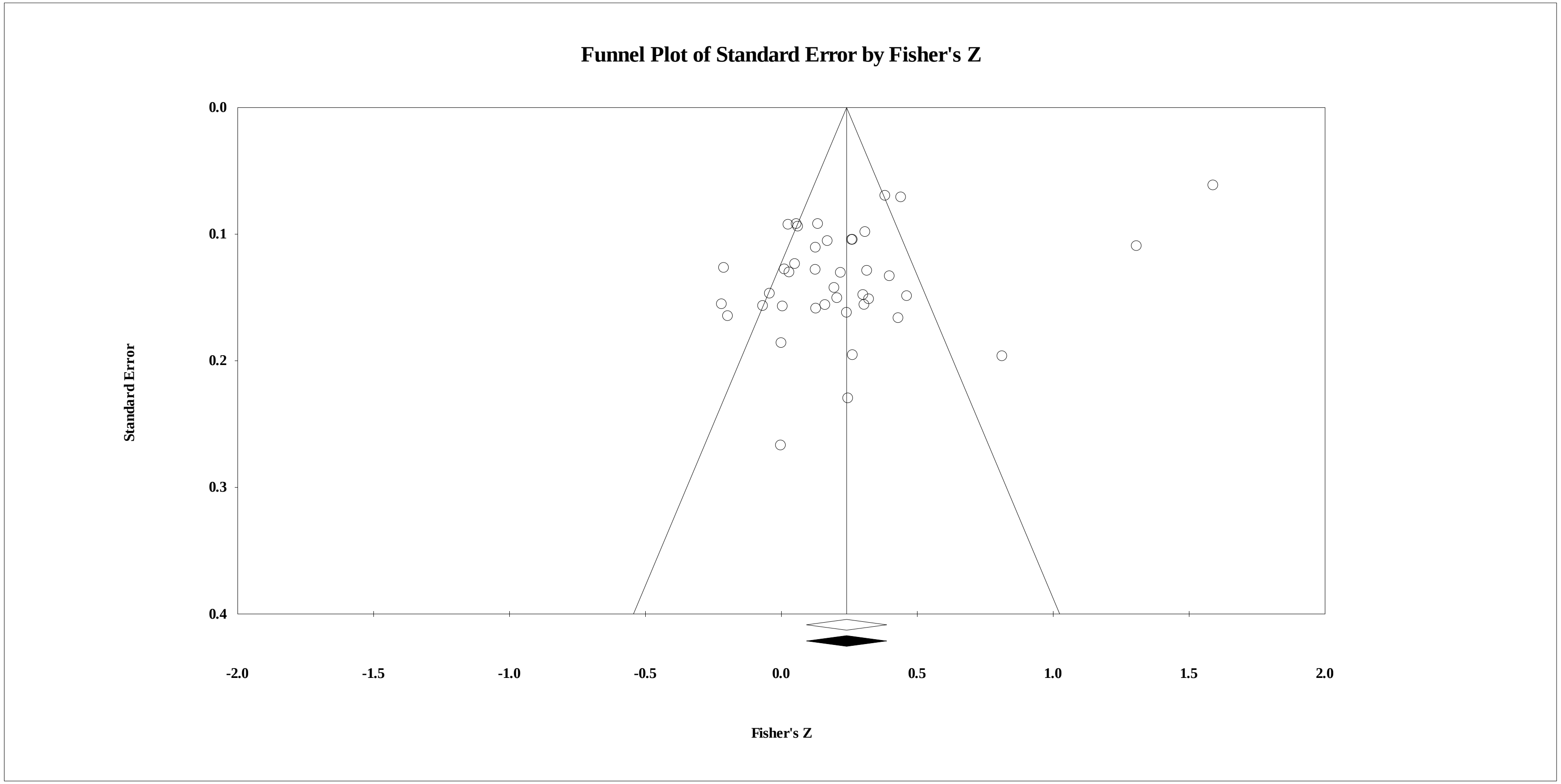

Figure 8. Funnel plot for the relationship between executive function and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean.

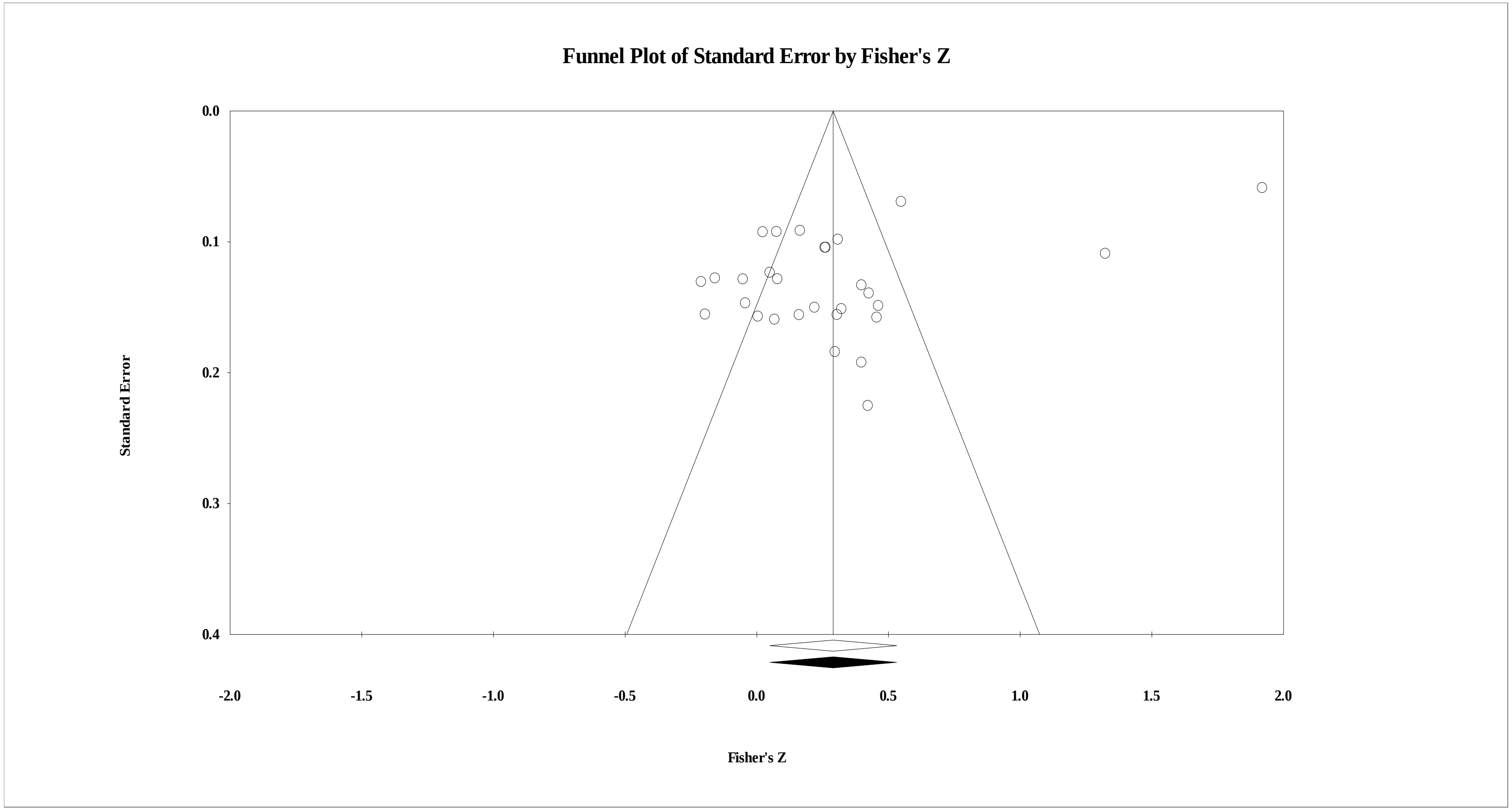

Figure 9. Funnel plot for the relationship between executive function efficiency and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

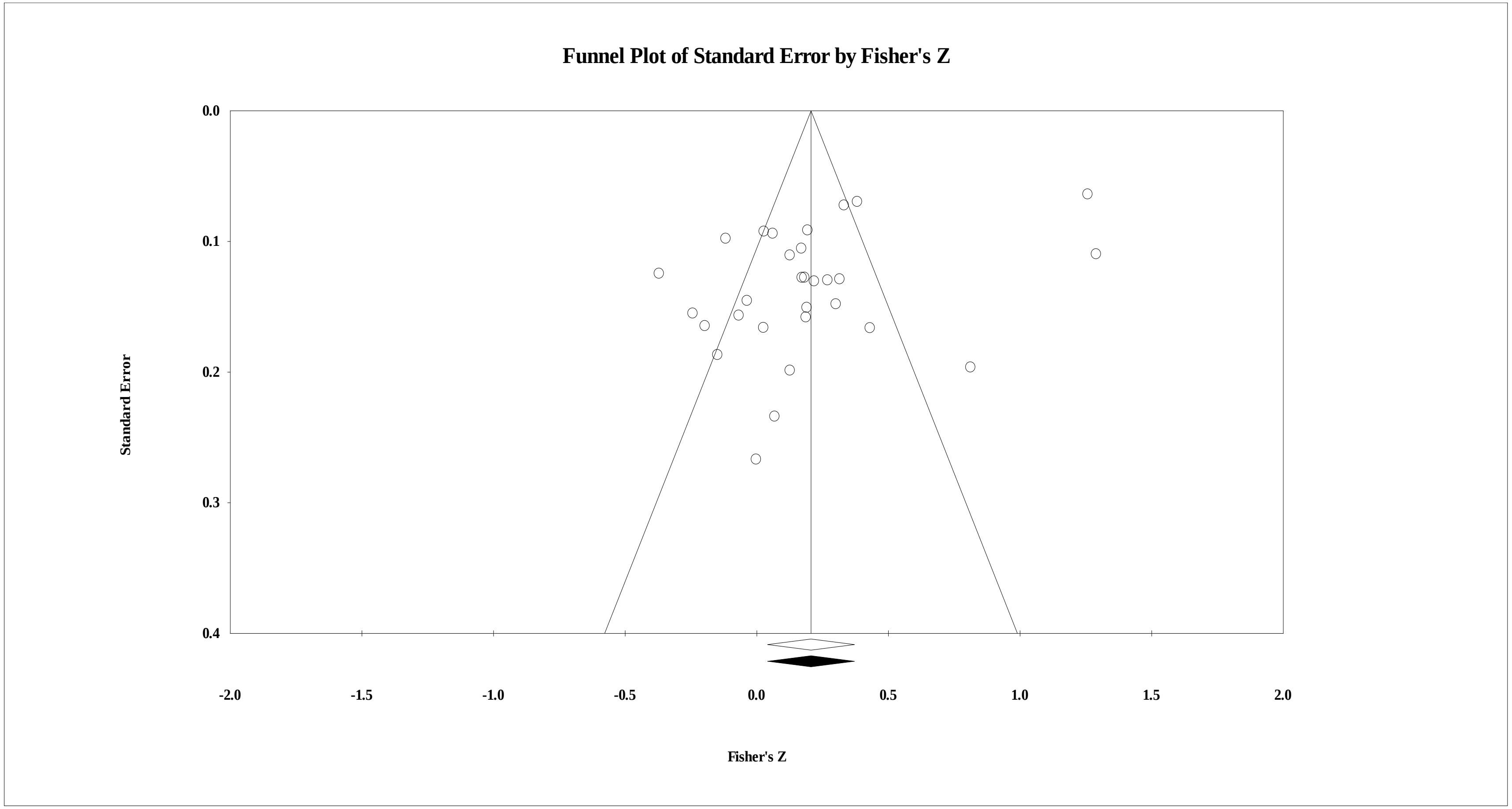

Figure 10. Funnel plot for the relationship between executive function effectiveness and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

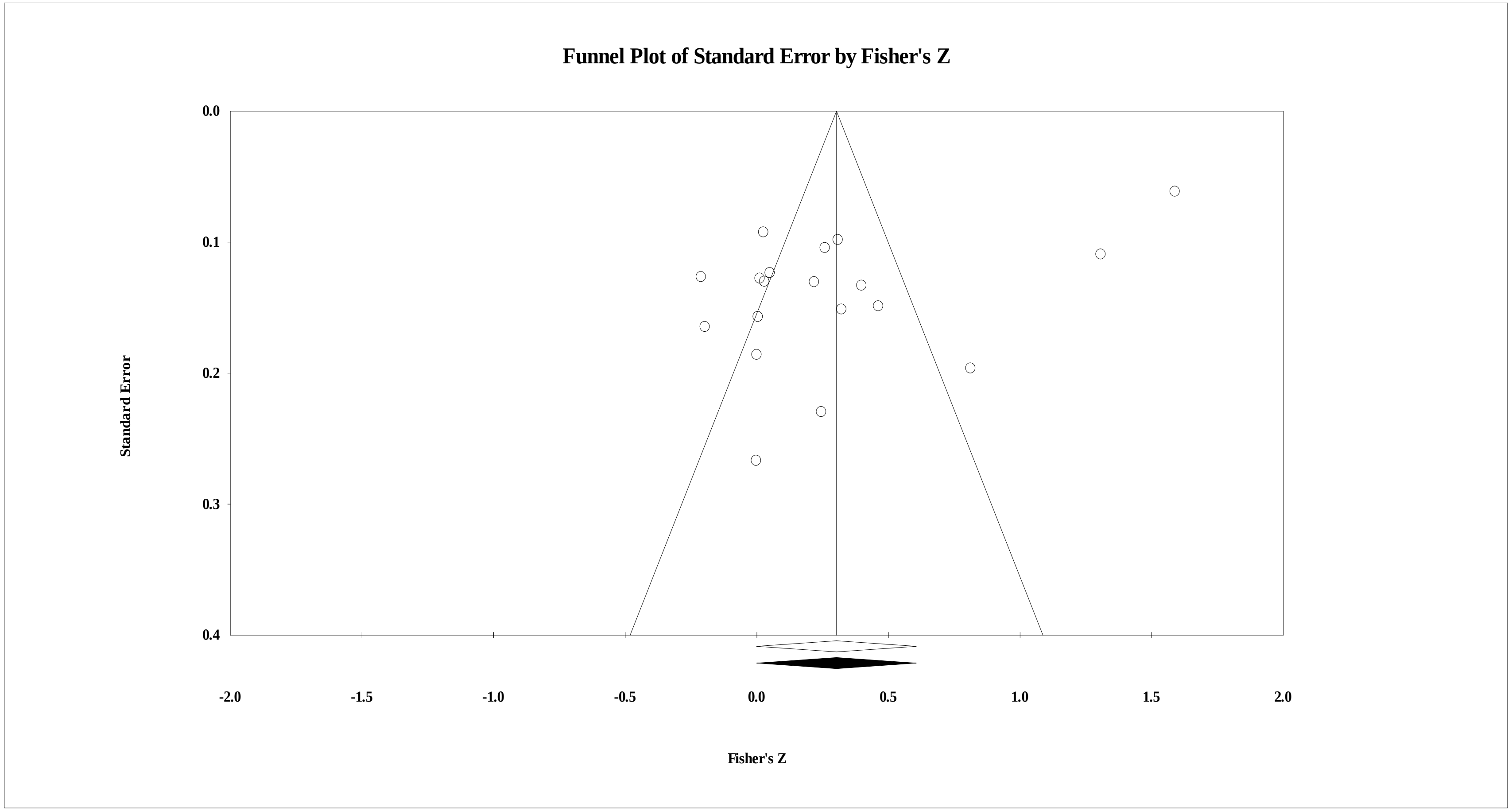

Figure 11. Funnel plot for the relationship between inhibitory control and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

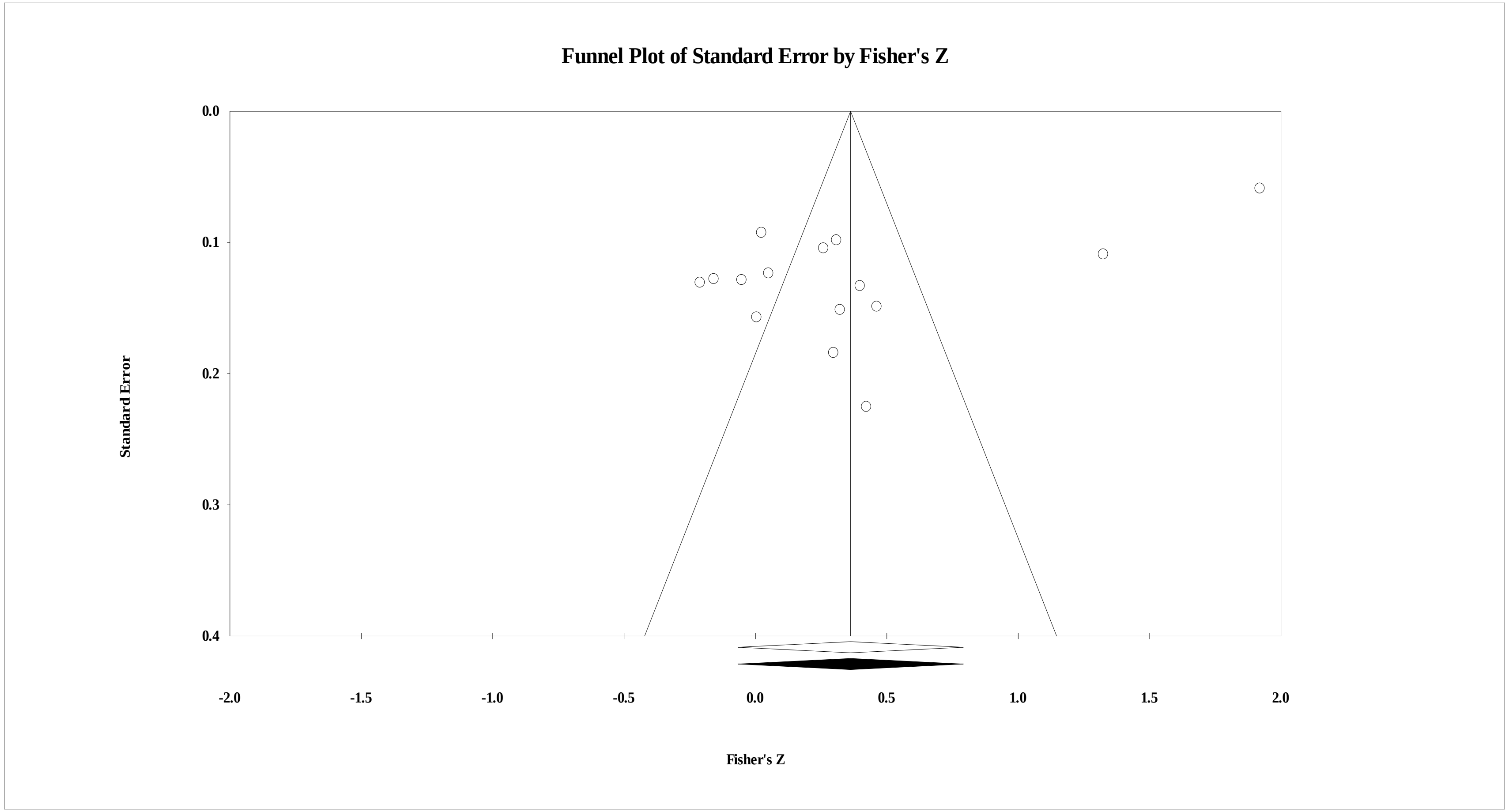

Figure 12. Funnel plot for the relationship between inhibitory control efficiency and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

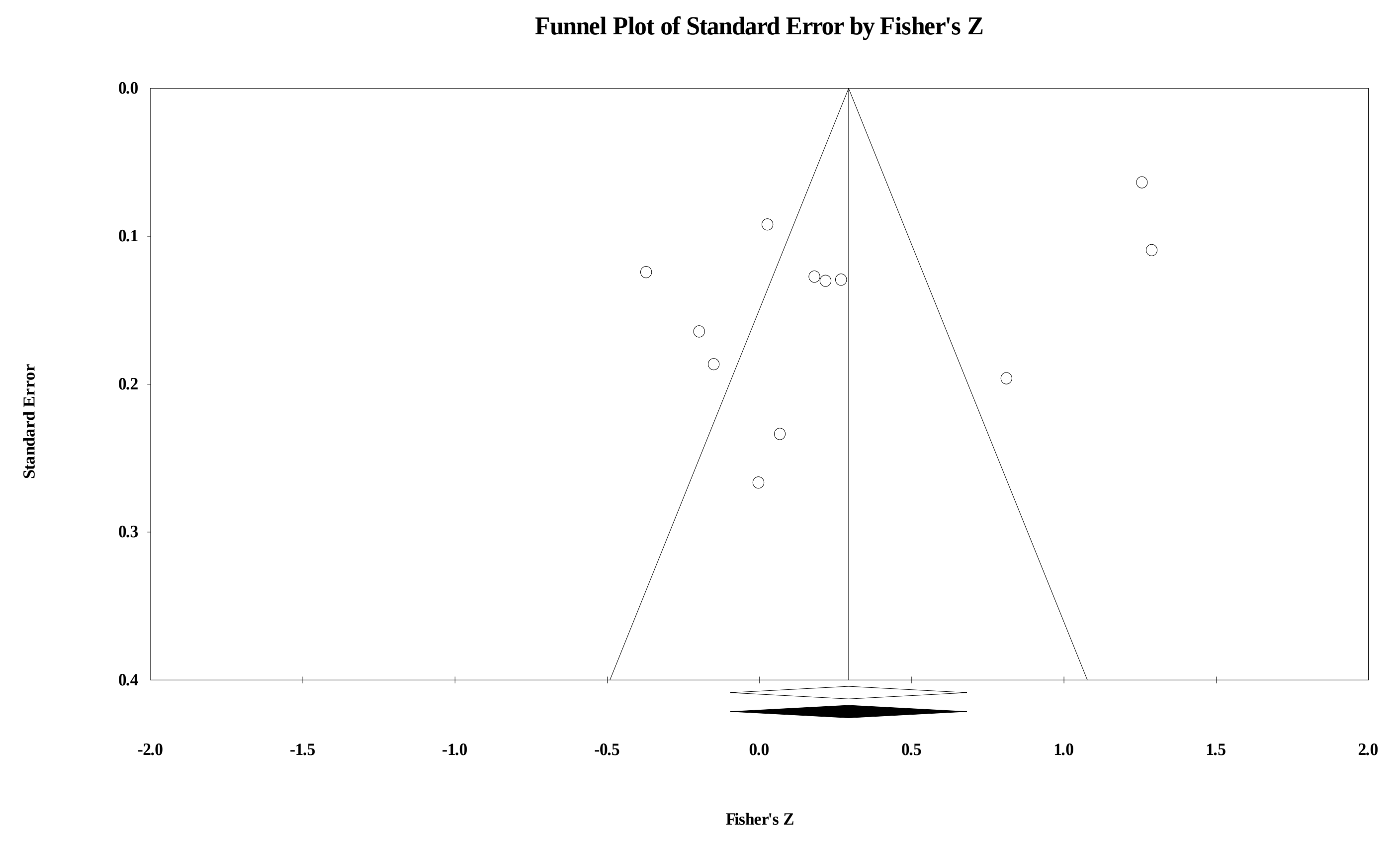

Figure 13. Funnel plot for the relationship between inhibitory control effectiveness and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean.

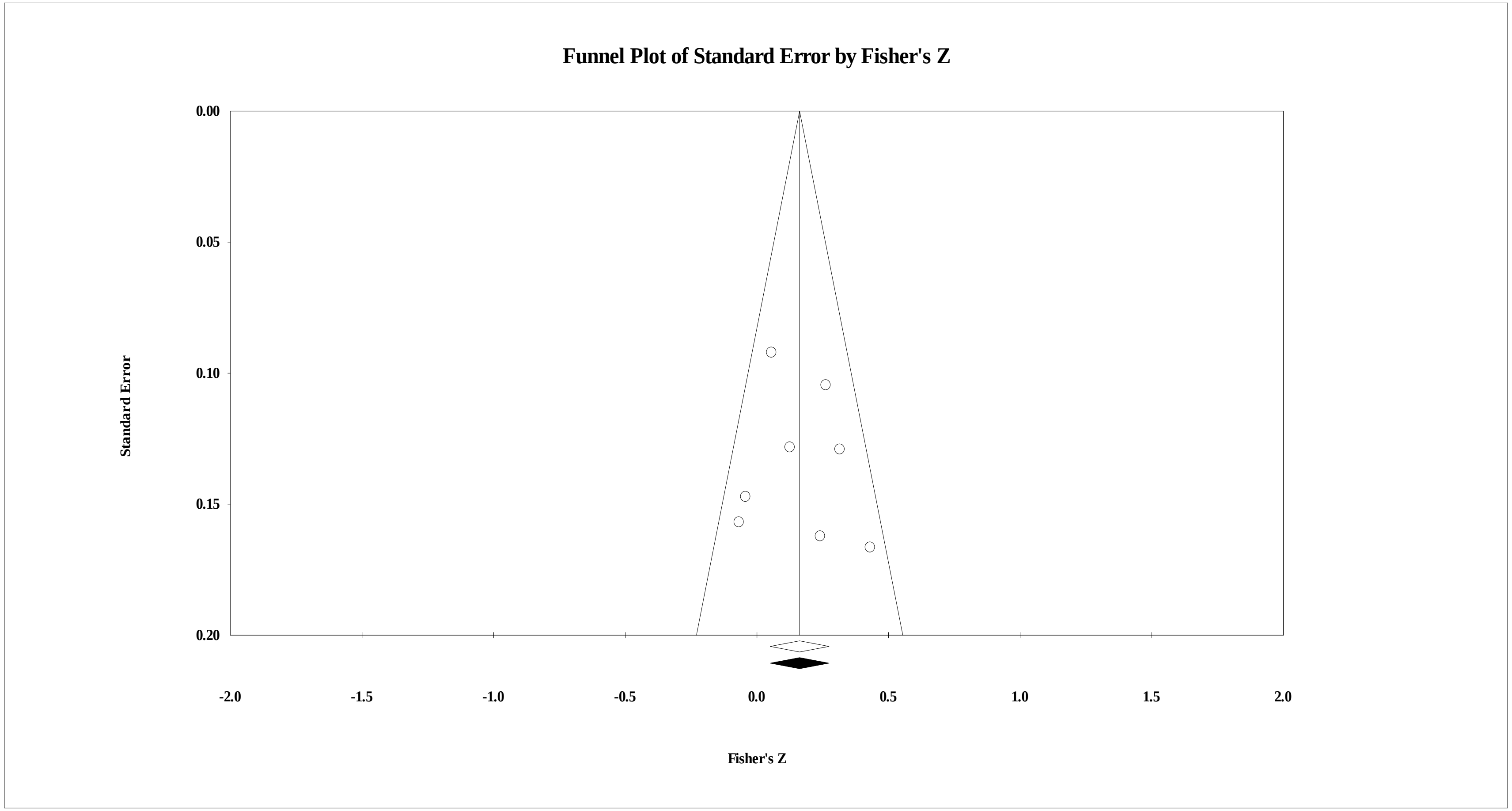

Figure 14. Funnel plot for the relationship between cognitive flexibility and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean.

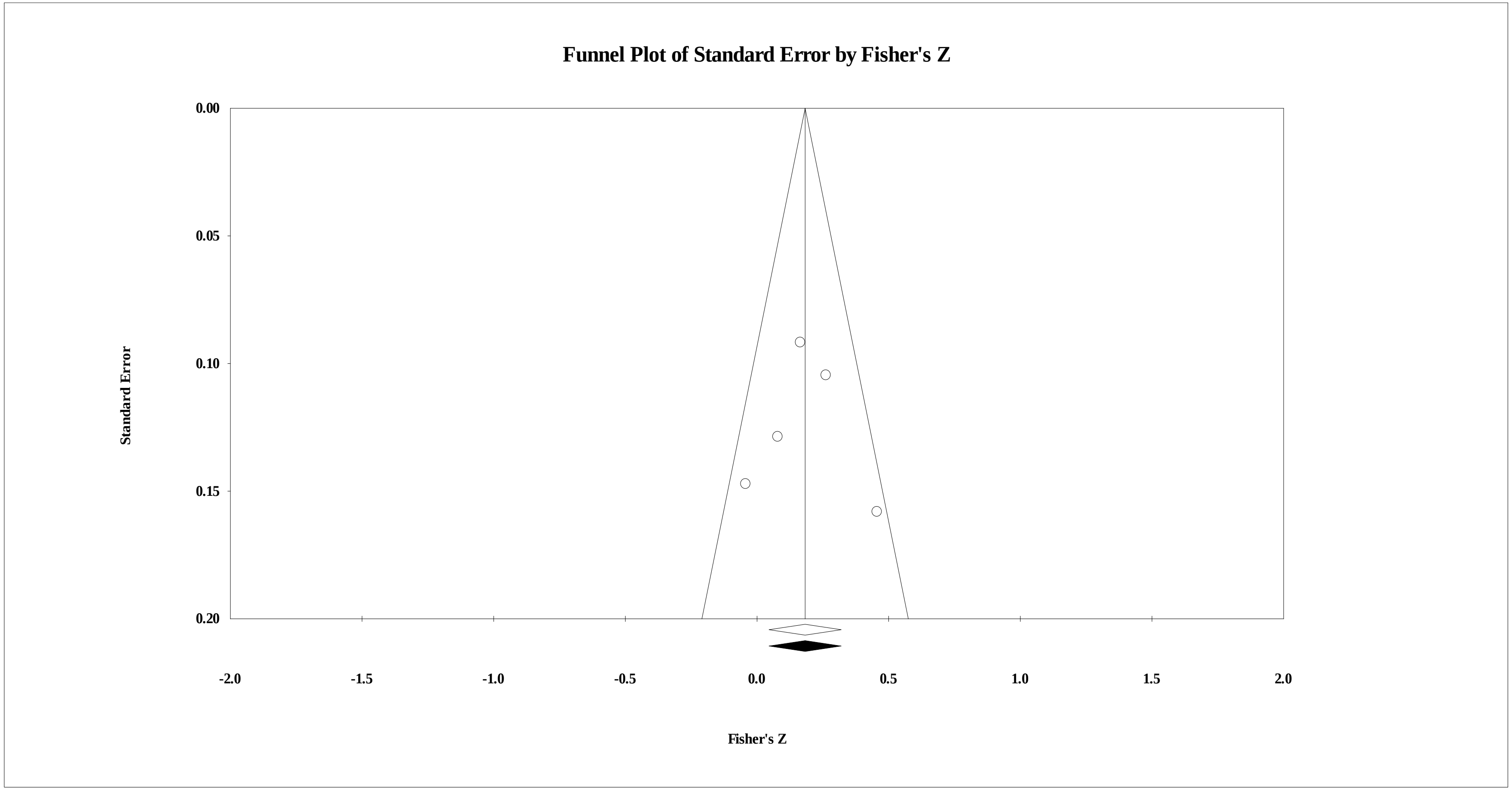

Figure 15. Funnel plot for the relationship between cognitive flexibility efficiency and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

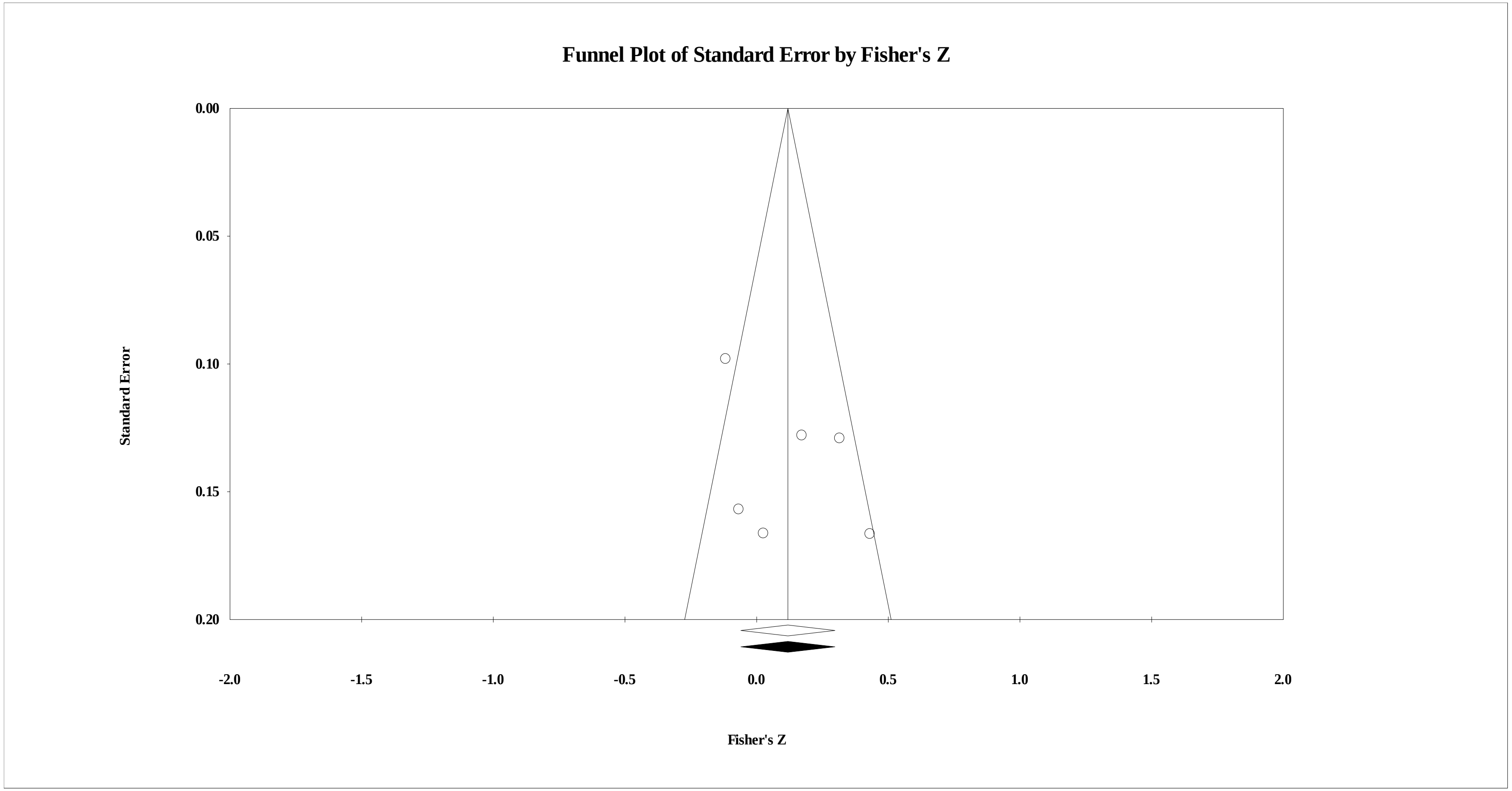

Figure 16. Funnel plot for the relationship between cognitive flexibility effectiveness and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

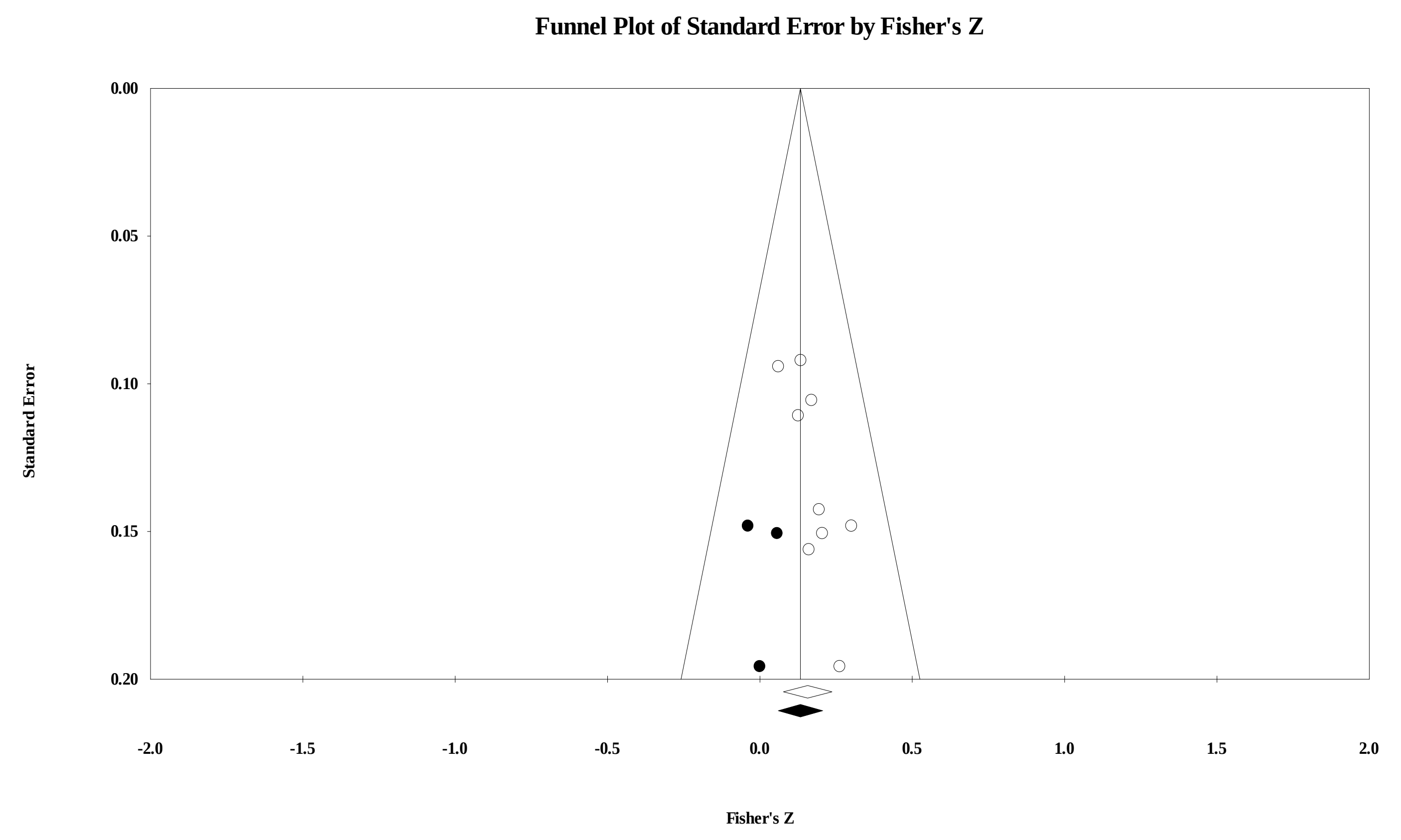

Figure 17. Funnel plot for the relationship between working memory and athletic expertise with imputed studies. Open circles correspond to observed point estimates. Filled in circles correspond to imputed studies. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

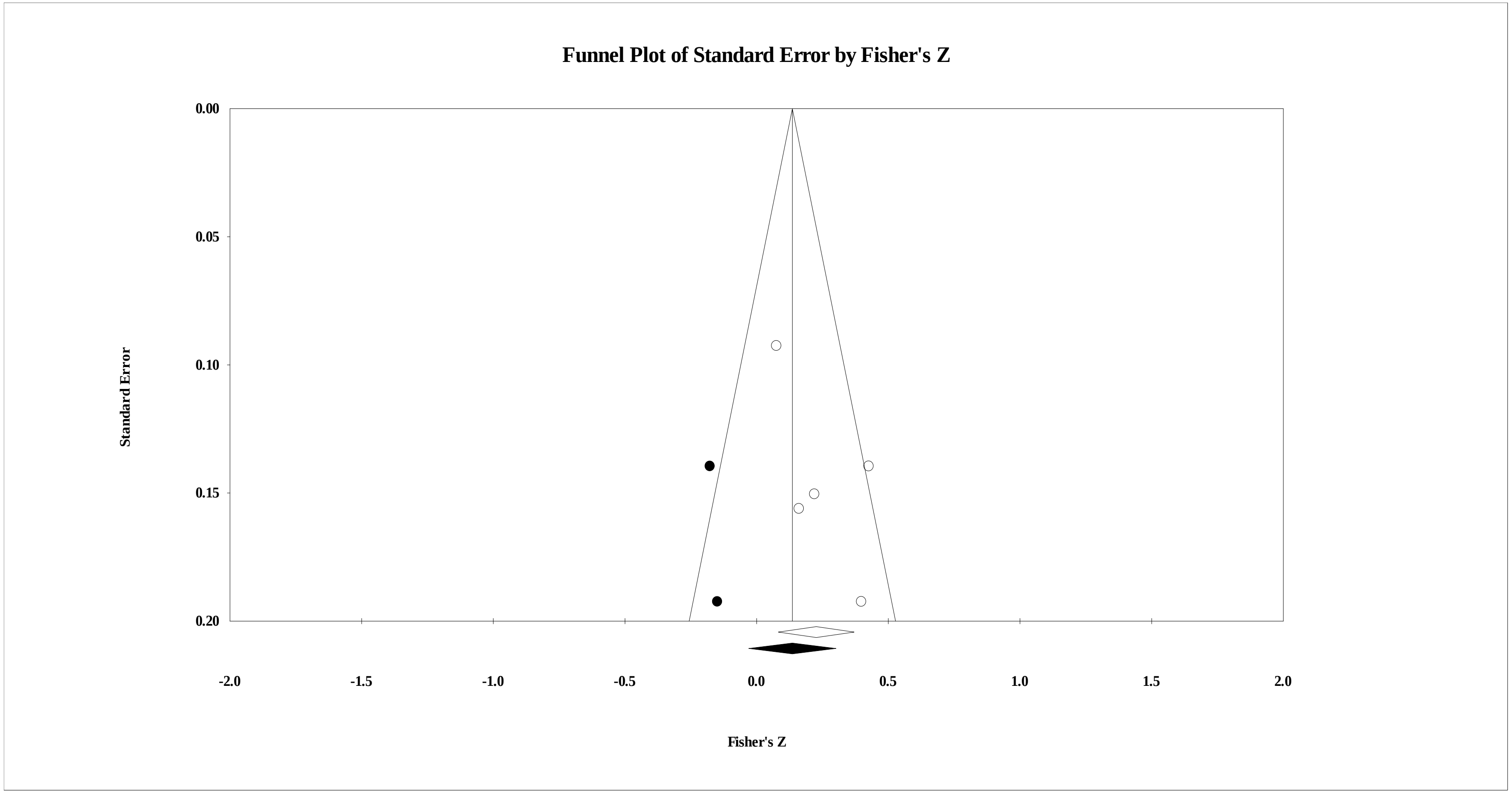

Figure 18. Funnel plot for the relationship between working memory efficiency and athletic expertise with imputed studies. Open circles correspond to observed point estimates. Filled in circles correspond to imputed studies. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

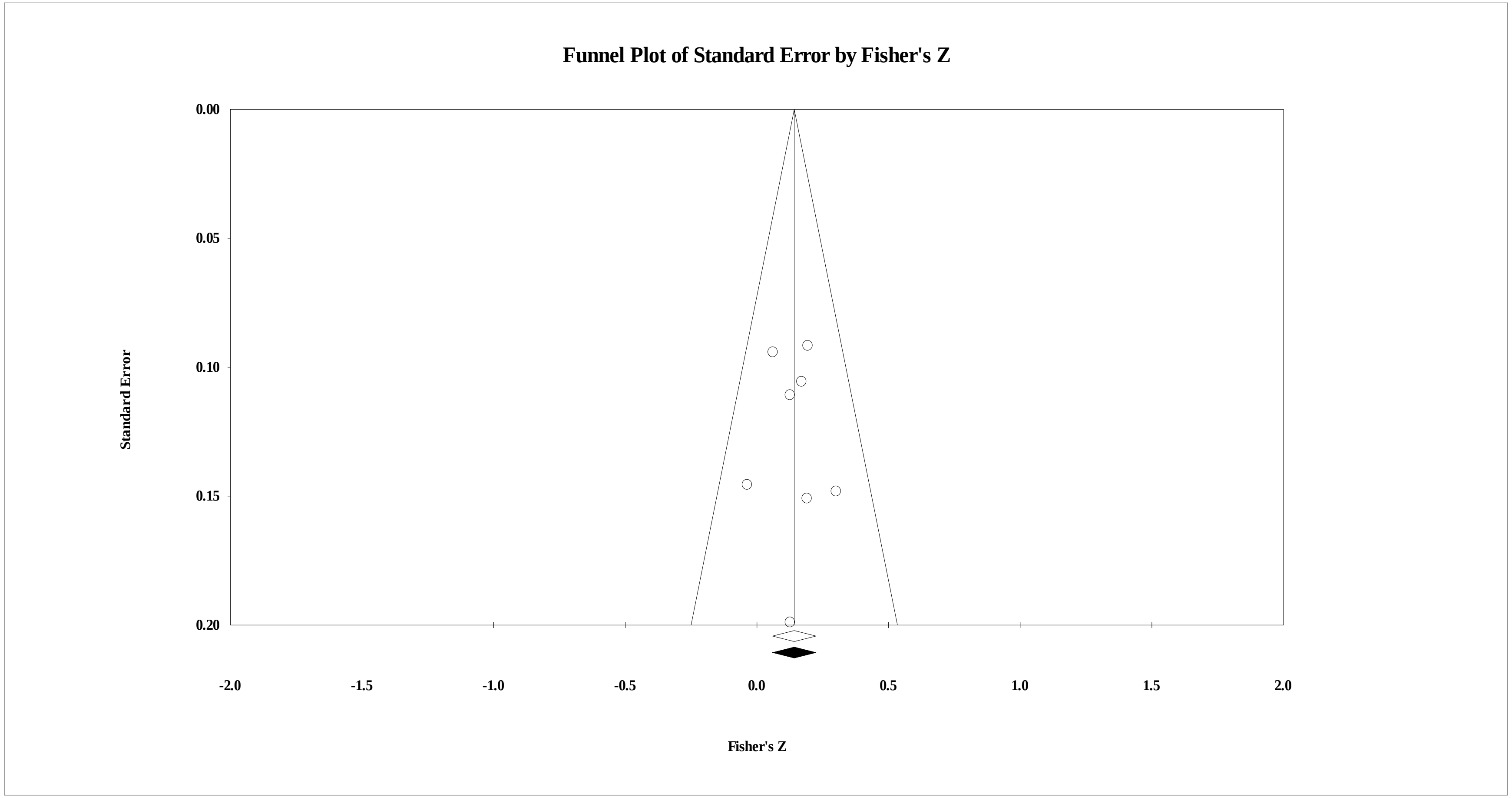

Figure 19. Funnel plot for the relationship between working memory effectiveness and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

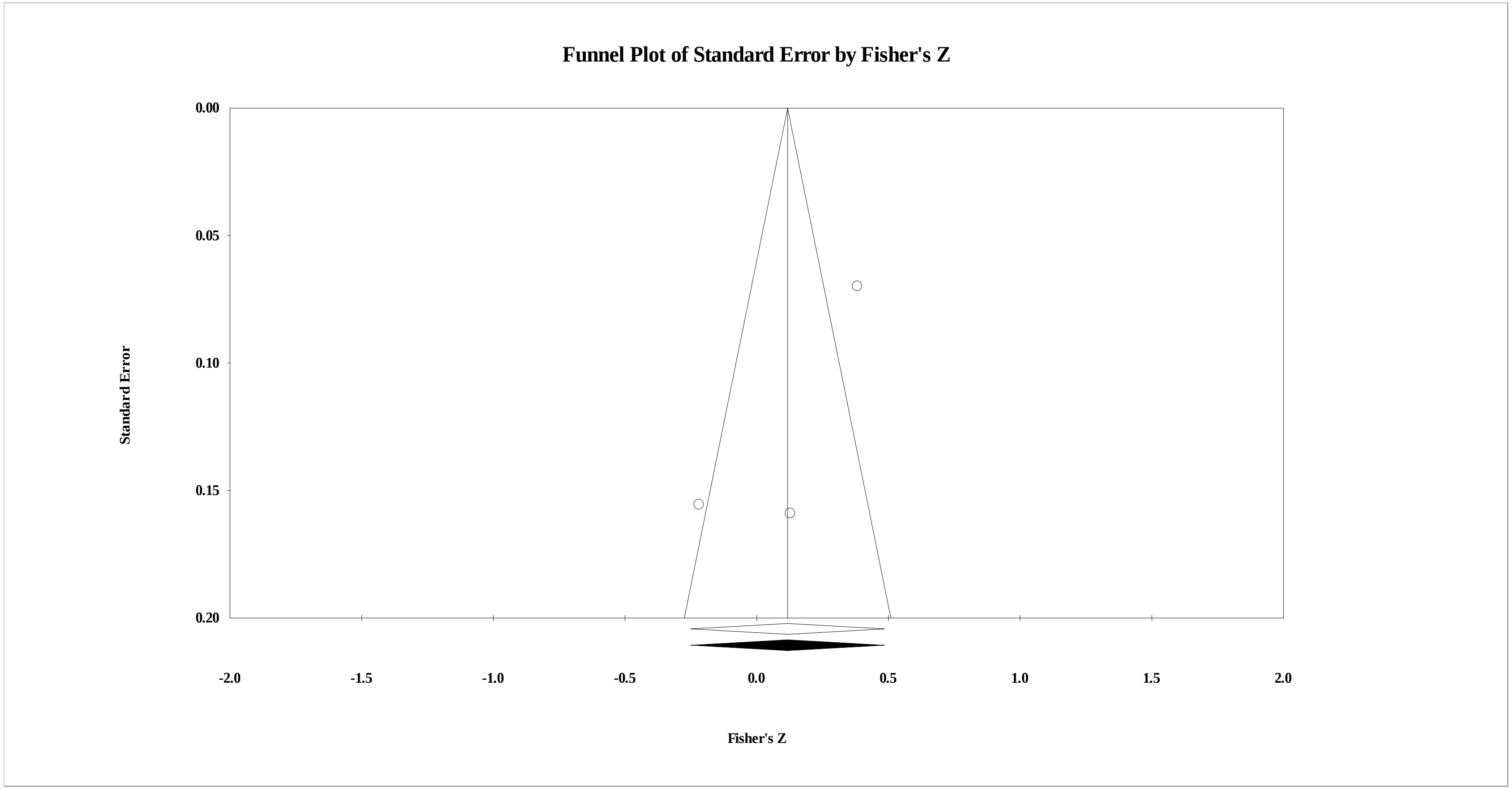

Figure 20. Funnel plot for the relationship between planning and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean

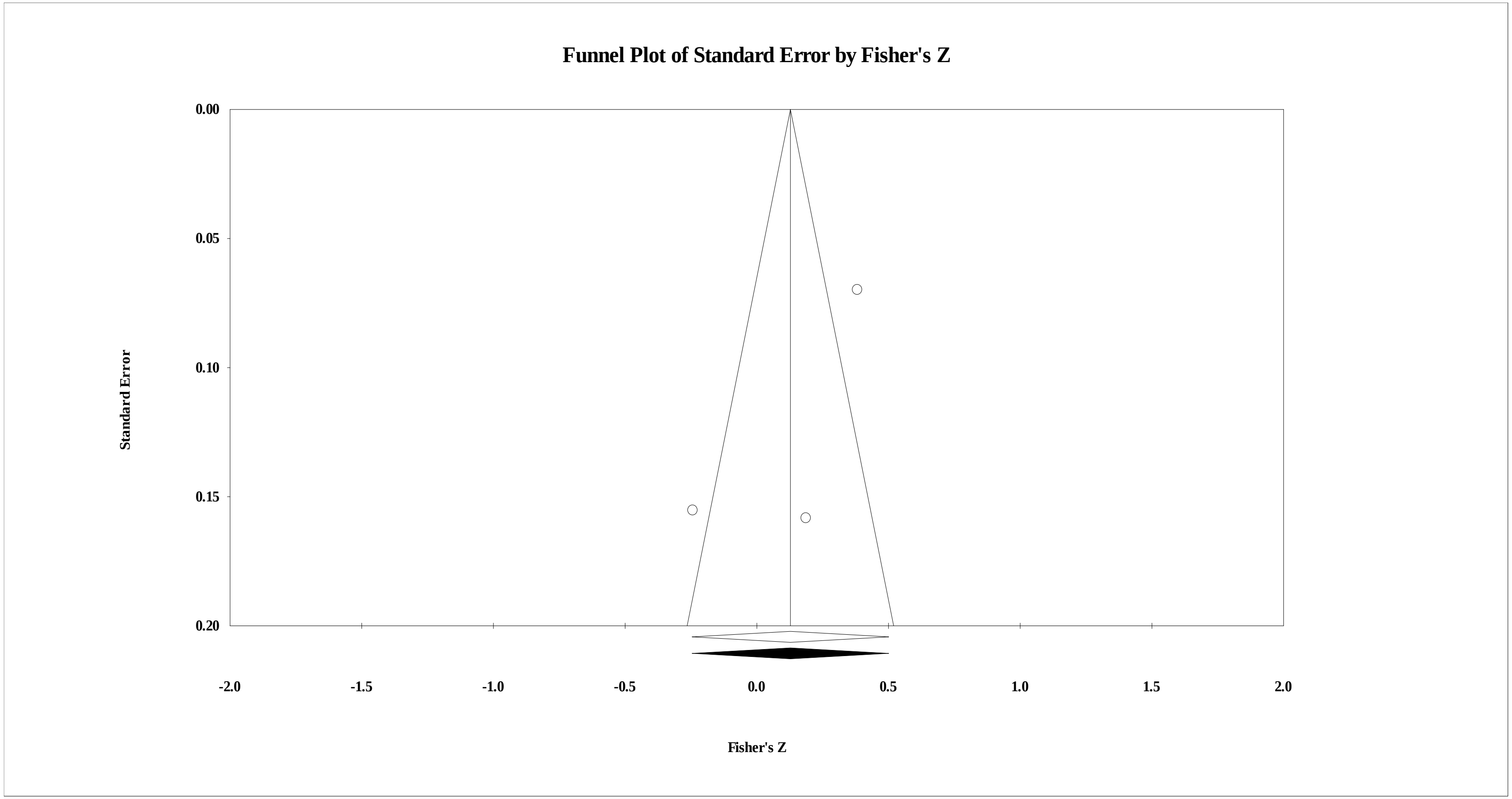

Figure 21. Funnel plot for the relationship between planning effectiveness and athletic expertise with imputed studies. Open circles correspond to observed point estimates. The open diamond corresponds to the observed point estimate. The filled in diamond corresponds to the imputed point estimate. The expected direction of missing studies was specified as being to the left of the mean