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A meta-analysis of performance advantages on athletes in multiple object tracking tasks

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This study compared the multiple object tracking (MOT) performance of athletes vs. non-athletes and expert athletes vs. novice athletes by systematically reviewing and meta-analyzing the literature. A systematic literature search was conducted using five databases for articles published until July 2024. Healthy people were included, specifically classified as athletes and non-athletes, or experts and novices. Potential sources of heterogeneity were selected using a random-effects model. Moderator analyses were also performed. A total of 23 studies were included in this review. Regarding the overall effect, athletes were significantly better at MOT tasks than non-athletes, and experts performed better than novices. Subgroup analyses showed that expert athletes had a significantly larger effect than novices, and that the type of sport significantly moderated the difference in MOT performance between the two groups. Meta-regression revealed that the number of targets and duration of tracking moderated the differences in performance between experts and novices, but did not affect the differences between athletes and non-athletes. This meta-analysis provides evidence of performance advantages for athletes compared with nonathletes, and experts compared with novices in MOT tasks. Moreover, the two effects were moderated by different factors; therefore, future studies should classify participants more specifically according to sports levels.

Keywords Multiple object tracking, Athletes, Experts, Novices, Performance

Visual attention plays a crucial role in all tasks involving perception and action, particularly in sports. In highly dynamic and constantly changing scenarios, players need to flexibly adjust their visual attention while simultaneously performing various activities to act successfully, requiring continuous attention throughout the process[1,2]. Nakayama and Mackeben[3] first linked perceptual research to attention by dividing it into instantaneous and continuous attention. This study focused on continuous dynamic attention, involving multiple moving objects simultaneously over a period of a few seconds. Continuous attention may be static or dynamic, as the stimulus may remain stationary, or motion may occur during sustained attention to the target. The process of multiple object tracking (MOT) involves continuous attention. The core aspects of attention include selectivity, capacity limitations, and subjective effort[4]; MOT serves as a visual illustration of these three components of attention[5].

The MOT paradigm is a cognitive task originally developed to study visual attention[4]; the paradigm was later used by researchers to evaluate and enhance the ability to track targets within a dynamic environment where all objects are in constant motion[6,7]. Performance on MOT tasks is defined as being able to successfully track several moving circles within a specified arena[8]. Typically, tasks require participants to track multiple targets. The general procedure is as follows: first, objects with all the same characteristics appear in the visual field (usually 6 to 10 objects); then, several of these objects are designated as targets (usually 2 to 5 objects), and the participant tracks the objects during the following time period. At the end of the object movement, the tracking performance for one or all targets is tested. Researchers can manipulate the number of targets[9] and distractors[10], speed of movement[11], and tracking duration[12] to explore and compare the dynamic visual attention of various populations. Differences in MOT performance among experts and novices in various fields have also been studied, such as drivers[13], video game players[14], and athletes[12,15]. Especially in sports, many studies have focused on the MOT performance advantages of expert athletes.

However, previous study on the performance advantages of athletes in MOT are controversial. Some studies found that individuals with sports expertise can perform better on MOT tasks, including tracking accuracy[16], reaction time[17], and tracking speed thresholds[6]. A previous study found that volleyball athletes had faster reaction

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times than nonathletes when detecting changes in targets in MOT[18]. Recent studies have also found that basketball and volleyball athletes have a performance advantage over nonathletes in MOT tasks[10,18–22]. Professional athletes in soccer, ice hockey, rugby, and other sports also outperformed high-level amateur athletes and nonathletes in MOT tasks, and showed higher learning efficiency[23]. These studies investigated players from team ball games (e.g., basketball[19,24]) because dynamic visual attention plays a key role in these types of sports. Players need to simultaneously pay attention not only to the spatial position of the ball and to the court but also to the movement and position of teammates and opponents[25].

Nevertheless, not all empirical evidence is consistent with this conclusion; some studies have found no statistical difference between athletes and non-athletes or experts and novices. Memmert et al.[26] showed that team sports experts did not perform better than novices on visual attention tasks. Li et al.[27] also found that there was no significant difference in tracking accuracy between expert athletes and novices when the number of tracking targets was small. These findings demonstrated that there was no discernible difference in the performance of MOT tasks between athletes and nonathlete college students or athletes of different levels. In addition, one study found that basketball players had lower MOT scores than nonathletes[28]. This demonstrates that the MOT performance advantages of athletes are controversial.

Given the inconsistent findings in prior studies concerning the MOT, no meta-analyses have examined MOT performance advantages in athletes. A meta-analysis on whether athletes show performance advantages in MOT is worth considering. Following the cognitive skill transfer hypothesis, training in a cognitive task may enhance performance on related, but untrained, cognitive tasks[29,30]. The so-called broad transfer hypothesis argues that long-term experience in team sports leads to adaptations in basic cognitive abilities causing performance differences between experts and novices even on tasks independent to experts' domain[31,32]. In this regard, the specific cognitive demands of open-skill sports like basketball, or soccer were argued to cause superior cognitive abilities in elite athletes[33].

The cognitive advantages in other areas for expert athletes have been explored in many meta-analyses[31,34]. A previous meta-analysis[31] that examined whether professional athletes remained 'experts' in the cognitive lab found that expert athletes performed better on measures of processing speed and a category of varied attentional paradigms (e.g., the Paced Auditory Serial Addition Task (PASAT) and the Eriksen arrow flankers task). They proposed further research with higher-level cognitive tasks, such as tasks of executive function and complex tasks involving attention (e.g., MOT)[31]. Previous systematic reviews have also shown that sporting experts are more successful than novices when reacting to an upcoming event, while recruiting fewer attentional resources and devoting more attention to subsequent targets analysis in unexpected situations[35]. For MOT tasks, attentional resource theory[36] would hold that there is a pool of resources required for tracking objects, and that the limit on tracking depends on the resource demands required to track each object. For example, if the tracking task were so difficult that tracking one target consumed all available tracking resources, then only a single item could be tracked. However, if each item only required 1/4th of the total available resources, then four objects could be tracked. Experts may require less attentional resource for each item due to their superior cognitive abilities[37]. Therefore, it is reasonable to speculate that this expert advantage may be revealed in MOT tasks.

Furthermore, the reasons for differences in the results of MOT tasks performed by athletes with different expertise levels in previous studies may vary; they may include task parameters, task presentation, and the type and experience of participants. Therefore, the moderating factors affecting the differential performance in MOT need to be examined. The difficulty level of the MOT task can be varied parametrically (e.g., number of targets[38]; number of distractors[39]; speed of the target[40]; and duration of tracking[41]), which may result in group differences (i.e., expertise effects[20,42]). For example, Qiu et al.[10] conducted MOT tests with graded levels of the number of targets (two, three, or four); compared with nonathletes, athletes performed better in the three- and four-target conditions. Zhang et al.[43] found that as the speed of the movement increased, athletes showed a stronger tracking advantage than non-athletes; moreover, the higher the skill level of the athletes, the more obvious the effect. As different settings of MOT parameters affect the MOT performance, the number of targets and distractors, speed of the targets, and duration of tracking should be used as moderating variables in meta-analysis.

In recent years, MOT has not been limited to 2D frames; with the development of virtual reality technology, 3D-MOT in sports has attracted the attention of researchers. Compared to 2D-MOT, 3D-MOT can bring advantages to motion performance, such as creating and controlling virtual motion scenes[44], presenting stereoscopic vision[7] and immersing the visual scene; that is, the athletes can experience the sports scene in person instead of watching the video from a third-person perspective[45]. Based on these advantages, some studies indicated that virtual reality technology can more effectively measure perception and motor performance in the field of motion than traditional methods[46]. Cooke et al.[47] found that the tracking accuracy of 3D-MOT tasks was better than that of 2D-MOT tasks; when the object distance increased, individuals could track objects at a faster speed in 3D-MOT task. This suggests that an increase in depth information enhances tracking performance by increasing object differentiation because objects that are confused in a two-dimensional plane are likely to be distinguished in a three-dimensional space. However, the effect of 3D-MOT on the final score remains unclear. The nature of this difference is to display whether it is 3D or 2D, which we studied as a moderating variable called the display type.

Moreover, athletes' sports level and sport type may influence MOT performance. A meta-analysis of cognitive function in expert and elite athletes showed that high-performance-level athletes have superior cognitive function compared to low-performance-level athletes[48]. This indicates that the competitive level plays a role in athletes' MOT performance. However, the cognitive functions in Scharfen and Memmert's[48] study only included executive functions, visual perceptual ability, and motor inhibition and did not focus on MOT. In addition, a previous meta-analysis found a significant moderating effect of sport type on the relationship between expertise level and perceptual cognitive skills, suggesting that the difference in performance between experts and novices may differ in various sports[34]. This suggests that the type of sport may have an effect on perceptual cognition; therefore, the effect of competitive level and sport type on MOT was also explored in this study.

Additionally, previous studies on the advantage of expert athletes included different group comparisons; some compared experts with novices[35], while others compared athletes with non-athletes[16,49]. This difference in classification is mainly due to differences in the control group; that is, the classification and characteristics of novices and nonathletes are inconsistent. However, there is no unified concept for novice athletes. For example, one study considered novice athletes to be players with no more than two years of formal experience in any sport[26], while others defined novice athletes as players with less than a few years of practice in particular sports, such novice athletes in martial arts had less than one year of practice[50] and those in badminton had less than 2–3 years of practice[51]; some studies referred to novice athletes as people with no sports experience[52], that is, confusing novice athletes with non-athletes.

Thus far, similar meta-analyses on differences in athletes' advantages have compared experts with novices in areas such as cognitive function[48], visual search[53], and quiet eyes[54]. However, it is important to note that these studies differentiated only between experts and novices and mixed different athletic levels (non-athletes were not distinguished from novices), which may not be the clearest comparison, and the results may be different if further differentiation is made. Vague definitions of novices or experts directly affect performance[53]. One study[43] categorized participants into three groups: experts, novices, and controls or non-athletes, and found that the tracking accuracy of the expert group was significantly higher than that of the control group. Furthermore, the difference in tracking accuracy between the novice and control groups was marginally significant, whereas there was no significant difference between the expert and novice groups. This suggests that different categories produce differences in performances.

Based on previous studies, this meta-analysis addresses the differences between athletes and non-athletes. Athletes include both expert athletes and novice athletes, who have different level of sports experiences, while non-athletes refer to those who have no sports training experience. Therefore, we aimed to distinguish the performance advantage between athletes and nonathletes, as well as between expert and novice athletes. This approach is necessary to avoid potential confounders caused by unclear definitions.

In sum, the MOT performance advantage in athletes is controversial and is affected by various factors. However, no previous meta-analysis has reported the dominant performance of athletes in MOT tasks. Therefore, the present study aimed to conduct a systematic review and meta-analysis to obtain a clearer and stronger conclusion about the differences between athletes vs. nonathletes or experts vs. novices in dynamic visual tracking in sports. Potential moderators such as athletes' competitive level, type of sport, parameters of the MOT task and type of display were considered. Based on the above discussion, we made the following hypotheses:

H1 (hypothesis related to overall effect sizes):

Athletes would have a significant MOT performance advantage over non-athletes (H1a), and likewise experts would have a MOT performance advantage over novices (H1b), although the extent of this advantage may vary.

H2 (hypothesis related to moderator analyses of athletes vs. non-athletes):

Type of sport (H2a), parameters of the MOT task (H2b), type of display (H2c) and athletes' competitive level (H2d) would significantly modulate the differential performance of MOT task for comparisons athletes vs. non-athletes.

H3 (hypothesis related to moderator analyses of experts vs. novices):

Type of sport (H3a), parameters of the MOT task (H3b) and type of display (H3c) would significantly modulate the differential performance of MOT task for comparisons experts vs. novices.

H4 (hypothesis related to comparison of the two groups: athletes vs. non-athletes and experts vs. novices):

A comparison of effect sizes between athletes vs. nonathletes and experts vs. novices would reveal a significant difference.

Materials and methods

The review procedures followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[55]. Following recent best practices to enhance transparency, replicability, and robustness of systematic reviews in sport and exercise psychology, this study was registered via the Open Science Framework. The systematic review, search strategy, and meta-analysis are detailed in a registration document available in the Open Science Framework, as are all supplemental files (https://osf.io/ncq7v/).

Data search and selection criteria

The categories for comparison of MOT performance between athletes and other groups included athletes and non-athletes, as well as experts and novices. This review focused on published research that explored the differences in performance on MOT tasks between athletes and non-athletes or experts and novices.

Systematic database searches were performed up to July 2024 using the Web of Science, PubMed, SPORTdiscus, ProQuest and Scopus. As there are many related Chinese studies, the Chinese database-Chinese National Knowledge Infrastructure (CNKI) was also included in the search. For the searches, the terms 'multiple object tracking*' OR 'MOT' OR '2D-MOT' OR '3D-MOT' were combined (AND) with 'sport*' OR 'athlete*' OR 'expert*' OR 'player*' OR 'elite*' OR 'novice*' OR 'nonathlete*'. Additionally, we conducted a manual search using Google Scholar. We searched references of eligible articles and used Google Scholar to identify articles that cited eligible articles. Two experienced researchers conducted the literature search with assistance of two other researchers.

After removing duplicates, an initial screening at the titles and/or abstracts was conducted using the following inclusion criteria to identify relevant research reports (articles, dissertations, and theses): (1) involving healthy athletes, (2) performed MOT tasks and performance on MOT tasks is reported. Following the initial screening, studies were included if they (1) included athletes and non-athletes or experts and novices, (2) reported a comparison of MOT task performances between experts and novices or athletes and non-athletes, (3) reported participation outcomes, and (4) had sufficient data to calculate effect sizes. If relevant research/data was not available online, the authors were contacted personally.

Exclusion criteria related to insufficient data reporting included lack of data on athletes or nonathletes, no specific sport mentioned, and no MOT exposure. Literature reviews were excluded.

Data extraction

Data were extracted independently by two authors, and the remaining authors were responsible for verification. The extracted data included study characteristics (authors, publication year, and sports), sample characteristics (team country, sample size, age, and so on.), MOT parameters (number of targets and distractors, targets' movement speed, and duration of tracking), type of MOT display, and outcomes. The coding process was conducted by two authors separately according to a coding manual determined in advance and then cross-checked[56]. The disputed documents were discussed in groups and a consensus was reached to ensure the accuracy of the coding. The final consistency was 97.4% (ICC).

The basis for the comparative classification of the articles was as follows: first, according to the different definitions of nonathletes and novices, samples in previous difference comparison studies were divided into athlete and nonathlete comparison groups or expert and novice comparison groups. As the athletes included both experts and novices, they were divided into two groups (expert and novice athletes) for the moderating analysis. This is different from the comparison of experts and novices in the other group classification. This classification effectively distinguishes two different control groups: for the comparison of athletes vs. non-athletes, the subgroups were expert athletes vs. non-athletes and novice athletes vs. non-athletes, both using non-athletes as the control; for the comparison of experts vs. novices, the control group was novice athletes.

Different studies often used different classification criteria, and we attempted to match these criteria. The classification criteria for athletes and nonathletes, as well as experts and novices, were as follows: In previous studies, the highest level of competition among athletes and years of training experience were commonly used as criteria to distinguish expertise levels[57]. This study considered the highest level of competition and years of experience as criteria for evaluating the classification of athletes. Based on the division of years of training by Memmert et al.[26], the study also divided experts and novice athletes by years of exercise (over 10 years and under 10 years). For the highest level of competition, those at the provincial level and above are classified as experts. In addition, in most Chinese articles included, the grades of the athletes were listed, and sports-level certification was the main criterion for evaluating Chinese athletes. Chinese athletes are typically classified into three technical grades: master sportsman, national first-level athletes, and national second-level athletes. Among these, master sportsman is deemed the highest title awarded by the State Sports Commission of China. Athletes with the master sportsman certificate are required to participate in international competitions and have achievements in international competitions such as the Olympic Games, World Championships, World Cup, Asian Games, and Asian Championships. Athletes with the national first-level athlete certificate are required to place in the top three non-team events or fourth to eighth places in team events in the national Championships. As the criteria for master sportsmen and national first-level athletes are comparable to the criteria for expert athletes in other countries, they were classified as expert athletes. Meanwhile, athletes with the national second-level athlete certificates are those who have participated in the National A-League, B-League, Cup League, and National Youth Games, or who have won first to fourth place in provincial, autonomous region, and municipality championships, and were classified as novice athletes[43]. In addition to certified athletes, some physical education students in sports colleges in China also receive systematic sports training, but their level is usually lower than the Chinese national second-level athletes; they were also classified as novice athletes. Finally, if a study included a mix of two categories in one, the category with the highest level was considered. Table 1 shows the criteria for defining experts, novices, and non-athletes in this study. Participants were classified as those who met one or more of these criteria. Table 2 shows the classification of the two comparison groups (athletes and non-athletes[10,12,16,17,19–22,24,28,43,58–65]; experts and novices[10,21,26,27,43,51,60,66]) of the studies included in this meta-analysis.

Assessment of study quality

As the studies were non-randomized by nature (i.e., experts were compared with novices) and the term 'exposure' was more appropriate than 'intervention', Cochrane's RoBANS tool[67] was used to assess the risk of bias arising from (i) participant selection, (ii) confounding variables, (iii) measurement of exposure, (iv) blinding of outcome assessment, (v) incomplete outcome data, and (vi) selective outcome-reporting. Six categories each were assessed as 'high risk', 'unclear risk', or 'low risk'. The risk of bias was considered similar for all primary outcomes, as the

		Athletes	
Variable	**Non-athlete**	**Novice athlete**	**Expert athlete**
A. Years of experience	No training experience	Athletes with training experience less than 3 years	Athletes with training experience more than 10 years
B. The highest level of competition	No highest level of competition	College sports team	Provincial level and above competitions; Semi-professional competitions and above
C. Sports-level	No sports-level	Chinese national second-level or below	Chinese master sportsman or national first-level athletes

Table 1. Defining criteria for expert athletes, novice athletes and non-athletes.

Classification I	Classification II	Study
Athletes vs. non-athletes	Expert athletes vs. non-athlete	X. Zhang et al., 2008; Martín et al., 2017; Qiu et al., 2018; Zhu et al., 2019; Qiu et al., 2019; Jin et al., 2020; Y.H. Zhang, Lu, Wang, Zheng, et al., 2021; Jin et al., 2022; Vu et al., 2022; Zwierko et al., 2022; P. Jin, Zhao, et al., 2023; Mackenzie et al. 2024; Styrkowiec et al., 2024; Wierzbicki et al., 2024
	Novice athletes vs. non-athlete	Gong et al., 2016; Qiu et al., 2018; Y.H. Zhang, Lu, Wang, Zheng, et al., 2021; Y. Zhang et al., 2021; Gou et al., 2023; Su et al., 2024
Expert athletes vs. Novice athletes	N/A	Memmert et al., 2009; Li et al., 2021; Ji & Liu, 2015; Qiu et al., 2018; Y.H. Zhang, Lu, Wang, Zheng, et al., 2021; Y.H. ZhanZg, Lu, Wang, Zhou, et al., 2021; P. Jin, Ji, et al., 2023
	N/A	

Table 2. The classification of the two comparisons (athletes and non-athletes; experts and novices) of studies included in this meta-analysis.

data were generated from the same MOT technology in each study. Therefore, only one risk of bias assessment was performed for each study. The RoBANS assessment was conducted independently by two authors (L and Z). Disagreements were resolved by consensus or consultation with a third assessor (C), when required.

Summary measures, synthesis of results, and publication bias

MOT data were analyzed using Comprehensive Meta-Analysis 3.3 (CMA 3.3) software (Biostat, Englewood, NJ, USA) for meta-analysis and meta-regression. The level of statistical significance was set at $p < 0.05$. The MOT outcomes were (1) MOT task accuracy (ACC), (2) MOT task reaction time (RT), and (3) tracking speed thresholds. The two groups were compared based on the above outcomes. Based on previous study about the methods for dealing with multiple outcomes in meta-analysis[56,68], for different categories of outcomes MOT variable, we conducted each analysis followed by moderator analyses.

Hedges' g (standardized mean difference effect size) between the two groups with the corresponding 95% confidence interval (95% CI) was calculated. A random-effects model was used to account for differences between studies[69]. The evaluation criteria for the effect size were as follows[70]: trivial: <0.2; small: 0.2–0.6; moderate: 0.6–1.2; large: 1.2–2.0; very large: 2.0–4.0; and extremely large: >4.0. The direction of Hedges' g was manually adjusted to consider variable outcomes, with a positive effect size indicating that the athlete or expert performed better on the MOT task.

The heterogeneity test of variance of the effect sizes in this study was carried out using the Q statistic. Q statistic is a measure of the total observed dispersion of the estimated effect sizes. Total heterogeneity (Q_T) is used to determine whether the effect sizes for all studies are homogeneous[71]. If a significant Q_T value is observed ($p < 0.05$), this indicates heterogeneity of results and may result in a search for potential moderating variables[72]. In the moderator analyses, a Q_B and Q_W statistic is computed to test respectively, for between- and within-group homogeneity. Q_W signifies the degree of heterogeneity of studies within a moderator category, whereas the Q_B statistic refers to a difference in the pooled effect sizes between moderator categories[71]. In addition to the Q statistics, the I^2 statistic was also utilized to analyze the heterogeneity test results. The I^2 statistic is a more thorough metric that shows the percentage of variability related to true heterogeneity. Heterogeneity was classified as follows: low, moderate, and high when the I^2 values were <25%, between 25 and 75%, and >75%, respectively[73].

Publication bias for the studies pooled for the meta-analysis was assessed by visually inspecting funnel plots and by computing Egger's test results[74]. Statistical significance was defined as 2-sided $p < 0.05$, which was taken as a reflection of the presence of publication bias. In the absence of publication bias, the funnel plots should resemble an inverted funnel shape, with studies scattered symmetrically around the pooled effect size estimate.

Moderator analyses

Using a random-effects model for analysis, potential sources of heterogeneity likely to influence MOT performance in athletes, non-athletes, experts, and novices were examined.

The potential moderating effects of participant and/or study characteristics (covariates) on the mean overall effect size were explored using meta-regression[75] and subgroup analysis. Continuous variables including (1) number of targets, (2) number of distractors, (3) speed of target movement, and (4) duration of tracking were analyzed using meta-regression. Categorical variables including (5) type of sport, (6) competitive level, and (7) type of display were used for subgroup analysis. No moderator analysis was conducted for gender because of an insufficient number of studies reported results for different sexes separately.

Coding of subgroup variables

For a subgroup (categorical) variable, each subgroup should have a minimum of 4 studies($k \geq 4$)[76].

Competitive level

Based on the classification criteria in our data extraction section, we categorized athletes into expert and novice athletes as shown in Table 1. However, the competitive level as a moderating variable was only applicable for comparisons between athletes and non-athletes. Due to insufficient available literature, competitive level could not be used as a moderating variable for expert vs. novice comparisons.

Type of sport

The included studies span various sports, including basketball, ice-hockey, handball, soccer, volleyball, rugby, badminton, swimming, and mixed sports. Given the number of studies on non-ball sports (e.g., swimming) was small (k < 4) and the mixed sports contained both ball and non-ball sports, and they were both a single category that could not be easily unified into one category, we did not include non-ball and mixed sports in the subgroup analysis. Sports with more than four effect sizes, such as basketball, ice hockey, and handball, were grouped into individual categories. Ball sports with fewer than four effect sizes were combined into an "other ball sports" category.

Type of display

The classification was based on the display mode of MOT. 2D-MOT was conducted on a computer display, while 3D-MOT used a perceptual-cognitive training system based on a 3D virtual environment[77]. However, since only one study included 3D-MOT, this type of display was not incorporated in the meta-analysis.

Results

Search results

The search process identified 1,571 studies (462 from Web of Science, 112 from PubMed, 160 from SPORTdiscus, 197 from ProQuest, 424 from Scopus, 211 from CNKI, and 5 additional records identified through other sources (Google Scholar)). A PRISMA flow diagram of the screening process and the number of retrieved and excluded articles is shown in Fig. 1 ref.[55]. Among these, 492 duplicate studies were excluded. A further 1031 studies were excluded after reading their titles and abstracts. After full-text screening, 9 additional studies were excluded because: (1) there was no difference comparison[78–80]; (2) participants were grouped according to MOT scores rather than skill[81]; (3) data were insufficient[82]; (4) the participants were athletes with intellectual disabilities[83]; (5) the number of targets was only one[84]; (6) participants did not include non-athletes or novices[85] (soccer

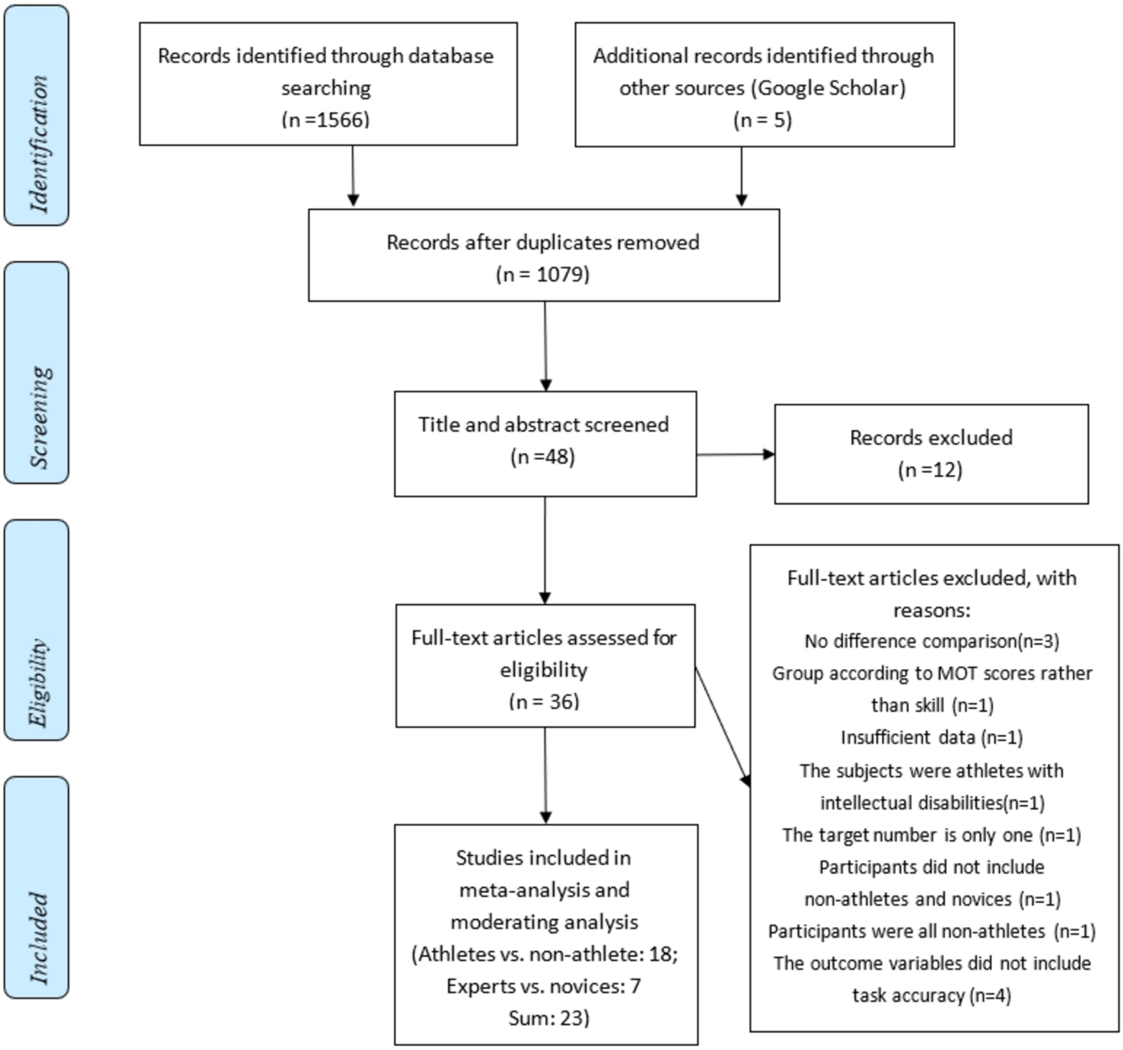


Fig. 1. PRISMA flowchart of article screening and selection.

experience: ≥6.4 years); (7) participants were all non-athletes[11] (they had only been involved in sports activities). For one study with insufficient data, the original data were obtained from the author via email[12].

After reviewing the full texts, we identified 27 articles that met the inclusion criteria. These articles included three outcome variables for MOT: accuracy (ACC), reaction time (RT), and speed thresholds. Ideally, a meta-analysis should be performed for each outcome variable. However, only one article used RT as the sole outcome variable, and three articles used speed threshold as the sole outcome variable. Additionally, although three papers included both RT and ACC, and one paper included both speed and ACC, the number of articles that included RT or speed, and could be classified into athlete vs. non-athlete or expert vs. novice groups, was fewer than three. Due to the limited number of articles reporting RT and speed variables, we decided to include only articles that reported ACC outcomes. Consequently, four articles that did not include ACC indicators were excluded[6,18,86,87]. Ultimately, we included 23 articles that utilized ACC as the outcome variable for meta-analysis and moderator analysis.

Accordingly, 23 studies were considered eligible for meta-analysis with 25 comparisons. Eighteen presented comparisons between athletes and non-athletes, and seven between expert and novice athletes. Studies by Qiu et al.[10] and Zhang et al.[43] included experts, novice players, and non-athletes; therefore, the 2 studies both included the comparison between athletes and non-athletes as well as between experts and novices. The classifications are listed in Table 2.

Study characteristics

The sample characteristics and exposures used in the included studies are shown in the supplemental file (Table S1). The main content included is shown below. (1) Sample size: a total of 1453 participants participated in the included studies. The groups' sample sizes ranged from 8 to 44. (2) Age: all studies reported the ages of the participants. The age range was between 16 and 29 years old with a mean age of 22.05 years old. (3) Competitive level: all studies reported the competitive level of the participants. Of the included studies, 14 reported on expert athletes (61%), 11 reported on novice athletes (48%), and 2 included both experts and novices. (4) Type of sport: among the 23 articles, there was 9 articles about basketball (39%), 3 articles about handball (13%), 3 articles about soccer (13%), 2 articles about ice-hockey (8%), one about rugby (5%),one about badminton (5%) and four about mix sport (including ball sports and non-ball sports)(17%), respectively. (5) Type of display: only one study reported 3D-MOT (4%) while other 22 study reported 2D-MOT (96%). (6) MOT parameters: 18 articles (78%) reported all parameters of MOT (number of targets, number of distractors, speed of target movement, and duration of tracking). Of the remaining five articles, two did not report duration of tracking and three did not report tracking speed.

Study quality

Regarding participant selection, a low risk of bias was identified in 96% of the studies. The remaining 4% were at high risk due to the vague definition of novice inclusion. A low risk of bias was reported in 61% of the studies when analyzing the issue of confounding variables, as almost half of the trials included a single-blind experiment. However, in some studies, this was not mentioned or the participants knew the purpose of the experiment, which may have influenced the results because of the Hawthorne effect. Most studies had a low risk of bias for exposure measurement (83%), as most trials provided familiarization with the testing procedures and reported the procedures of the MOT task in detail. Regarding the blinding outcome assessment, usually, testers were not blinded, but in some studies, a second, independent tester provided inter-rater reliability calculations. In cases where this did not occur, we judged the study to be at high risk for blinding outcome assessment. A low risk of bias was found in 91% of the studies. For incomplete outcome data, most studies had a low risk of bias (74%) and often not only reported the final sample, but also provided a clear indication of whether the participants were part of a larger sample of the initially recruited group. Finally, considering selective outcome reporting, almost half of the studies had a pre-registered or pre-published protocol with which to compare manuscripts. Therefore, it was unclear whether the reporting outcome was complete or selective in 39% of the studies. The complete quality scores for each study are presented in the supplemental file (Table S2).

Effect sizes

Athletes vs. non-athletes

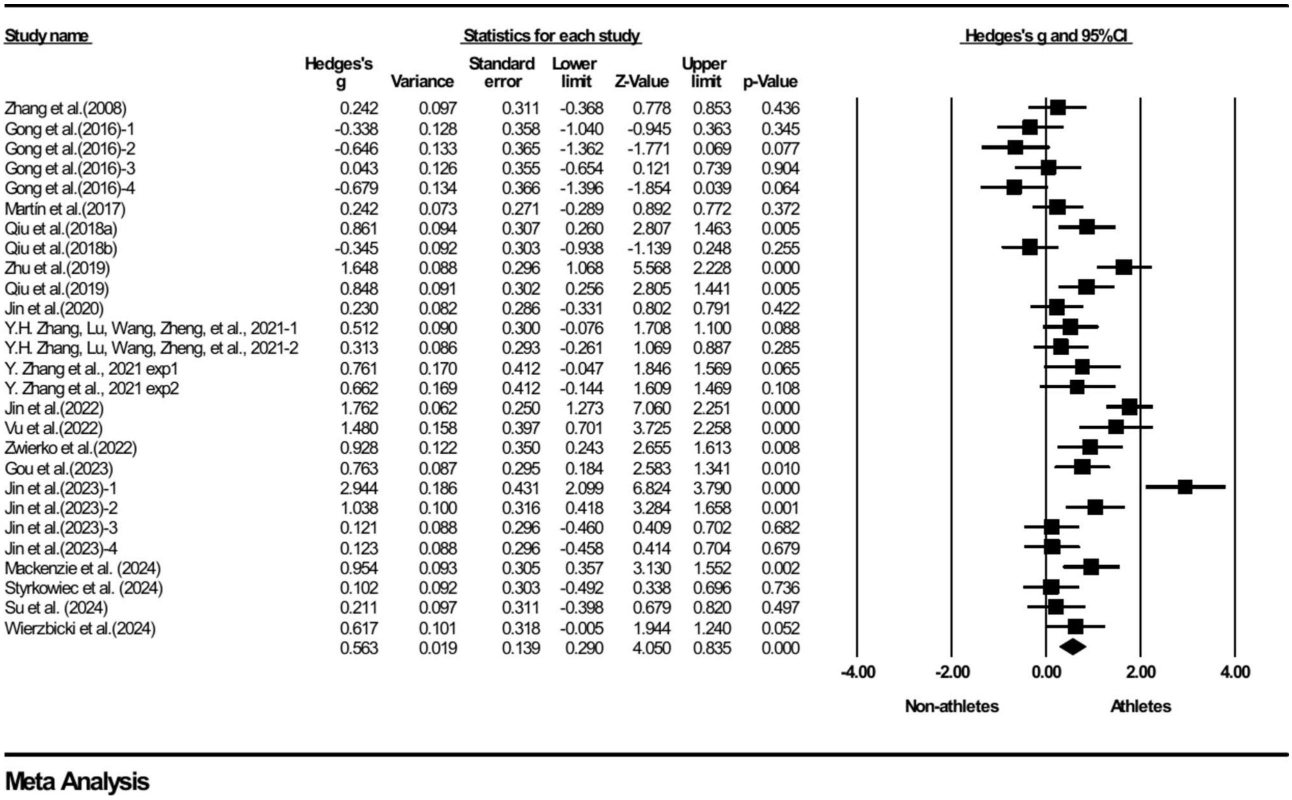
The results of this meta-analysis showed a significant small effect, with a better MOT performance for athletes compared to non-athletes (g = 0.56; 95% CI = 0.29 to 0.84; $p < 0.001$; Fig. 2). There was high heterogeneity in the overall effect ($Q_T = 130.478$, $p < 0.001$, $I^2 = 80.37\%$). No significant bias was detected within Egger's test ($p = 0.993$). Visual inspection of the funnel plots also indicated low publication bias (supplemental file: Fig. S1-A).

Expert athletes vs. novice athletes

The results of this meta-analysis showed a significant moderate effect, with a better MOT performance for expert athletes compared to novice athletes (g = 0.92; 95% CI = 0.45 to 1.39; $p < .001$; Fig. 3). There was high heterogeneity in the overall effect ($Q_T = 60.25$, $p < 0.001$, $I^2 = 83.40\%$). No significant bias was detected within Egger's test ($p = 0.088$). Visual inspection of the funnel plots also indicated low publication bias (supplemental file: Fig. S1-B).

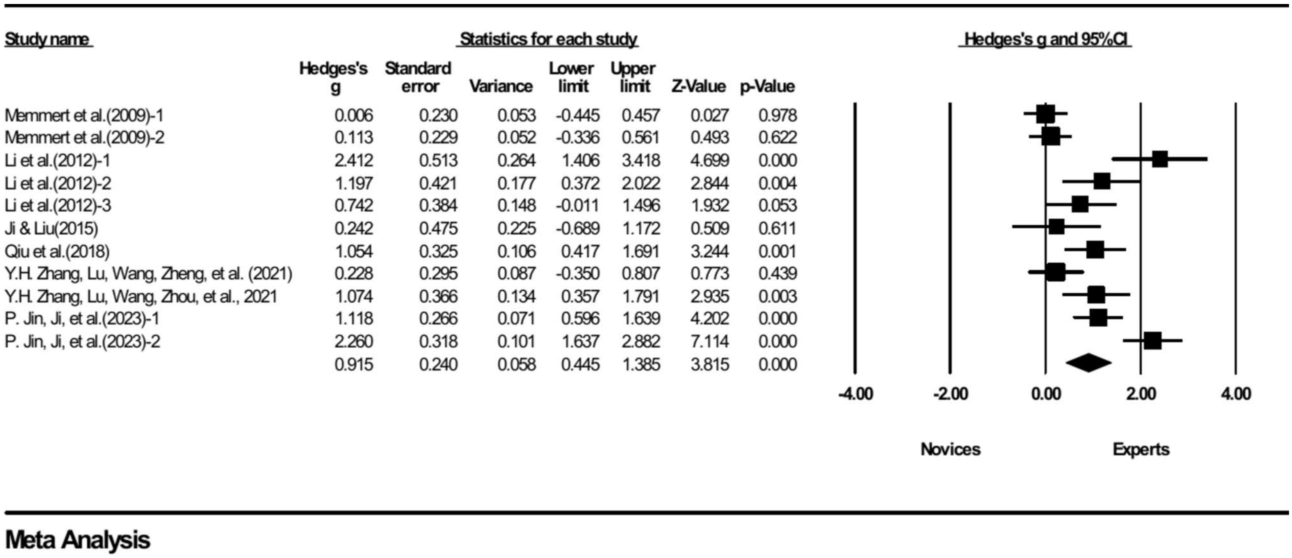
Comparison of the two differences

A comparison of the effect sizes of the difference between athletes and nonathletes and between expert and novice athletes showed no significant difference in the effect sizes ($Q_B = 2.14$, $p = 0.144$).



Study name	Hedges's g	Variance	Standard error	Lower limit	Z-Value	Upper limit	p-Value
Zhang et al.(2008)	0.242	0.097	0.311	-0.368	0.778	0.853	0.436
Gong et al.(2016)-1	-0.338	0.128	0.358	-1.040	-0.945	0.363	0.345
Gong et al.(2016)-2	-0.646	0.133	0.365	-1.362	-1.771	0.069	0.077
Gong et al.(2016)-3	0.043	0.126	0.355	-0.654	0.121	0.739	0.904
Gong et al.(2016)-4	-0.679	0.134	0.366	-1.396	-1.854	0.039	0.064
Martín et al.(2017)	0.242	0.073	0.271	-0.289	0.892	0.772	0.372
Qiu et al.(2018a)	0.861	0.094	0.307	0.260	2.807	1.463	0.005
Qiu et al.(2018b)	-0.345	0.092	0.303	-0.938	-1.139	0.248	0.255
Zhu et al.(2019)	1.648	0.088	0.296	1.068	5.568	2.228	0.000
Qiu et al.(2019)	0.848	0.091	0.302	0.256	2.805	1.441	0.005
Jin et al.(2020)	0.230	0.082	0.286	-0.331	0.802	0.791	0.422
Y.H. Zhang, Lu, Wang, Zheng, et al., 2021-1	0.512	0.090	0.300	-0.076	1.708	1.100	0.088
Y.H. Zhang, Lu, Wang, Zheng, et al., 2021-2	0.313	0.086	0.293	-0.261	1.069	0.887	0.285
Y. Zhang et al., 2021 exp1	0.761	0.170	0.412	-0.047	1.846	1.569	0.065
Y. Zhang et al., 2021 exp2	0.662	0.169	0.412	-0.144	1.609	1.469	0.108
Jin et al.(2022)	1.762	0.062	0.250	1.273	7.060	2.251	0.000
Vu et al.(2022)	1.480	0.158	0.397	0.701	3.725	2.258	0.000
Zwierko et al.(2022)	0.928	0.122	0.350	0.243	2.655	1.613	0.008
Gou et al.(2023)	0.763	0.087	0.295	0.184	2.583	1.341	0.010
Jin et al.(2023)-1	2.944	0.186	0.431	2.099	6.824	3.790	0.000
Jin et al.(2023)-2	1.038	0.100	0.316	0.418	3.284	1.658	0.001
Jin et al.(2023)-3	0.121	0.088	0.296	-0.460	0.409	0.702	0.682
Jin et al.(2023)-4	0.123	0.088	0.296	-0.458	0.414	0.704	0.679
Mackenzie et al. (2024)	0.954	0.093	0.305	0.357	3.130	1.552	0.002
Styrkowiec et al. (2024)	0.102	0.092	0.303	-0.492	0.338	0.696	0.736
Su et al. (2024)	0.211	0.097	0.311	-0.398	0.679	0.820	0.497
Wierzbicki et al.(2024)	0.617	0.101	0.318	-0.005	1.944	1.240	0.052
	0.563	0.019	0.139	0.290	4.050	0.835	0.000

Fig. 2. The effect sizes (Hedges' g) of the MOT performance for athletes compared with non-athletes included in the meta-analysis. 95%CI = 95% confidence interval. The size of the plotted squares reflects the statistical weight of each study.



Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Memmert et al.(2009)-1	0.006	0.230	0.053	-0.445	0.457	0.027	0.978
Memmert et al.(2009)-2	0.113	0.229	0.052	-0.336	0.561	0.493	0.622
Li et al.(2012)-1	2.412	0.513	0.264	1.406	3.418	4.699	0.000
Li et al.(2012)-2	1.197	0.421	0.177	0.372	2.022	2.844	0.004
Li et al.(2012)-3	0.742	0.384	0.148	-0.011	1.496	1.932	0.053
Ji & Liu(2015)	0.242	0.475	0.225	-0.689	1.172	0.509	0.611
Qiu et al.(2018)	1.054	0.325	0.106	0.417	1.691	3.244	0.001
Y.H. Zhang, Lu, Wang, Zheng, et al. (2021)	0.228	0.295	0.087	-0.350	0.807	0.773	0.439
Y.H. Zhang, Lu, Wang, Zhou, et al., 2021	1.074	0.366	0.134	0.357	1.791	2.935	0.003
P. Jin, Ji, et al.(2023)-1	1.118	0.266	0.071	0.596	1.639	4.202	0.000
P. Jin, Ji, et al.(2023)-2	2.260	0.318	0.101	1.637	2.882	7.114	0.000
	0.915	0.240	0.058	0.445	1.385	3.815	0.000

Fig. 3. The effect sizes (Hedges' g) of the MOT performance for experts compared with novices included in the meta-analysis. 95%CI = 95% confidence interval. The size of the plotted squares reflects the statistical weight of each study.

Moderating effect

Athletes vs. non-athletes

The competitive level, type of sport, and type of display were analyzed for the subgroups. Based on previous studies, the athletes included in this study were further categorized into expert and novice athletes. Seventeen effect sizes were reported for expert athletes and ten for novice athletes. The competitive level of the sample had a significant effect on the effect size, Q_B (1) = 10.21, p = 0.001. The effect size for expert athletes vs. non-athletes in the MOT task (g = 0.84, $p < 0.001$; moderate effect; Q_W (16) = 80.15, $p = 0.001$) was significantly higher than that for novice athletes vs. non-athletes (g = 0.07, $p = 0.673$; trivial effect; Q_W (9) = 22.49, $p = 0.007$). Regarding the type of sport, we divided the types of sports into basketball, ice-hockey, handball, and other ball sports. Sports type had no significant effect on effect size Q_B (4) = 4.94, $p = 0.177$. For the display type, only one effect size was reported for 3D display while 74 were reported for 2D displays; therefore, it was not included in the moderating analysis.

The MOT parameters were analyzed using meta-regression. The number of tracked targets ranged from 2 to 6, and had no effect on the effect size (coefficient: -0.01, $p = 0.970$). The number of distractors ranged from 2 to 12, and had no effect on the effect size (coefficient: 0.04, $p = 0.228$). The speed of the targets ranged from 3 to 25.5°/s, and had no effect on the effect size (coefficient: -0.01, $p = 0.689$). The tracking duration ranged from 4s to 12s, and had no effect on the effect size (coefficient: 0.05, $p = 0.094$). Results of the moderating analysis are summarized, with the full values presented in Table 3.

Expert athletes vs. novice athletes

The type of sport was analyzed for each subgroup. Regarding type of sport, we divided the types of sports into basketball, ice hockey, and other ball sports as moderating variables. Sports type had a significant effect on the effect size Q_B (2) = 12.26, $p = 0.002$. The results indicated that sport type had a significant moderating effect on the difference in MOT performance between experts and novices. Further analysis showed that the effect sizes of the basketball (g = 1.46, $p < 0.001$; large effect; Q_W (22) = 107.23, $p < 0.001$) was significant, whereas those of ice hockey (g = 0.41, $p = 0.079$; small effect; Q_W (3) = 6.64, $p = 0.084$) and other ball sports (g = 0.92, $p = 0.081$; moderate effect; Q_W (3) = 35.78, $p < 0.001$) subgroups were not. For the display type, no one effect size was reported for 3D display; therefore, it was not included in the moderating analysis.

The MOT parameters were analyzed using meta-regression. The number of tracked targets ranged from 2 to 8, and had a positive and significant effect on the effect size (coefficient: 0.23, $p = 0.004$). As the number of targets increased, the effect size also increased. The duration of tracking ranged from 1 to 8s, and had a significant negative effect on effect size (coefficient: -0.12, $p = 0.040$). The longer the tracking duration, the smaller the effect size. The number of distractors ranged from 4 to 8, and the speed of targets ranged from 3°/s to 10°/s. However, there was no significant effect size for either the number of distractors (coefficient: 0.18, $p = 0.350$) or speed of targets (coefficient: −0.01, $p = 0.980$). Results of the moderating analysis are summarized, with the full values presented in Table 4.

Discussion

This meta-analysis compared the performance of different populations (athletes, nonathletes, experts, and novices) on MOT tasks. The results highlighted performance differences in MOT tasks among different populations and, importantly, that the magnitudes of these effects depended on population characteristics. The effect size between nonathletes and athletes was not affected by the MOT parameters, whereas the effect size between experts and novices was affected. Although there was great heterogeneity in the methods of exposure stimulation, athletes, particularly experts, displayed superior performances on MOT tasks.

	Subgroup analysis			**Heterogenicity**					
Moderate variable	**k**	**Hedges' g (95%CI)**	***Z***	***p*$_{(z)}$**	**Q_W**	***p*$_{(QW)}$**	**I^2(%)**	**Q_B**	***p*$_{(QB)}$**
Competitive level								10.21	0.001
Expert athletes	17	0.84 (0.51 to 1.17)	5.00	< 0.001	80.15	0.001	80.04		
Novice athletes	10	0.07 (− 0.26 to 0.41)	0.42	0.673	22.49	0.007	59.99		
Type of sport								4.94	0.177
Basketball	43	0.62 (0.42 to 0.82)	6.01	< 0.001	162.45	< 0.001	74.15		
Ice-hockey	6	0.41 (0.13 to 0.69)	2.85	0.004	6.92	0.227	27.70		
Handball	4	0.22 (− 0.08 to 0.52)	1.45	0.147	2.16	0.540	0		
Other ball sports	5	0.42 (0.03 to 0.81)	2.12	0.034	8.84	0.065	54.75		
			Meta-regression						
Moderate variable	**k**	**Coefficient (95%CI)**	**I^2**	***Z***	***p*$_{(z)}$**				
Number of the targets	72	−0.01 (−0.14 to 0.14)	66.11	-0.04	0.970				
Number of the distractors	72	0.04 (−0.03 to 0.11)	65.39	1.21	0.228				
Targets' speed	46	−0.01 (−0.05 to 0.03)	67.99	-0.40	0.689				
Duration of tracking	62	0.05 (−0.01 to 0.11)	67.94	1.68	0.094				

Table 3. Results of the subgroup analysis and meta-regression for moderate variables on athletes and non-athletes. Bolded p values mean significant ($p < 0.05$). k: number of effect size; Hedges' g: standardized mean difference effect size; 95%CI: 95% confidence interval; I^2: percentage of heterogeneity due to study differences; Z: Z-test values; Q_W: heterogeneity within groups; Q_B: heterogeneity between groups.

	Subgroup analysis						Heterogenicity		
Moderate variable	**k**	**Hedges' g (95% CI)**	**Z**	**$p_{(z)}$**	**Q_W**	**$p_{(QW)}$**	**I^2(%)**	**Q_B**	**$p_{(QB)}$**
Type of sport								12.26	**0.002**
Basketball	23	1.46 (1.08 to 1.83)	7.59	< **0.001**	107.23	< **0.001**	79.48		
Ice-hockey	4	0.41(−0.05 to 0.86)	1.76	0.079	6.64	0.084	54.83		
Other ball sports	4	0.92 (−0.11 to 1.94)	1.75	0.081	35.78	< **0.001**	91.62		
			Meta-regression						
Moderate variable	**k**	**Coefficient (95% CI)**	**I^2**	**Z**	**p**				
Number of the targets	32	0.23 (0.07 to 0.39)	80.18	2.86	**0.004**				
Number of the distractors	11	0.18 (−0.20 to 0.55)	80.14	0.93	0.350				
Targets' speed	29	−0.01 (−0.17 to 0.17)	81.95	−0.03	0.980				
Duration of tracking	32	−0.12 (−0.22 to 0.01)	82.46	−2.06	**0.040**				

Table 4. Results of the subgroup analysis and meta-regression for moderate variables on experts and novices. Bolded p values mean significant ($p < 0.05$). k: number of effect size; Hedges' g: standardized mean difference effect size; 95%CI: 95% confidence interval; I^2: percentage of heterogeneity due to study differences; Z: Z-test values; Q_W: heterogeneity within groups; Q_B: heterogeneity between groups.

Overall difference analysis

Consistent with Hypothesis 1a, our study demonstrated athletes have a MOT performance advantage over non-athletes. Compared with nonathletes, athletes demonstrated a significant advantage in MOT task performance (g = 0.56), indicating that sports experience may transfer from a sport-specific task to MOT tasks. This finding is consistent with those of the majority of the studies included, which showed that athletes exhibit superior dynamic visual attention compared to non-athletic university students. Expertise in the sports domain, characterized by dynamically changing, high-paced, and unpredictable scenarios, may be transferred to a more general perceptual-cognitive domain (i.e., MOT)[23]. A previous review suggested that the possible reasons for the benefits of exercise on executive function are either the aerobic hypothesis or the athlete's cognitive demand for exercise itself, both of which have been explored in different ways[88]. In team ball sports, players not only monitor the position and movement of the ball, but also track the positions of opponents and teammates in the field, which are comparable to the cognitive demands of the MOT paradigm[89]. Therefore, it is reasonable to suggest that professional players in ball sports may exhibit superior MOT performance owing to their high demand for wider attention[90]. Harris et al.[11] found that individuals who regularly engaged in object-tracking sports displayed improved tracking performance relative to those engaging in non-tracking sports but reported no differences in gaze strategy. Training on an adaptive MOT task led to improved working memory capacity, but no significant changes in gaze strategy. Consequently, MOT expertise is more closely linked to processing capacity limits than to perceptual-cognitive strategies[11]. Future studies should focus on whether expertise depends on overt visual attention or capacity limitations.

Some studies showed that basketball players do not exhibit superior MOT performance[10,28]. Nevertheless, Gong et al.[28] found that expert athletes had a wider field of vision, gazed longer at blank areas between the tracking targets, and predicted the changing locations of the targets. This indicates that players may be focused not only on the targets but also on the relevant area of their future direction. This tracking strategy may be consistent with real-world sports scenarios. Therefore, researchers should pay attention not only to the differences in task performance but also to the tracking strategies underlying the behavioral that underpin such differences[62]. However, the studies in this review mainly focused on strategic sports, and the moderating effect of sports type was significant. As only basketball played a significant role in this analysis, further research is required to determine whether the effect is significant in non-team ball sports.

Some studies have shown that superior tracking performance in MOT tasks is significantly related to players' training experience[10,23]. Consistent with H1b, the results supported that experts performed better than novice in MOT tasks. Compared with novice athletes, there was a moderate effect for performance advantages of expert athletes (g = 0.92). Experts tend to adopt a chunking strategy during cognitive processing, which, coupled with long-term training, enables them to better adapt to the fast-changing dynamics of sports[27]. The adjustable view of the focus of attention holds posits that the scope of attention can be controlled to either narrow or expand, allowing the focus of attention to range from 1 to 3–5 information blocks[91]. When the number of targets exceeds the attention focus capacity, experts tend to use a chunking strategy, integrating several targets into one information unit to produce one information block, and integrating several other targets into another information unit to produce another information block. Consequently, experts demonstrated a better tracking performance under high-workload conditions. Another plausible explanation is that individuals skilled in tracking multiple objects are more easily drawn to ball sports pursuits and continue to play ball sports, and sports training strengthens their ability to track multiple objects[20,92]. For team sports, many of the required sport skills may be translated into general cognitive domains[93]. This may also account for MOT performance differences between team sports experts and novices. Overall, our results extend previous studies and confirm that expert athletes have better visual tracking abilities than novices. Consequently, H1a and H1b were fully supported.

A comparison of effect sizes between athletes vs. nonathletes and experts vs. novices revealed no significant differences. Thus, H4 was not supported. However, this should not be interpreted as rendering the categorical comparisons meaningless. Imprecision in the criteria used to define athletes as experts or elite threatens the validity of sports expertise research. Recently, a study[94] reinforced the importance of a clear definition of athletes' level, highlighting that athletic success may be explained by different attributes, with athletic level influencing the intervention results. Therefore, it is crucial to consider the effects of comparing different classes of athletes, such as experts, novices, and non-athletes, on outcomes. One possible explanation for the lack of significant differences between the two categories in this study is that experts (i.e., all national first-level athletes or individuals with 10+ years of exercise experience) have a higher athletic level than athletes overall (comprising expert and novice athletes), and novices exhibit a higher athletic level than non-athletes, thereby resulting in similar disparities in athletic levels between these two groups. Thus, experts vs. novices produced an effect size similar to that of athletes vs. non-athletes. This adds to the evidence that competitive levels play an important role in MOT tasks. Interestingly, our results showed that the two classifications are affected by different moderating variables, suggesting that moderating variables may also influence the differences between different classifications. Taken together, future studies should aim to establish more consistent conditions to investigate nonathletes, along with expert and novice players.

Moderator analyses

For athletes vs. non-athletes, competitive level was considered a potential moderator in MOT task performance in the subgroup analysis. Our findings indicated a notable difference in effect sizes between studies involving expert athletes and non-athletes (g = 0.84; $p < 0.001$; moderate effect) compared to those involving novice athletes and non-athletes (g = 0.07; $p = 0.673$; trivial effect). This result supported H2d. Specifically, the higher the competitive level of the athletes, the more obvious the MOT difference between athletes and non-athletes. These results support previous research on the MOT that has consistently shown that expert athletes tend to perform better than intermediate or novice athletes[10]. Overall, our study provides further evidence for the differences in expertise observed between experts and novices.

The present study found a significant moderating effect of sport type (basketball, ice-hockey, and other ball sports) on the difference between expert and novice athletes results. Specifically, the effect size of the difference in MOT performance between basketball was significant (g = 1.46, $p < 0.001$; large effect). This suggests that the difference in MOT performance between basketball experts and novices was even more pronounced compared to other sports. For basketball players, MOT is an important indicator that separates novices from experts. Basketball is a fast-paced team sports game that requires the players to pay attention not only to the movement and position of teammates and opponents at the same time but also to the spatial position of the ball and the field[25]. Basketball players with good tracking abilities can predict and evaluate their athletic performance[15]. In addition, the actual motion scenario of basketball may be better suited for the MOT process than other sports. However, in our investigation of differences in MOT between athletes and nonathletes, the results were not entirely consistent with our hypothesis. H3a was supported, while H2a was not supported. We did not observe that sport type moderated these differences, which may also be associated with variations in competitive level (due to a mix of experts and novices). Nevertheless, further studies that focus on the surveillance of various sports are necessary to confirm these findings.

Regarding the MOT task parameters, first, compared with athletes and nonathletes, the difference in effect size between experts and novices was more subject to be moderated by the parameter settings of the MOT task (e.g., number of targets and duration of tracking). This is not exactly the same as our assumption that the parameters can significantly modulate both the two comparison groups. H3b was partially supported. Specifically, for the difference between experts and novices, we found that the larger the number of targets tracked, the greater the difference in effect size. This indicates that experts have a broader ability to focus on more targets than novices. Previous research has shown that the effects of expertise in team ball sports transferring to visual attention tracking tasks occur only in elite athletes with extensive training under higher attentional load[10]. According to the flexible resource theory[95], tracking is mediated by a finite attentional resource distributed among the targets. The number of objects that could be tracked would be inversely related to the resource demands for each individual object[37]. When tracking more targets, professional athletes allocated less attentional resource to each target than novice athletes, thereby professional athletes could track more targets with a limited pool of resources. In contrast, when tracking fewer targets, both experts and novices had sufficient resources for each set of targets to process information precisely. In addition, we found that with an increase in the duration of tracking, the difference in the magnitude of the effect between expert and novice athletes was significantly reduced. Perhaps because the situation on the sports field changes frequently, the tracking time is usually short and phased. Expert athletes need to keep tracking in a particular situation and change the tracking target when the situation changes; therefore, their advantages are reflected more in relatively short tracking. However, the effects of the MOT parameters were significant only between experts and novices, but not between athletes and non-athletes. H2b was not supported. This could be because the difference in competitive level between athletes and nonathletes was not very large (as athletes included experts and novices), while novices and nonathletes had small differences in MOT performance (g = 0.07, $p = 0.673$; trivial effect), resulting in a small overall effect size, and it was not easy to observe the moderating effect.

Unfortunately, due to the insufficient number of articles on 3D-MOT included in our study, a subgroup analysis of the moderating variable display type was not conducted. Therefore, H2c and H3c were not tested. However, exploring this factor remains meaningful. A comparative study of 2D-MOT and 3D-MOT found that soccer players were more efficient at visual tracking in 3D virtual reality dynamic tracking tasks and that the longer their professional sports experience, the better their tracking performance in 3D dynamic tracking tasks[86]. This suggests that differences may also be influenced by sports levels. The movement of objects in a real three-dimensional space at different depth positions is continuous rather than confined to different depth planes.

Moreover, current 3D-MOT tests typically use a staircase procedure[7], where the speed increases if the participant successfully tracks all targets and decreases if at least one target is missed. Speed thresholds in this procedure are determined using a one-up one-down method[7]. In contrast 2D-MOT usually employs a fixed speed and uses ACC as an outcome measure. Future research could focus on more other factors as moderating factors, not only 3D display but also staircases and field of view in 3D-MOT. Future studies also should include 3D-MOT interventions in athletes to gain deeper insight. Romeas et al.[7] demonstrated that 3D-MOT training could improve the accuracy of soccer-passing decisions. However, one review questioned the effectiveness of 3D-MOT training[96].

Recently, to make the 3D-MOT evaluation and training more effective, 3D-MOT has become more ecological in the field of virtual reality. Ehmann et al.[85,97] proposed a 360-degree alternative to the classical tracking task, with humanoid avatars running on a curved screen surrounding the observer. They validated the use of their tool to assess visuospatial performance in a visual tracking task[97] and discriminated the effect of expertise in young soccer players[85]. Vu et al.[63] used a multiple-soccer player tracking task in virtual reality to compare the visual tracking performance of soccer players and non-soccer players perceiving virtual players moving along real games or pseudo-random trajectories. Yet the results indicate that the use of soccer-specific trajectories may not be sufficient to replicate the representativeness of field conditions in a study on visual tracking performance. Future research should focus on the ecological application of 3D-MOT in various sports.

Limitations

Our results showed no support for a publication bias either when comparing the overall effect of athletes vs. nonathletes or experts vs. novices. Therefore, in the context of the existing statistical and methodological tools, it seems reasonable to assume that publication bias is not an issue. However, a more definite answer could be provided by recent initiatives for better scientific practices, including mandatory usage of open data repositories for all published studies[98]. Although the narrow inclusion criteria (e.g., the inclusion of studies involving athletes compared to nonathletes and experts compared to novices) helped reduce the risk of bias, it also produced certain limitations. Numerous studies on various team sports with large sample sizes and comprehensive data were excluded because they examined athletes exclusively or did not report sufficient data. This reduced the data in our meta-analysis, thereby weakening the evidence base, especially for team sports other than basketball. Among the 23 studies selected, 10 included basketball players as participants; therefore, basketball dominated the sample and results of our study. This may have impacted the moderating variable of sport type, which could potentially bias conclusions for team sports in general. This highlights the pressing need for further research in other sports to address this issue.

Another limitation was the heterogeneity of the estimates. The heterogeneity of the main effects in athletes vs. non-athletes ($I^2 = 80.37\%$) and experts vs. novices ($I^2 = 83.40\%$) both exceeded 75%, showing that there was a lot of dispersion in the results. Furthermore, although several moderators were tested for their potential influence on differences, there might have been other influencing factors not considered in our meta-regression because of a lack of information. For example, Ehmann et al.[85] demonstrated different MOT task performance levels among different age groups. Legault et al.[6] reported differences in MOT performance patterns between male and female athletes. Previous studies have found that visuospatial working memory can significantly predict MOT performance[99], and 3D-MOT is also significantly correlated with visuospatial working memory[97]. Future studies should consider the moderating effects of age, gender, visuospatial working memory, etc. In addition, our study included few individual sports, and future studies should consider both individual and team sports.

Conclusion

This meta-analysis provides evidence of superior performance in athletes, especially in higher-level athletes, on MOT tasks. Our results support the superior perceptual cognitive ability of athletes vs. non-athletes and experts vs. novices. Moreover, the difference in effect size between non-athletes and athletes was moderated by the athletes' competitive level. Similarly, the difference in the effect size of the MOT performance between experts and novices was influenced by the type of sport. Adjusting the parameters of the MOT task, such as the number of targets and the tracking duration, affected the difference in effect size between experts and novices, but did not influence the difference between athletes and non-athletes. Future studies should include a wider variety of sports; more clearly classify participants' sports levels, such as experts, novices, and non-athletes; and compare MOT performance between different age groups (such as high school athletes and peers) and genders.

Data availability

All relevant data are within the manuscript and its supplemental files.

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Author contributions

H.J.L. did the study conception and design, data collection, statistics, and writing; Q.Z. helped the study data collection, statistics, and writing; JL and YZ participated in study conception and design and writing; S.C. helped with the data collection and re-check data. J.L. and Y.Z. contributed equally to this work and should be considered co-coresponding authors. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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Competing interests

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Additional information

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