Université de Montréal

Évaluation multi-domaine des fonctions cognitives chez les athlètes de haut niveau selon l'influence de l'expertise, du type de sport et du sexe

Par

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Résumé

Les études publiées à ce jour ont mis en évidence des capacités cognitives supérieures chez les athlètes élites dit « experts » comparativement à la population générale, notamment les fonctions exécutives (FE). Toutefois, des études récentes ont remis en question cette supériorité cognitive et les recherches incluant des athlètes issus de différents types de sport ont rapporté des résultats contradictoires. De surcroît, les athlètes féminines sont sous-représentées dans les études mesurant la cognition, ce qui souligne la nécessité de s'y intéresser davantage. Cette étude visait donc à comparer l'impact de l'expertise sportive, du type de sport et du sexe sur divers domaines des fonctions cognitives.

Deux cent trente athlètes d'élite (Femme, n=124 ; Homme, n=106) représentant trois catégories de sport (sports d'équipe [*Team*][n=91], de précision et d'habileté [*Precision/skill-dependent*] [n=63], et de vitesse et de force [Speed/strength] [n=76]) ont participé à des évaluations cognitives à l'aide d'une batterie de tests neuropsychologiques informatisés (Vienna Test System, Schuhfried). Les évaluations comprenaient des tests mesurant les FE (flexibilité cognitive, planification, inhibition, mémoire de travail) ainsi que des tests d'attention sélective et soutenue. Les performances aux tests ont été mesurées à l'aide des scores T et des valeurs brutes du temps de réaction et de la précision.

Les athlètes ont obtenu de meilleures performances ($p < 0,004$) par rapport aux normes dans 7 des 11 variables des tests cognitifs. Il est intéressant de noter que les performances des athlètes sont restées dans la moyenne de la population générale pour presque toutes les fonctions cognitives si l'on considère leurs résultats sur une échelle normative, à l'exception de l'attention soutenue pour laquelle ils ont obtenu des résultats justes au-dessus de la haute moyenne (+1 écart-type). Il n'y a pas eu d'effet principal significatif de la catégorie sportive après correction pour les comparaisons multiples. De plus, seulement un effet principal significatif du sexe sur les mesures du temps de réaction motrice a été montré pour l'attention sélective ($p < 0,001$) et soutenue ($p < 0,001$), où les hommes ont obtenu des performances plus rapides que les femmes.

À l'exception de l'attention soutenue, « l’avantage cognitif » des experts était moins évidant lors de l’utilisation d’une échelle normative dans cet échantillon. La performance des athlètes aux tâches cognitives étaient similaire à celle de la population normale, ce qui soulève davantage de questions sur l'étendue du lien entre l'expertise sportive et les performances aux tests cognitifs. De même, le type de sport ne semblait pas avoir d'influence sur les fonctions cognitives dans notre échantillon. Bien que les hommes aient répondu plus rapidement que les femmes dans les tâches d'attention liées au temps de réaction moteur, cette étude n'a pas révélé d'autres différences de fonctionnement cognitif entre les sexes. L'implication des tests neuropsychologiques pour identifier le profil cognitif des athlètes est discutée.

Mots clés : cognition ; fonctions exécutives ; attention ; expertise ; identification de talent

Abstract

Consistent evidence has shown that cognitive abilities, especially executive functions (EF), tend to be superior in sport experts. However, recent studies have questioned this cognitive advantage. Additionally, research on cognitive performance across different sport types has yielded inconsistent findings. There is also a notable underrepresentation of female athletes in cognitive studies, emphasizing the need for further attention. Therefore, this study aimed to compare the impact of sport expertise, sport type, and gender on various domains of cognitive functions.

Two hundred and thirty elite athletes (n_{Female}=124, n_{Male}=106) representing three sport categories (Team [n=91], Precision-skill dependent [n=63], and Speed-strength [n=76] sports) underwent cognitive assessments using a computerized neuropsychological test battery (Vienna Test System, Schuhfried). The assessments encompassed tests of EF (cognitive flexibility, planning, inhibition, working memory), as well as tests of selective and sustained attention. Test performance was measured using T-scores and raw values of reaction time and accuracy.

Athletes achieved a better performance ($p < 0.004$) compared to normative values in 7 out of 11 cognitive test variables. Interestingly, the performance of athletes remained in the average range of the general population for almost all cognitive functions considering their results along a normative scale, except for sustained attention where they performed just above the high average range (+1 SD). There was no significant main effect of sport category after correcting for multiple comparisons, and only a significant main effect of sex on motor reaction time measures of selective ($p < 0.001$) and sustained ($p < 0.001$) attention, where males performed faster than females.

Except for sustained attention, the apparent 'expert advantage' on general cognitive tests was less prominent when utilizing a normative scale. This indicates that athletes' cognitive functions fell within the range of the normal population, raising further questions about the extent of the link between sport expertise and cognitive test performance. Similarly, sport type did not seem to show any influence on cognitive functions such as EF and selective attention in our sample. Although males responded faster than females in motor reaction time tasks of attention, this study did not reveal any other sex differences in cognitive functioning. The implication of neuropsychological tests for identifying athletes' cognitive profile is discussed.

Keywords: cognition; executive functions; attention; expertise; talent identification

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Liste des sigles et des abréviations

DT-S1	Determination Test (sous-test 1)
EF	Executive function (fonction exécutive)
e.g.	For exemple
FRQNT	Fond de recherche Nature et technologie du Québec (FRQNT)
i.e	That is
INHIB-S9	Response inhibition (sous-test 9)
INS Québec	Institut National du Sport du Québec
M	Mean (Moyenne)
MDT-S2	Movement Detection Test (sous-test 2)
ms	Milisecondes
NBN-S1	N-Back Non-Verbal (sous-test 1)
η^2	Eta-squared
PRIDI	Programme de Recherche, d'Innovation et de Diffusion de l'Information
s	Second (seconde)
SD	Square deviation (Écart-type)
SIGNAL-S4	Signal Detection (sous-test 4)
TOL-S11	Tower of London – Freiburg Version (sous-test 11)

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Article

Multi-domain assessment of cognitive functions in elite athletes: contrasting evidence for the influence of expertise, sport type and sex

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Abstract

Consistent evidence has shown that cognitive abilities, especially executive functions (EF), tend to be superior in sport experts. However, recent studies have questioned this cognitive advantage. Additionally, research on cognitive performance across different sport types has yielded inconsistent findings. There is also a notable underrepresentation of female athletes in cognitive studies, emphasizing the need for further attention. Therefore, this study aimed to compare the impact of sport expertise, sport type, and gender on various domains of cognitive functions. Two hundred and thirty elite athletes (n_{Female}=124, n_{Male}=106) representing three sport categories (Team [n=91], Precision-skill dependent [n=63], and Speed-strength [n=76] sports) underwent cognitive assessments using a computerized neuropsychological test battery (Vienna Test System, Schuhfried). The assessments encompassed tests of EF (cognitive flexibility, planning, inhibition, working memory), as well as tests of selective and sustained attention. Test performance was measured using T-scores and raw values of reaction time and accuracy.

Athletes achieved a better performance ($p < 0.004$) compared to normative values in 7 out of 11 cognitive test variables. Interestingly, the performance of athletes remained in the average range of the general population for almost all cognitive functions considering their results along a normative scale, except for sustained attention where they performed just above the high average range (+1 SD). There was no significant main effect of sport category after correcting for multiple comparisons, and only a significant main effect of sex on motor reaction time measures of selective ($p < 0.001$) and sustained ($p < 0.001$) attention, where males performed faster than females.

Except for sustained attention, the apparent 'expert advantage' on general cognitive tests was less prominent when utilizing a normative scale. This indicates that athletes' cognitive functions fell within the range of the normal population, raising further questions about the extent of the link between sport expertise and cognitive test performance. Similarly, sport type did not seem to show any influence on cognitive functions such as EF and selective attention in our sample. Although males responded faster than females in motor reaction time tasks of attention, this study did not reveal any other sex differences in cognitive functioning. The implication of neuropsychological tests for identifying athletes' cognitive profile is discussed.

Keywords: cognition; executive functions; attention; expertise; talent identification

1. Introduction

Besides physical and technical abilities, cognition is recognized as a crucial component of sport performance and has received a lot of attention lately. Four meta-analyses found that higher sport expertise was associated with better cognitive performance when participants were tested on computerized neuropsychological tasks within a laboratory setting (Kalén et al., 2021; Logan et al., 2022; Scharfen & Memmert, 2019; Voss et al., 2010). More specifically, original studies reported athletes superiority in cognitive domains related to executive functions (EF) including cognitive flexibility, working memory, and inhibitory control (Alves et al., 2013; Elferink-Gemser et al., 2018; Holfelder et al., 2020; Vaughan & Laborde, 2020; Verburgh, Königs, et al., 2014; Vestberg et al., 2012, 2017), as well as attention, visuospatial attention and processing speed (Alves et al., 2013; Faubert, 2013; Gou & Li, 2023; Qiu et al., 2018; Vaughan & Laborde, 2020; Zhang et al., 2009). Furthermore, prior observations have demonstrated direct positive correlations between on-field performance and scores in EF assessed through laboratory-based tasks (Cona et al., 2015; Trecroci et al., 2021; Vestberg et al., 2012, 2017). These findings were mostly based on the rationale that: 1) physical activity enhances the development of cognitive functions through a neurotrophic cascade leading to neuroplasticity (Kramer et al., 1999), and/or that 2) the cognitive demand of sport requires high level cognitive functioning (e.g., attention, planning, decision making) which implies that better on-field performance is tied to better cognitive performance (Vestberg et al., 2012).

However, recent studies have started to provide mixed evidence and have suggested multiple biases in the literature. In their umbrella review including 24 meta-analyses limited to randomized control trials, Ciria et al. (2023) found a negligible effect of physical exercise on cognitive functions after controlling for methodological and publication bias. In addition, other studies found that the development of EF in elite adolescent soccer players was not different from that of the general population (Beavan, Chin, et al., 2020; Beavan, Spielmann, et al., 2020). Similarly, Radke et al. (2023) demonstrated that when controlling for age, cognitive performance was no longer a predictor of athletic performance in elite soccer athletes. In a recent critical review, Furley et al. (2023) raised several concerns relative to the magnitude of previously reported effects, small sample sizes, validity and heterogeneity of the cognitive tests used, risks of experimenter effects, publication bias, and rapid adoption of cognitive evaluations for talent identification in sports. Therefore, more robust empirical studies are required in this field.

Besides comparing sport experts to lower-skilled groups, researchers have also started to look at the influence of the type of sport on cognitive functions. Based on the assumption that physiological, or technical and cognitive demands differ between sports (e.g., soccer player vs wrestler), studies have assessed whether sport types shape the cognitive profile of athletes. For example, a previous study observed that volleyball athletes performed better on tasks measuring visual attention and motor inhibition compared to badminton athletes (Meng et al., 2019).

According to the authors, these findings were mostly attributed to the specific characteristics of volleyball practice, which was suggested to involve more complex cognitive processes compared to badminton. On the contrary, Logan et al. (2022) demonstrated in their meta-analysis that the cognitive advantage of athletes, as reflected in cognitive test performance, was primarily attributed to aerobic sports and team-based sports involving high-intensity interval training. When examining the broader body of literature, a lot of mixed results have been reported (Bravi et al., 2022; Chang et al., 2017; Contreras-Osorio et al., 2022; De Waelle et al., 2021; Gu et al., 2019; Heilmann et al., 2022; Koch & Krenn, 2021; Krenn et al., 2018; Ong, 2017; Reigal et al., 2022; Russo et al., 2022; Sato et al., 2022; Spanou et al., 2022; Wang et al., 2013; Yongtawee et al., 2017, 2022), with one major confounding factor being the type of sport classification that was used to group sports into categories. In fact, sport classification clarity and complexity can vary whether it is based on the physiological, technical and/or cognitive demand of the sport. For example, in studies where sports were classified as closed-skill (i.e., internally-paced, predetermined movement, stable environment) or open-skill (i.e., externally-paced, changing movement solutions and environment) (Allard & Burnett, 1985; Singer, 2010), the results consistently indicated that athletes in open-skill sports performed better on EF tasks, particularly in terms of inhibitory control, compared to those in closed-skill sports (Heilmann et al., 2022; Wang et al., 2013). On the other hand, when sports were classified as static (i.e., self-paced), interceptive (i.e., coordination between body part – object – environment), and strategic (unpredictable situations during team sports) (Mann et al., 2007; Voss et al., 2010), results were more difficult to interpret. For instance, while some studies found an advantage for athletes of strategic sports over the others in EF and visual attention (Krenn et al., 2018; Meng et al., 2019), a meta-analysis showed that those practicing interceptive sports performed better in information processing speed and attention paradigms (Voss et al., 2010). To summarize, existing literature presents mixed findings regarding the impact of sport type on athletes' cognitive performance, leaving it unclear whether specific sport demands significantly shape an athlete's cognitive profile.

Additionally, it is not well understood whether sex influences the outcomes on cognitive performance in sports. This is mainly due to research on cognitive functions mirroring the general trend of underrepresentation of female participants in sport sciences (Costello et al., 2014; Cowley et al., 2021). In fact, most studies on cognitive performance have been conducted only in male participants, with conclusions mostly applicable to this group, despite rare efforts from researchers to include female participants (Beavan et al., 2022). Transposing conclusions based solely on one group can lead to generalization of results and misinterpretation. For example, Voss et al. (2010), authors of one of the most influential meta-analysis in the field, reported that among the sample of 694 participants included in their meta-analysis, 63.7% were males. Alarmingly, 25.4% of the included studies did not provide information on participants' sex, leaving the representation of females at only 10.9%. In addition, past research involving healthy adults has presented inconsistent findings regarding the impact of sex on cognitive functions. Some studies have shown better performance in males (Brown et al., 2002; Keith et al., 2008; Voyer et al., 2017), while others suggested better performance in females (Keith et al., 2008). Overall, the prevailing trend supports the gender similarities hypothesis (Hyde, 2014). In the athletic population, studies involving both male and female participants have reported comparable performance levels on selective attention (Alves et al., 2013), visual attention (Jin et al., 2022), and EF (Vestberg et al., 2012). Similar results in EF were observed in the military (Jamro et al., 2022). Nevertheless, Voss et al. (2010) showed higher cognitive performance in male athletes compared to female athletes, whereas Ong (2017) demonstrated that female athletes outperformed male athletes in measures of cognitive flexibility.

Therefore, it is relevant to conduct further research to examine the moderating role of sex on cognitive performance in sports.

As described above, the literature reports numerous inconsistent findings on the relationship between cognition, sport expertise, sport type, and sex. Many of these inconsistencies can be attributed to methodological limitations such as small sample size, lack of standardization in expertise and sport classification, variability in the tests utilized, experimenter effects as well as underrepresentation of female participants. Considering these limitations, the present study sought to comprehensively evaluate various domains of cognitive functions in a substantial sample of elite athletes, considering their level of expertise, sport category, and sex as variables. The first objective aimed to compare elite athletes' performance with a normative group representing the general population on computerized neuropsychological tests assessing EF (working memory, inhibition, cognitive flexibility, planning) and attention (selective, sustained). Based on prevalent evidence, it was anticipated that elite athletes would outperform the normative group. The second objective sought to compare the cognitive performance of elite athletes across different sport types and sex. Based on the concept of sport-specific demands, it was expected that athletes from various sport categories (Team sports, Precision/skill-dependent sports, and Speed-strength sports) would demonstrate differing performances. Despite the mixed evidence of previous studies in the athletic population regarding the influence of sex on cognitive performance, it was anticipated that elite female and male athletes would exhibit a similar level in this area.

2. Methodology

2.1. Participants

A total of 230 athletes (n_{Female} = 124, n_{Male} = 106; Mean age ± SD: 21.22 ± 3.51 years) from a Canadian national sport institute were included in this retrospective study. Five participants were excluded from the original database, which initially consisted of 235 individuals, as it was impossible to ascertain their sex and sport identification. The athletes' average level of sport expertise was defined as "Elite/International Level" (Tier 4) according to the Participant Classification Framework (McKay et al., 2022). The education level of the participants was categorized as: < 9 (1.3%), 9-10 (7.0%), 10-12 (40.0%), 12-13 (40.0%), and > 13 (11.7%) years of schooling. The study received ethical approval from the Comité d'Éthique de la Recherche en Éducation et en Psychologie (CEREP) of the Université de Montréal.

2.2. Sport categories

The athletes in the sample represented seven distinct sports, which were organized into three categories utilizing the sport classification system presented by Mckay et al. (2022) (Table 1). The categorization was determined by considering specific physiological demands, tactical components, and skill requirements of each sport. This particular classification was chosen for its clear criteria, aiding in a more accurate classification of sports based on various attributes, including cognitive demand. The three categories examined in this study were Team sports, Precision/skill-dependent sports, and Speed/strength sports.

INSERT TABLE 1 ABOUT HERE

2.2. Cognitive tests

The computerized neuropsychological tests were conducted in a quiet room at the training center's medical clinic by two proficient sport neuropsychologists. Data collection was consistently carried out during the athletes' preseason medical assessments spanning from 2013 to 2021 using the same battery of tests. The assessments were scheduled during specific periods: between March and April for winter sports (short track speed skating, figure skating) and between September and October for summer sports (water polo, American football, diving, artistic swimming, trampoline).

To mitigate familiarization bias, data from the athletes' initial exposure to the neuropsychological tests were exclusively utilized, particularly if they underwent preseason evaluations annually. Athletes who had experienced a concussion within three months preceding the evaluation were excluded from the data collection. Test administration and sequencing were standardized across all participants and typically lasted around one hour, breaks included. Some participants were unable to complete certain tasks due to tardiness or time constraints during the session. For a comprehensive account of missing data, please refer to Table 4 in the supplementary material.

2.3. Cognitive tests

The cognitive functions of the participants were assessed using the Vienna Test System (Schuhfried GmbH, Moedling, Austria), a validated computerized neuropsychological test battery (Gierczuk et al., 2012; Gierczuk & Ljach, 2012; Gonçalves e al., 2017; Gröpel et al., 2014; Khani et al., 2012; Kiss & Balogh, 2019; Ong, 2015, 2017; Schumacher et al., 2018). The psychometric qualities of this battery were previously found to be acceptable (Gierczuk & Ljach, 2012). Six specific cognitive tests from the Vienna Test System were utilized to assess multiple cognitive functions. For each test, two variables were chosen to evaluate performance, aiming to consider accuracy and reaction time to control for potential speed-accuracy trade-offs. This approach ensured a comprehensive assessment of cognitive performance.

Executive functions

Working memory. Working memory capacity was measured using the NBN-S1 task (Schelling et al., 2009). In this n-back task, participants were presented with abstract shapes one at a time on a screen and were instructed to press a button as quickly as possible if the current shape resembled the shape presented two positions earlier. The test took approximately nine minutes to complete. The variables considered for analysis were the number of correct answers (accuracy) and the mean time for correct answers (reaction time in s). Norms were based on 311 healthy individuals from the general population, aged between 15.8 and 84.1 years. It is important to mention that 161 participants were missing in the working memory task due to its later introduction in the evaluation process (for additional information, see Supplementary material).

Inhibition. Inhibition capacity was assessed using the INHIB-S9 test (Kaiser et al., 2010). During this task, participants were instructed to press the keyboard number '5' swiftly when an upward-pointing triangle was displayed on the screen and press '6' when a triangle pointed downward. However, if a circle appeared, participants were to refrain from pressing any key. The test took approximately eight minutes to complete. The variables considered for analysis were the number of commission errors (accuracy) and the mean reaction time for correctly processed stimuli (s). Norms were based on 378 healthy individuals from the general population, aged between 16.0 and 84.4 years.

Cognitive flexibility. Cognitive flexibility was evaluated using the DT-S1 test (Neuwirth & Benesch, 2012). In this task, participants were required to respond using both their hands (keyboard) and feet (pedals) to visual and auditory stimuli under high pressure conditions. On the screen, 10 circles changed color in a random order (red, green, blue, white, and yellow). Participants had to press the keyboard button corresponding to the color of the circle displayed. Additionally, rectangular shapes would appear randomly on either the left or right side of the screen. Participants were instructed to press the left pedal if the stimulus was on the left and the right pedal if the stimulus was on the right. Simultaneously, high or low tones were played, and participants had to press the black button for low tones and the gray button for high tones. The stimuli's speed varied based on the athlete's performance according to an adaptive staircase. The total administration time for the test was six minutes. The variables collected were the number of correct answers (accuracy) and the median reaction time (s). Norms were based on 759 healthy individuals from the general population, aged between 14.6 to 88.7 years.

Planning. Planning abilities were evaluated using the TOL-f test (Kaller et al., 2016). In this task, a "model" was displayed on the screen, representing a platform with three bars placed side by side. Marbles of various colors and configurations were to be inserted into these bars. Before the participant could start reproducing the model, the marbles were arranged in a specific configuration on the participant's platform. The participant then had to move certain marbles, aiming to complete the task in the least amount of marble movements possible while following the rules. The task had an administration time of eight minutes. Planning performance was assessed based on two accuracy measures. The first was the number of four to six-move items solved in the minimum number of moves, providing a measure of planning accuracy (accuracy 1). The second was the total number of correct solutions, offering a secondary accuracy measure for the task (accuracy 2). Norms were based on 269 healthy individuals from the general population, aged between 16 and 84 years.

Attention

Selective attention. The MDT-S2 task (Schelling, 2016) was used to assess selective attention. In this task, a small ball rapidly moved towards one of the four corners of the screen, each identified by a distinct color. The participant's objective was to promptly identify the direction of movement and press the corresponding-colored button (red, blue, yellow, or green) associated with that corner. The task was completed in a total of six minutes. Two variables were collected for analysis: median reaction time (reaction time 1 in ms) and motor time (reaction time 2 in ms). Norms were based on data from 492 healthy individuals from the general population, with ages ranging from 16.3 to 84.7 years.

Sustained attention. The SIGNAL-S4 test (Schuchfried, 1992) was employed to assess sustained attention. During the test, participants were required to press a button as swiftly as possible upon the appearance of the target stimulus (e.g., a constellation of square dots) within a field of randomly arranged dots that emerged and vanished. The test duration was approximately 17 minutes. Two variables were used for analysis: median detection time (s) and the count of correct responses (accuracy), categorized into immediate (when the stimulus was still visible on the screen) and delayed (when the stimulus disappeared but within a specified interval) reactions. Norms were based on data from 380 healthy individuals from the general population, aged between 17.7 and 83.4 years.

2.4. Statistical analyses

To compare athletes' performance with normative values from the general population, T-scores were used for every variable of each cognitive test. T-scores were automatically computed by the Vienna Test System and exported in a CSV format for further analysis. Notably, T-scores were not available for the reaction time variable of the DT-S1 test. Thus, a total of 11 variables were considered for this analysis.

To assess the deviation from the normative sample mean value (M=50, SD=10, 95% CI), eleven one-sample Student t-tests were conducted using the means of athletes' T-scores for each variable. The alpha threshold was adjusted for multiple comparisons ($p < 0.005$). Effect sizes were reported using Cohen's d, with approximately 0.2 denoting a small effect, around 0.5 indicating a medium effect, and approximately 0.8 signifying a large effect (Cohen, 1988). Furthermore, means of T-scores for each variable were compared with the normative values of the general population using a normative scale commonly applied in clinical settings.

To analyze the influence of sport category and sex on cognitive performance, a two-way ANOVA was conducted using the raw scores of the 12 test variables. The analysis incorporated between-subject factors: Sport category (Team, Precision/skill-dependent, Speed/strength) and Sex (Female, Male). Age was not considered as a covariate in this analysis due to the similarity in age among the participants and groups. An adjusted alpha threshold was set at $p < 0.004$ to account for multiple comparisons. In case of significant interactions, Bonferroni corrections were applied for the multiple comparisons. Effect sizes were reported using Eta-squared (η^2), which characterizes the magnitude of the associated effect concerning the null hypothesis. Specifically, a threshold of < 0.01 denoted a weak effect, < 0.06 signified a moderate effect, and < 0.14 indicated a large effect. All statistical analyses were performed using IBM SPSS v. 25 software.

3. Results

3.1. Cognitive test performance in elite athletes compared to normative values

The one-sample t-tests conducted between the T-score means of athletes and the normative mean indicated significant differences (all $p < 0.005$) in 8 out of 11 variables. Athletes exhibited superior performance compared to the normative mean in 7 of these variables and performed less effectively in inhibition test accuracy (Table 2). Athletes' performance and normative values did not differ for working memory (NBN-S1 reaction time variable), planning (TOL-S11 accuracy variable), and selective attention (MDT-S2 cognitive reaction time).

INSERT TABLE 2 ABOUT HERE

T-score comparisons to the normative scale revealed that athletes performed within the average range of normative values on the majority of cognitive tests. The normative values used has a mean of 50 with a SD of 10. However, in sustained attention (SIGNAL-S4), athletes scored slightly above average on both the accuracy variable (M=57.08) and the reaction time variable (M=57.36) (Figure 1).

INSERT FIGURE 1 ABOUT HERE

3.2. Effect of Sport category and Sex on cognitive test performance

No significant interaction between Sport Category and Sex were found (Table 3). There was no significant main effect of Sport Category on any tests after correcting for multiple comparisons (all $p > 0.004$). It should be noted that a trend was observed ($p < 0.05$) for inhibition (INHIB-S9 reaction time variable), cognitive flexibility (DT-S1 accuracy variable), and selective attention (MDT-S2 motor reaction time variable).

There was a large significant main effect of Sex on selective attention (MDT-S2 reaction time variable; $F[2,222]=0.140$, $p < 0.001$, $\eta^2=0.119$). Post-hoc analysis showed that males (M=0.162, 95%CI=[0.155-0.169]) performed about 24 ms faster than females (M=0.186, 95%CI=[0.181-0.191]). Additionally, there was a moderate significant main effect of Sex on sustained attention (SIGNAL-S4 reaction time variable; $F[2,218]=0.324$, $p < 0.001$, $\eta^2=0.056$). Post-hoc analysis showed that males performed about 70 ms faster (M=0.774, 95%CI=[0.742-0.805]) than females (M= 0.844, 95%CI=[0.822-0.867]). There was no other significant effect for the other test variables.

INSERT TABLE 3 ABOUT HERE

4. Discussion

4.1. Impact of sport expertise on cognitive test performance

Findings revealed that athletes scored generally higher than the normative mean on most of the cognitive tests (7 out of 11 variables) which is in line with previous findings. However, when comparing the T-scores using a normative scale typically utilized in clinical settings, this effect remained robust only for sustained attention where athletes performed at the high average range (+1 SD). These results partially contradict our main hypothesis, which anticipated a pronounced cognitive advantage in sport experts, as observed in numerous previous studies. Upon closer examination of studies reporting data using normalized scores similar to ours, results from the present study still deviate from the existing literature, albeit to a lesser degree. For example, Vestberg et al. (2012) reported above average (+1-2 SD) and high average (+1 SD) performance respectively in high and low division soccer players on a design fluency test (e.g., creativity, inhibition, cognitive flexibility) when using scaled scores. However, they also reported results in the average range with two other tests of EF, namely the colour-word interference (e.g., Stroop) and trail making tests. The authors argued that the design fluency test was more representative of the '*chain of decision making*' that can be seen during sport situations, compared to the other tests. However, such a link should be further described. Similarly, Elferink-Gemser et al. (2018) reported that elite and sub-elite table tennis players outperformed the normative mean (M=10) on multiple cognitive tests (e.g., working memory, inhibition, cognitive flexibility) using scaled scores. Yet, when comparing the scores on a normative scale, a perspective not directly addressed in their study, it could be observed that 13 out of 16 test variables would align with the average performance of the normal population. Similar conclusions could be drawn from other studies using normalized scores but not directly reporting performance against a normative scale (Verburgh, Scherder, et al., 2014; Vestberg et al., 2017). Compared to these previous studies, the current one includes a larger sample size and suggests that comparing normalized scores to a normative scale could be useful to avoid any over-interpretation of results or to limit any misinterpretation of p-values (Halsey, 2019).

The observed effect on sustained attention appears robust considering that both accuracy and reaction time were found to be superior in athletes. Previously, sustained attention had been identified as a cognitive function that had not received much attention in the sports literature (Memmert, 2009). And only recently, Sanchez-Lopez et al. (2016) demonstrated that there is a particular neural signature for sustained attention in black belt martial arts athletes compared to novice athletes likely related to their sport expertise, suggesting that these athletes possess more efficient neural mechanisms for sustained attention. Therefore, sustained attention warrants further research to verify its role in expertise. In contrast, athletes performed significantly worse in inhibition accuracy which is not in line with recent findings (Fleddermann et al., 2023). However, there are several considerations to take into account regarding our result. First, the inhibition test had a different ceiling effect for the accuracy variable compared to the other tests (max. T-scores = 60 vs 80), making it less sensitive in distinguishing between good and lesser-performing athletes. Despite this ceiling effect performance still fell within the average range of the normative sample. Finally, the results for the reaction time variable on the same test indicated that athletes outperformed the normative average. For these reasons, caution should be taken when interpreting the present results on inhibitory capacity.

This study reports the qualitative interpretation of performance based on standardized normative scales (e.g., low average, average, high average) and suggests that it could be helpful in future research to avoid or to temper any overestimation of an effect. In addition, sustained attention stands out as a superior cognitive function among elite athletes which requires further examination.

4.2. Impact of sport type on cognitive test performance

It was hypothesized that cognitive test performance would differ according to the category of sport because of the different demands (physiological, technical, cognitive) of different types of physical activities. Even though speed-strength sports demonstrated a superior performance in one variable of the cognitive flexibility test compared to team sports, no other effects were observed. Therefore, it raises questions about the influence of the specificity of the sport demand (e.g., physiological, technical, cognitive) on cognitive functions.

These findings are not consistent with most prior studies reporting differences between sport types (Heilmann et al., 2022; Krenn et al., 2018; Mann et al., 2007; Meng et al., 2019; Voss et al., 2010; Wang et al., 2013). However, it is important to highlight that the direction of the reported effect was not consistently straightforward across studies, with some research reporting the advantage of one category over another and sometimes the opposite effect (e.g., strategic sports superior to interceptive sports and vice-versa). In addition, there is still no clear understanding of which characteristic of sport demands (e.g., physiological, technical, cognitive) impacts cognitive functioning, if any. Regarding the cognitive development theory, animal studies have previously reported that enriched environments combined with access to running resulted in similar effects on cognitive plasticity compared to environments with only access to running, so that running was the key contributor to neurogenesis (Kobilo et al., 2011). In line with these findings, a recent meta-analysis in athletes suggested that physiological demand (e.g., aerobic sports and high intensity interval training team-based sports) was one of the main contributors for athletes' superiority in cognitive tests (Logan et al., 2022). Yet, it has been shown that practicing endurance sports (e.g., marathon), sport engaging complex motor skills motor (e.g., kung fu), or recreational type of activities did not result in distinct cognitive test performance (Chang et al., 2017). This evidence reinforces the idea that it is still uncertain if a specific demand within a sport has can influence cognitive test performance. And there is even less evidence that the cognitive (e.g., attention, planning, decision making, etc.) rather than the physiological demand of a sport, can influence cognitive test performance and that de latter should guide self-selection of a sport. Furthermore, the sporting literature has used multiple sport classification frameworks, none of which accounts for the singular cognitive demand of sports (Heilmann et al., 2022). For example, the open/closed-skill classification tends to oversimplify grouping sports within two categories based on the type of pacing, types of movements, and dynamics of the sporting environment. These are broad domains which seem to lack specific criteria to distinguish between types of sports and make it difficult to understand exactly what characteristics positively influenced cognitive functioning in open compared to closed-skill sports.

To illustrate this, short track speed skating would fall into the closed-skill sport category, while this sport is highly dynamic and unpredictable in nature. Similar observations could be drawn from the static/interceptive/strategic classification which included more distinction between sport types, but where a wrestler and a badminton athlete, who must sustain completely different demands, would still fall into the same category (e.g., interceptive). For these reasons, the present study employed a more specific classification framework distinguishing sports into seven sport categories based on their physiological demand, tactical components, and skills required, the last two components being more susceptible to encapsulate the cognitive demand between sport types (McKay et al., 2022). As noted above, we did not observe differences in cognitive performance based on this classification. If we assume that the cognitive demand truly differs between sports, it is possible that the neuropsychological cognitive tests used in the present study lacked the sensitivity to capture the cognitive specificity of each sport type.

For a practical application in talent identification and development, future studies should further examine their potential for this purpose or invest in developing tests that are more specifically tailored to the demands of each sport. For example, tests targeting sport specific perceptual-cognitive-motor functions seem to demonstrate a greater sensitivity towards a sport specific expertise (Kalén et al., 2021). Research should also clarify what characteristics of the sports' demands impact cognitive functioning and use a well-described sport classification framework to better support the research hypotheses.

4.3. Impact of sex on cognitive functions

It was hypothesized that male and female athletes would not show differences in cognitive performance. Results demonstrated no differences between them on most of the variables except in the motor reaction time of sustained (~74 ms) and selective attention (~24 ms) tasks where males responded slightly faster. Most studies in the athletic population reported similar cognitive test performance between females and males on measures of EF and attention (Alves et al., 2013; Jin et al., 2022; Vestberg et al., 2012). Although Voss et al. (2010) observed superior cognitive performance in male athletes compared to female athletes, it is important to note that their sample was predominantly male (~63.7-89.1%), which could have introduced bias into their results. Conversely, Ong (2017) reported that female athletes performed better than male athletes on both measures of accuracy and reaction time in cognitive flexibility on the same DT task that was used in the present study. Nevertheless, these effects were relatively moderate (η^2=0.04), and their sample was composed of significantly more females (n=96) compared to males (n=37). The imbalanced sample used in these two studies may account for these equivocal results. As noted above, the one sex difference observed that males performed faster than females on motor reaction time measures of attention. Prior research has reported faster motor reaction time in males compared to females (Hodgkins, 1963; Jain et al., 2015; Landauer et al., 1980). One study by Landauer et al. (1980) found that males were faster than females on motor reaction time but not on cognitive reaction time, which is in line with our motor speed findings. However, no differences were seen in motor reaction time in any of the EF tasks. EF tasks can be considered more complex compared to the attention tests, so it could be that the difference in motor reaction between males and females disappears when the task becomes more cognitively demanding, such as when more information must be processed simultaneously to carry out several manoeuvres (e.g., DT) or when more rules and instructions must be managed (e.g., TOL). This hypothesis would require further investigation.

4.4. Strengths and limitations

This study reports the raw results of 230 North American female and male elite athletes tested under standardized conditions, thus enabling the creation of a comprehensive dataset for the development of sport-specific norms for various cognitive tests within the Vienna Test System battery. With the use of multiple tests of cognitive functions and normative scales, findings of this study were able to highlight possible overestimation of the cognitive advantage of sport experts. We also used a clear classification framework to improve the characterization of sport expertise and sport types. However, this study has some limitations. First, the normative values were not representative of the North American population and the participants included in the normative values were not the same for each test but were collected in similarly high-income European countries (Austria, Germany, Switzerland). Furthermore, considering the visual nature of the cognitive tasks (i.e., culturally free), we believe the origin of the norms had a limited impact on the study results. Finally, the distribution of sex was not equal in each sport and each category which may limit the generalisation of the present findings. Also, the use of a fixed mean and standard deviation for the analysis is a limitation of the study because it's a logical datum based on theory, but not on created standards, which is less precise than if we'd had a comparative group. The last limitation of this study that we found is that few psychometric studies have been carried out to validate the tests used in this study. Further validation studies are required.

5. Conclusion

This study suggests that cognitive functioning of elite athletes falls within the average range except for sustained attention. In addition, cognitive performance is more likely to be relatively similar between sports and sexes, or it could be that neuropsychological cognitive tests are unable to capture the specific cognitive attributes unique to each sport. It is recommended for future studies to include normative scales when comparing the results of athletes' cognitive tests and to further explore the specific cognitive characteristics associated with various sports.

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Table 1. Characteristics of sport categories

Sport category	**Sport**	**Sample size**					
		All		Females		Males	
		n	%	n	%	n	%
Team	Water polo	49	53.85	34	37.36	15	16.48
	American football	42	46.15	0	0.00	42	46.15
	Total	91	39.57	34	37.36	57	62.64
Precision/skill-dependent	Diving	23	36.51	15	23.81	8	12.70
	Artistic swimming	31	49.21	31	49.21	0	0.00
	Trampoline	3	4.76	2	3.17	1	1.59
	Figure skating	6	9.52	4	6.35	2	3.17
	Total	63	27.39	52	82.54	11	17.46
Speed/strength	Short track speed skating	76	100.00	38	50.00	38	50.00
	Total	76	33.04	38	50.00	38	50.00
Total		230	100	124	53.91	106	46.09

Table 2. Athletes' T-score mean performance against the mean of normative values (M=50, SD=10) on six cognitive tests

Test variable	Mean ± SD	t-test	95% [CI]	d
Executive functions				
Working memory (NBN-S1)				
Accuracy	55.80 ± 9.528	t(68) = 5.05, p < .001*	[4.02 - 6.29]	0.59
Reaction time	48.51 ± 9.440	t(68) = -1.31, p = .097	[3.51 - 8.09]	0.15
Inhibition (INHIB-S9)				
Accuracy	47.28 ± 9.531	t(223) = -4.27, p < .001*	[3.93 - 6.08]	0.28
Reaction time	54.25 ± 7.242	t(223) = 8.78, p < .001*	[-3.97 - -1.46]	0.49
Cognitive flexibility (DT-S1)				
Accuracy	55.00 ± 7.793	t(203) = 9.17, p < .001*	[3.93 - 6.08]	0.50
Planning (TOL-S11)				
Accuracy 1	48.41 ± 9.901	t(226) = -2.43, p = .008	[6.13 - 8.59]	0.16
Accuracy 2	52.00 ± 8.309	t(226) = 3.63, p <.001*	[-2 .89 - -0.30]	0.22
Attention				
Selective attention (MDT-S2)				
Reaction time 1	51.13 ± 9.877	t(227) = 1.72, p = .043	[3.29 - 5.20]	0.11
Reaction time 2	55.16 ± 8.688	t(227) = 8.97, p < .001*	[-0.16 - 2.42]	0.55
Sustained attention (SIGNAL-S4)				
Accuracy	57.08 ± 9.638	t(223) = 10.99, p < .001*	[-3.76 - 0.77]	0.72
Reaction time	57.36 ± 9.342	t(223) = 11.79, p < .001*	[5.81 - 8.35]	0.76

*Significant effect (p < 0.005)

Table 3. Cognitive test performance of elite athletes according to sport categories and sex

Test variable	Main effect ANOVA Sport category			Main effect ANOVA Sex			ANOVA interaction Sport category x Sex
	Sport category	Mean ± SD	(dof)=F, p, η^2	Sex	Mean ± SD	(dof)=F, p, η^2	(dof)=F, p, η^2
Executive functions							
Working memory (NBN-S1)							
Accuracy	Team	8,69 ± 0.61	(2,65)=0.079, 0.924, 0.002	M	8.74 ± 0.55	(1,65)=0.002, 0.967, 0.000	(1,65)=0.010, 0.920, 0.000
	Precision/skill-dependent	9,12 ± 0.69		F	8.89 ± 0.45		
	Speed/strength	8,83 ± 0.52					
Reaction time	Team	0.79 ± 0.04	(2,64)=1.794, 0.175, 0.053	M	0.83 ± 0.04	(1,64)=0.023, 0.880, 0.000	(1,64)=0.072, 0.790, 0.001
	Precision/skill-dependent	0.85 ± 0.05		F	0.84 ± 0.03		
	Speed/strength	0.89 ± 0.04					
Inhibition (INHIB-S9)							
Accuracy	Team	3.18 ± 0.36	(2,218)=1.820, 0.164, 0.016	M	2.83 ± 0.41	(1,218)=0.047, 0.828, 0.000	(2,218)=0.021, 0.980, 0.000
	Precision/skill-dependent	3.20 ± 0.55		F	2.94 ± 0.31		
	Speed/strength	2.26 ± 0.39					
Reaction time	Team	0.37 ± 0.01	(2,218)=0.978, 0.378, 0.013	M	0.36 ± 0.01	(1,218)=5.810, 0.017, 0.026	(2,218)=0.978, 0.378, 0.009
	Precision/skill-dependent	0.38 ± 0.01		F	0.38 ± 0.01		
	Speed/strength	0.36 ± 0.01					
Cognitive flexibility (DT-S1)							
Accuracy	Team	262.01 ± 2.94	(2,198)=4.621, 0.011, 0.045	M	265.94 ± 3.24	(1,198)=0.331, 0.566, 0.002	(2,198)=0.704, 0.496, 0.007
	Precision/skill-dependent	264.61 ± 4.35		F	268.29 ± 2.48		
	Speed/strength	274.74 ± 3.14					
Reaction time	Team	0.701 ± 0.006	(2,198)=0.069, 0.934, 0.001	M	0.69 ± 0.01	(1,198)=3.578, 0.060, 0.018	(2,198)=0.276, 0.759, 0.003
	Precision/skill-dependent	0.700 ± 0.008		F	0.71 ± 0.01		
	Speed/strength	0.703 ± 0.006					
Planning (TOL-S11)							
Accuracy 1	Team	6.70 ± 0.25	(2,221)=1.493, 0.227, 0.013	M	6.66 ± 0.29	(1,221)=0.041, 0.840, 0.000	(2,221)=1.422, 0.243, 0.013
	Precision/skill-dependent	6.19 ± 0.39		F	6.59 ± 0.21		

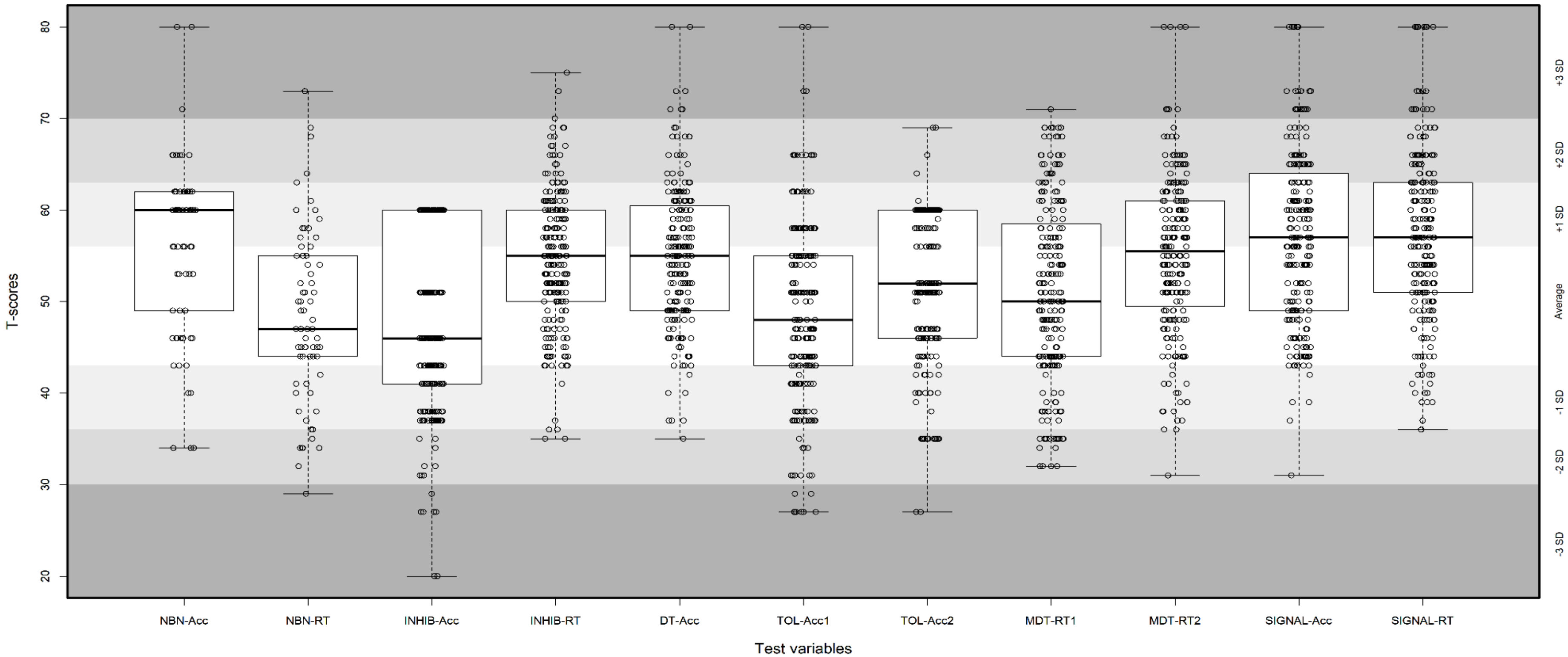
	Speed/strength	6.99 ± 0.26					
	Team	8.81 ± 0.42					
Accuracy 2	Precision/skill-dependent	7.35 ± 0.67	(2,221)=2.294, 0.103, 0.020	M F	7.90 ± 0.49 8.06 ± 0.36	(1,221)=0.069, 0.793, 0.000	(2,221)=0.440, 0.645, 0.004
	Speed/strength	7.78 ± 0.45					
Attention							
Selective attention (MDT-S2)							
	Team	347.28 ± 4.36					
Reaction time 1	Precision/skill-dependent	355.14 ± 6.68	(2,222)=1.129, 0.325, 0.010	M F	347.98 ± 4.94 348.86 ± 3.69	(1,222)=0.021, 0.886, 0.000	(2,222)=0.140, 0.869, 0.001
	Speed/strength	342.90 ± 4.68					
	Team	168.51 ± 3.07					
Reaction time 2	Precision/skill-dependent	172.79 ± 4.71	(2,222)=3.265, 0.040, 0.029	M F	161.85 ± 3.48 185.68 ± 2.60	(1,222)=30.078, 0.000*, 0.119	(2,222)=0.652, 0.522, 0.006
	Speed/strength	179.99 ± 3.30					
Sustained attention (SIGNAL-S4)							
	Team	73.60 ± 0.66					
Accuracy	Precision/skill-dependent	73.60 ± 0.66	(2,218)=6.490, 0.837, 0.002	M F	74.41± 0.77 72.60 ± 0.56	(1,218)=3.646, 0.058, 0.016	(2,218)=1.703, 0.185, 0.015
	Speed/strength	73.84 ± 0.71					
	Team	0.81 ± 0.01					
Reaction time	Precision/skill-dependent	0.82 ± 0.02	(2,218)=0.223, 0.800, 0.002	M F	0.77 ± 0.02 0.84 ± 0.01	(1,218)=12.916, 0.000*, 0.056	(2,218)=0.324, 0.723, 0.003
	Speed/strength	0.80 ± 0.02					

*Significant effect ($p < 0.004$)

Table 4. Missing data

Variables	Male	Female	Team	Precision/skill-dependent	Speed/ Strength
DT/S1					
Correct	13	13	11	7	8
Median reaction time	13	13	11	7	8
INHIB/S9					
Number of commissions errors	2	4	1	3	2
Mean reaction time	2	4	1	3	2
MDT/S2					
Median cognitive reaction time	1	1			1
Median motor time	1	1			1
NBN/S1					
Correct	79	81	68	46	46
Mean time “correct“	79	82	68	46	47
SIGNAL/S4					
Number correct and delayed	3	3	1	2	3
Median detection time	3	3	1	2	3
TOL/S11					
Planning	1	2		2	1
Number of correct solutions	1	2		2	1

Figure 1. *T-scores of elite athletes relative to a normative scale representative of the general population as a function of eleven test variables assessing six cognitive functions.*



Note: NBN-Acc/RT: working memory task accuracy and time; INHIB-Acc/RT: inhibition task accuracy and reaction time (note that the test has a ceiling effect at 60 for the accuracy variable); DT-Acc: Cognitive flexibility task accuracy; TOL-Acc1/2: planning ability task accuracies; MDT-RT1/2: selective attention task cognitive and motor reaction time; SIGNAL-Acc/RT: sustained attention task accuracy and reaction time.