Neurocognitive Characteristics of Professional Action Video Game Players

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Abstract

Action video games represent one of the most widely followed and cognitively demanding genres in e-sports. Currently, the cognitive ability profiles of professional action video game players remain poorly understood. Cross-sectional studies targeting professional players and high-ranked individuals have demonstrated that professional action video game players exhibit faster attentional selection, more stable sustained attention, superior attentional blink performance, enhanced multiple object tracking capacity, and greater working memory capacity. The superior attentional performance of professional players is primarily associated with higher P3 amplitude, while working memory performance is linked to plastic changes in regions such as the dorsolateral prefrontal cortex and right posterior parietal cortex. Furthermore, professional players exhibit enhanced functional connectivity between the central executive network and multiple brain networks. Currently, the extent of cognitive enhancement from game training is insufficient to bridge the cognitive gap between professional players and novices. Basic cognitive abilities demonstrate limited predictive validity for players' gaming performance. Future research could expand to investigate more advanced cognitive aspects such as game decision-making, game chunking, or game patterns.

Full Text

Cognitive Neural Characteristics of Professional Action Video Game Players

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Abstract

Action video games (AVGs) represent one of the most popular and mentally demanding genres in e-sports. However, the cognitive profile of professional AVG players remains unclear. Cross-sectional studies targeting professional players and high-ranked gamers have revealed that professional AVG players exhibit faster attentional selection, more stable sustained attention, better attentional blink performance, superior multiple-object tracking ability, and greater working memory capacity. Specifically, their advantage in spatial working memory capacity is particularly pronounced. Additionally, professionals show reduced susceptibility to the attentional blink effect. The superior attentional performance of professional players appears to be associated with higher P3 amplitude, while working memory performance correlates with plastic changes in the dorsolateral prefrontal cortex and right posterior parietal cortex. Furthermore, professional players demonstrate enhanced functional connectivity between the central executive network and multiple other brain networks. Currently, the degree of cognitive enhancement from game training is insufficient to fully account for the cognitive gap between professional and novice players. Basic cognitive abilities show limited predictive power for gaming performance. Future research should extend to more advanced aspects of gaming cognition, including decision-making, chunking, and pattern recognition based on spatial locations of game characters.

Keywords: e-sports, action video games, professional players, cognitive characteristics, neural characteristics

Classification Codes: G804; G842

E-sports officially became China' s 99th competitive sport in 2003 (later reclassified as the 78th) and made its debut as an official event at the 19th Asian Games in Hangzhou 2022. E-sports refers to organized electronic game competitions that require specific skills, involve fine motor control, have broad audiences, and exert certain social influence (Jenny et al., 2016). Action video games (AVGs) currently rank among the most popular competitive game genres and constitute the main events in e-sports tournaments, including titles such as *League of Legends* (LOL), *Counter-Strike: Global Offensive* (CSGO), *DOTA2*, and *StarCraft 2*. Based on previous criteria, AVGs are characterized by fast pacing, strong indirect competition, high degrees of freedom, and emphasis on real-time strategy, all of which demand focused, divided, and shifting attention (Bediou et al., 2018; Dale et al., 2020).

[Figure 1: see original paper] Classification of Game Players

In published AVG cognitive studies, excluding patients with internet gaming disorder or other psychiatric/neurological conditions, recruited players can be broadly categorized into three groups based on gaming performance and duration (Figure 1): professional players, amateur players, and novices. Regarding specific inclusion criteria for professional AVG players (Table 1), one category comprises professional esports athletes (Benoit et al., 2020; Ding et al., 2018; Tanaka et al., 2013). Another includes players ranked in the top 7% of their game server' s matchmaking rankings (MMR) with at least two years of specialized gaming experience (Gan et al., 2020; Qiu et al., 2018; Yao et al., 2020). A few studies have employed questionnaire-based assessments to screen professional players (Cain et al., 2012; Wong & Chang et al., 2018). All three screening methods are encompassed within our definition of professional players. Novices are defined as players with less than one hour of weekly gaming in the past six months or those without AVG experience (Wong & Chang et al., 2018). Amateur players represent the group intermediate between professional players and novices. MMR refers to a player' s public ranking achieved through a relatively fair Elo matchmaking system after a certain number of matches (Elo, 1978). MMR serves as a unified metric for measuring player skill and performance.

Games serve as an excellent vehicle for studying cognition (Bavelier et al., 2018). First, games involve extensive cognitive processes ranging from attention and working memory to complex reasoning and decision-making (Banyai et al., 2019; Dale & Green 2017). Second, given their computer-based environment, examining how games influence cognition and how cognition predicts e-sports performance may have good ecological validity. Third, the large player base facilitates data collection on cognitive characteristics and their changes during game interactions. Previous research has primarily explored the effects of gaming on cognition and emotion in players or individuals with gaming addiction (Weinstein & Lejoyeux 2020), with few studies investigating the psychological characteristics of professional players. However, preliminary neural evidence suggests unique features of professional AVG players, including stronger functional connectivity between the central executive system and default mode network, as well as distinctive EEG microstates (Cui et al., 2021; Gong et al., 2019). Current research has not adequately clarified the relationships among the cognitive neural characteristics of professional AVG players, making it important to review the identified cognitive neural features. Investigating the cognitive neural characteristics of professional players can provide a basis for talent selection, training, and industry standard establishment in e-sports, while also deepening our understanding of human mental potential under complex, competitive conditions and offering references for research and applications in competitive sports and artificial intelligence (Bonny et al., 2020; Font & Mahlmann, 2019).

Based on current cross-sectional and longitudinal game intervention studies on professional AVG players'cognitive abilities, we will discuss their cognitive neural characteristics from basic to advanced cognition, covering attention, working memory, mathematical and reasoning abilities. We will also explore partial causes of these cognitive characteristics and their predictive effects on gaming performance.

2.1 Attention

Attention forms the foundation of conscious cognitive activity and represents a key focus in current research on professional AVG players'cognition. This section examines professional players' attentional processing and related neural features through cross-sectional studies on attentional selection, attentional inhibition, multiple-object tracking, attentional blink, and sustained attention.

2.1.1 Attentional Selection and Inhibition in Professional AVG Players

Faster stimulus capture in the visual field constitutes an important cognitive advantage of professional AVG players. The useful field of view (UFOV) task is a classic paradigm for measuring visual attention allocation and selection, requiring individuals to rapidly capture briefly presented stimuli appearing randomly in central or peripheral visual fields. In a study by Qiu et al. (2018) that included 15 professional AVG players and 14 amateur players, UFOV testing revealed that professional players responded 11.33% faster than novices (Table 2), suggesting that professionals can capture stimuli more quickly. Event-related potential (ERP) results from this study showed that professional players exhibited lower N2 amplitude and higher P2 and P3 amplitudes. The P2 component is associated with attentional selection, while the P3 component relates to attentional resource allocation (Fritzsche et al., 2011; Polich, 2007). The combined EEG and behavioral results suggest that the rapid attentional selection in professional AVG players may be related to better attentional resource allocation.

Attentional selection involves not only resource allocation but also inhibition of irrelevant stimuli. Ding et al. (2018) used a Flanker task (judging the direction of a central arrow among five simultaneously presented arrows) to compare 10 professional AVG players, 10 trainee players, and 20 amateur players, finding no significant differences among the three groups. Cain et al. (2012) compared 23 professional AVG players and 21 novices on the Flanker task and observed no differences in attentional inhibition ability. Another study using a Stroop color-word task (reporting the font color of color words) compared 14 professional AVG players and 16 amateur players, also finding no significant Stroop task differences (Benoit et al., 2020). These studies consistently failed to find attentional inhibition differences between professional and amateur players. However, previous research has shown that AVG players exhibit significant attentional inhibition advantages compared to novices (Bavelier & Green, 2019; Bediou et al., 2018). The inconsistent results between expert and amateur players may stem from several factors: first, professional player sample sizes are generally small; second, control groups are not entirely consistent—Ding et al. (2018) and Benoit et al. (2020) used amateur players rather than novices as controls; third, inhibition ability is relatively specific, and its impairment is a hallmark of addiction (Weinstein & Lejoyeux 2020), meaning attentional inhibition may be affected by a history of gaming addiction. Among these three professional player studies, only Benoit et al. (2020) explicitly excluded relevant psychiatric histories.

Based on current evidence, the characteristics of attentional inhibition in professional players remain unclear. Future research should strictly control relevant variables.

Multiple-Object Tracking (MOT) is a dynamic attentional process involving selection, inhibition, and maintenance (Allen et al., 2006). MOT requires individuals to simultaneously track multiple moving objects, determining their positions, trajectories, and other features of interest, with primary measures being the number and speed of tracked targets (Pylyshyn & Storm, 1988). Action video games frequently involve multiple-object tracking. In a comparison of 10 professional AVG players, 10 trainee players, and 20 amateur players, Ding et al. (2018) used a 2D MOT task and found significant group differences: professional and amateur players tracked more objects, while trainee players tracked the fewest. However, this study did not report gaming duration or education level across groups, variables that could significantly influence results. Subsequently, Benoit et al. (2020) employed a VR-based 3D MOT task comparing 14 professional players and 16 amateur players. The task required participants to track 4 of 8 balls moving randomly in space for 8 seconds (with collision detection), with speed increasing after each successful trial. Results showed that professional players' tracking speed thresholds were significantly higher than those of amateur players, again indicating superior multiple-object tracking performance in professionals.

Neural research on multiple-object tracking abilities in professional players is extremely limited. Wei and Zhang (2019) suggested that attentional allocation between targets and non-targets during MOT relates to N1 and P1 components, tracking load relates to N2 and CDA components, and MOT involves the dorsolateral prefrontal cortex (DLPFC) and parietal regions (including the anterior intraparietal sulcus, posterior intraparietal sulcus, and superior parietal lobule). As previously noted, professional players' attentional selection is associated with lower N2 amplitude, and similar EEG evidence suggests that superior multiple-object tracking performance is a characteristic attentional feature of professional players.

Attentional Blink (AB) is a special phenomenon in attentional selection, referring to the slowed response to a second stimulus (Target 2, T2) within 200-500 ms after receiving the first target stimulus (Target 1, T1), which is associated with suppressed P3 amplitude (Vogel et al., 1998). A study examining AB performance in 19 professional AVG players and 19 amateur players found that professionals' accuracy on the AB task (with a 300 ms interval between T1 and T2) was approximately 10% higher than amateurs (Gan et al., 2020). Notably, professional players' accuracy for T1 (a 63 ms brief stimulus) was about 3-6% higher than amateurs, reflecting better stimulus capture ability that partially explains their AB advantage. ERP results from this study showed that professionals exhibited higher P3 amplitude for T2 than amateurs, consistent with Qiu et al.' s (2018) findings: higher P3 amplitude reflects better attentional resource allocation. Additionally, the study found that amateurs showed greater

P3 amplitude for T1 than T2, whereas professionals showed no P3 amplitude difference between T1 and T2. In AB tasks, larger P3 amplitude elicited by T1 results in fewer attentional resources allocated to T2 (McArthur et al., 1999; Shapiroa et al., 2006). Novices' greater P3 amplitude for T1 than T2 indicates they primarily allocate attentional resources to T1, making them more susceptible to the AB phenomenon. The absence of P3 amplitude differences between T1 and T2 in professional players confirms their superior ability to allocate attentional resources across tasks, or that their attentional resource capacity is sufficient to handle the task demands.

2.1.2 Sustained Attention in Professional AVG Players

Behavioral evidence demonstrates stable and sustained attentional characteristics in professional AVG players. In a comparison study between professional and amateur players, Benoit et al. (2020) measured sustained attention performance using a task requiring participants to cross out designated stimuli presented sequentially on cards within a time limit. They found that professional players' task fluctuation rate (the difference between best and worst performance across rows) was 20% lower than amateurs, while their correct responses were 9.88% higher. This reflects stable and efficient sustained attention abilities in professional players. In this study, professional players' weekly gaming duration was several times that of amateurs, suggesting their sustained attention advantage may result from intensive game training. Li et al. (2020) balanced weekly gaming duration and gaming years between professional and amateur players yet still found sustained attention advantages in professionals. This study used the Continuous Performance Test (CPT), a classic paradigm for measuring sustained attention typically consisting of 1-back trials with two-, three-, and four-digit numbers. Results showed that professional players' hit rate was 3.74% higher than amateurs, while their false alarm rate was 10.26% lower. These results align with real-world observations, indicating that professional players can maintain focus during extended gaming sessions and, more importantly, deliver precise performance simultaneously.

Overall, professional AVG players demonstrate outstanding performance across multiple attention tasks. This advantage is associated with lower N2 amplitude and higher P2 and P3 amplitudes during attentional processing, involving participation of the DLPFC and multiple parietal brain regions (Qiu et al., 2018; Gan et al., 2020).

2.2 Working Memory

Action video games extensively involve working memory, such as remembering positions and skill cooldown times of allies and enemies, and planning navigation routes. Working memory represents a key focus in AVG research. This section explores the cognitive neural characteristics of professional players from the perspectives of working memory capacity and the central executive system.

2.2.1 Working Memory Capacity in Professional AVG Players

AVG research has consistently found greater working memory capacity in professional players. Tanaka et al. (2013) compared 17 professional AVG players and 33 novices using a spatial working memory task requiring participants to remember colored blocks randomly presented on a screen. After the blocks disappeared, a probe block appeared at one location, and participants judged whether it matched the previous block at that position. Results showed that professional players' task accuracy was 5.7% higher than novices. Similarly, Yao et al. (2020) used a comparable spatial working memory task to compare 18 professional AVG players and 19 amateur players, finding that professionals' spatial working memory accuracy was approximately 2-8% higher than amateurs. The difference between professional and novice spatial working memory increased with memory load, suggesting that more difficult tasks better differentiate professionals from amateurs.

Benoit et al. (2020) compared 14 professional AVG players and 16 amateur players using spatial span (forward and backward recall of sequentially presented grid positions) and digit span tasks (forward and backward recall of numbers), finding that professionals had higher memory capacity on both tasks: their spatial span was 17.95% higher and digit span 15.93% higher than amateurs. This study matched gaming years between groups, though professionals' weekly gaming duration remained significantly higher than amateurs, suggesting their working memory capacity advantage may also benefit from more intensive game training. Correlation analysis revealed a moderate positive correlation between weekly gaming duration and spatial working memory span, indicating a connection between spatial working memory and game training. Tanaka et al.' s (2013) study found that better spatial working memory in professional AVG players was associated with increased gray matter volume in the right posterior parietal cortex, which may represent one neural characteristic of professionals' high working memory capacity. Electrophysiologically, contralateral delay activity (CDA) amplitude increases with the number of working memory stimuli, with differences in CDA amplitude across memory loads reflecting individual working memory capacity (Vogel et al., 2005). Yao et al. (2020) found that the difference in CDA amplitude between 4-block and 2-block conditions in spatial working memory was greater in professional players than amateurs, further validating professionals' working memory capacity advantage from an electrophysiological perspective. Consistent behavioral and neural evidence suggests that professional AVG players possess greater working memory capacity. As previously mentioned, multiple-object tracking load also relates to the CDA component (Wei & Zhang, 2019), indicating that different cognitive features share common neural mechanisms.

2.2.2 Central Executive System in Professional AVG Players

Baddeley (2012) proposed that the central executive system' s functions in working memory include task switching and execution. In the domain of task switching (mental flexibility), Cain et al. (2012) created a switching task based on the Flanker paradigm where two colors of the central arrow corresponded to two opposite response rules; participants had to respond according to the color presented each trial. This experiment tested 23 professional AVG players and 21 novices, observing no group differences in switching costs. However, they found that professionals showed similar switching costs under both color conditions, whereas novices showed larger differences in switching costs between the two color conditions. This "balanced allocation of cognitive resources" processing style in professional players resembles findings in the attention domain (Gan et al., 2020). Li et al. (2020) used a Stroop-Switch task (switching between color naming and word reading) to test 35 professional AVG players and 35 amateur players, finding that professionals' switching error rate was 3.79% lower than novices, and their switching cost was 1.97% lower, indicating a slight switching advantage. However, Benoit et al. (2020) used a Stroop task variant (participants had to read the word meaning or word color depending on whether the word had a box outline) to compare 14 professional AVG players and 16 amateur players, finding no differences between groups. AVGs often involve switching between different tasks, with real-time strategy games like *StarCraft 2* requiring control of multiple units and rapid switching between construction and attack/defense tasks. Li et al.' s (2020) game was LOL (a real-time strategy game), while Benoit et al.' s (2020) projects were mostly shooter games. Game genre differences may partially explain the inconsistent results. Overall, professional players show higher working memory capacity, but central executive system switching advantages remain unclear.

2.3 Mathematical and Reasoning Abilities

Action video games also involve mathematics-related abilities. Players often need to estimate total damage from attacks and calculate skill/item flight times and distances. In expertise research, mathematical ability has been linked to performance in chess experts (Burgoyne et al., 2016). Interestingly, several recent studies have recruited players of different skill levels without grouping them, instead searching for factors predicting gaming performance within larger samples, and have found positive associations between numerical ordering ability and game performance. The number processing task presents a row of numbers simultaneously, requiring participants to quickly judge whether the sequence is ascending or descending. Bonny and Castaneda (2017) tested 288 AVG players during the fifth DOTA2 International Championship using a number processing task and found that numerical processing ability positively correlated with MMR. Subsequently, Bonny et al. (2020) tested 335 AVG players during the sixth DOTA2 International Championship using the same task and found that numerical processing ability could predict 7.6% of MMR variance. Although direct comparison evidence between professional players and novices in mathematical ability is currently lacking, these studies suggest a positive relationship between numerical ordering ability and gaming performance.

In reasoning and planning abilities, one study divided 55 professional AVG players into elite and general professionals based on their previous season' s appearance rate, then used the Tower of London test (similar to the Tower of Hanoi, assessing reasoning, planning, and problem-solving) and found that elite professionals' Tower of London scores were 16.90% higher than general professionals (Kang et al., 2020). Benoit et al. (2020) used the Tower of Hanoi (D-KEFS-Towers) to test 13 professional AVG players and 16 amateur players, finding a marginally significant advantage for professionals in accuracy. In professional competitions, match outcomes largely depend on the quality of game planning and decision-making, suggesting that top professionals may possess planning and reasoning advantages. This planning advantage may contribute to better situation awareness: compared to average pilots, the best pilots tend to spend substantial time before flights gathering sufficient information and considering multiple scenarios to develop detailed flight plans, thereby ensuring flight safety when encountering different situations (Ericsson et al., 2018).

A meta-analysis found that mathematically gifted individuals have better interhemispheric coordination and prominent right-hemisphere advantages, with differences localized to brain regions including the cerebellar culmen, left middle frontal gyrus, right inferior parietal lobule, and right supramarginal gyrus (Zhang et al., 2020). Based on functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), and magnetic resonance spectroscopy (MRS) in general populations, studies have found that reasoning ability relates to the central executive network, corpus callosum white matter, and N-acetylaspartate, a marker of neuronal density (Assem et al., 2020; Gongora et al., 2020; Paul et al., 2016). The corpus callosum is associated with connectivity efficiency between hemispheres, while the central executive network is the core network for working memory. Increased local functional connectivity in the central executive network has also been observed in professional AVG players (Gong et al., 2019). Based on these studies, future research should increase investigations of mathematical and reasoning abilities in professional AVG players and control groups, and clarify the associated neural characteristics.

3. Relationship Between Cognitive Abilities and Game Training

Regarding the origins of professional AVG players' cognitive characteristics, one possibility is that individuals possess certain psychological traits that lead them to choose gaming. Alternatively, there may be a reverse causal relationship: game training enhances cognition. Currently, research on the former is almost nonexistent, with most studies focusing on longitudinal intervention research examining how game training affects cognition.

3.1 Evidence from Game Intervention Studies

In attentional selection, Neri et al. (2021) recruited 21 players without shooter game experience, dividing them into an adaptive-difficulty CSGO experimental group and a default-difficulty CSGO control group for approximately 2 hours of daily CSGO training. Post-training UFOV testing showed slightly reduced reaction times for all players, with significant reaction time reduction persisting at three-month follow-up (Table 3). The post-test was conducted 2 hours after the final training session, potentially affected by fatigue, but the three-month retention test demonstrated sustained improvement in attentional selection speed.

In multiple-object tracking, Benoit et al.' s (2020) study used MOT tasks as training content. After five 1-hour sessions, both professional and amateur players showed improved tracking speed thresholds with equivalent learning rates —professionals' tracking speed thresholds remained higher than amateurs both pre- and post-training. This confirms the stable advantage of professional players' multiple-object tracking ability and suggests the trainability of this skill. However, this study' s training content was the 3D MOT test itself rather than actual games. In game training research, Green and Bavelier (2006) used AVGs as training content and found that 30 hours of AVG training could improve novices' multiple-object tracking ability by 7.5%, suggesting that game training can enhance multiple-object tracking.

In attentional blink, Neri et al. (2021) found improvements in AB task reaction time and accuracy following CSGO training, with reaction time improvements persisting after three months. Similarly, Jakubowska et al. (2021) conducted a 4-week, 30-hour *StarCraft 2* training program with 43 novices and found that all participants' AB task accuracy improved by approximately 10%. Interestingly, stronger P3 amplitude in novices during the AB task (in the T2 time window) before training could predict better gaming performance. This result not only suggests that AVG training can reduce the AB effect but also reinforces that higher P3 amplitude during attentional processing may be a neural characteristic of professional AVG players (Mishra et al., 2011; Qiu et al., 2018). Combined with intervention and cross-sectional studies, the AB task may serve as a test for predicting player performance. An fMRI study also demonstrated that AB can be improved through game training and provided neural localization evidence: Momi et al. (2018) divided 29 novices into experimental and control groups, with the experimental group undergoing 4 weeks of CSGO training. Post-training, the experimental group showed greater improvement in AB task reaction speed than the control group, with effects persisting at three-month follow-up. Additionally, the degree of AB performance improvement at three months correlated with increased cortical thickness in the right parahippocampal cortex (PHC) and right superior parietal lobule (SPL). The hippocampus plays important roles in memory and spatial cognition (Zhang et al., 2022). The parietal lobe is involved in interference inhibition (Krishnan et al., 2013). The SPL is a core region affecting attentional breadth (Valdois et al., 2019). Increased SPL cortical thickness may indicate enhanced attentional resource capacity or attentional control ability. Furthermore, neural research has found enhanced functional connectivity between attentional and sensorimotor networks in professional AVG players, facilitating continuous stimulus capture and rapid response (Gong et al., 2015; Gong et al., 2017).

In working memory, a 10-day intervention study (1.5 hours daily) combined transcranial magnetic stimulation (TMS) with game training, dividing 27 participants into four groups based on gaming experience and anodal stimulation (localized to the right DLPFC). Results showed that game training improved digit span and enhanced discriminability index d'(difference between hit rate and false alarm rate) on a 3-back task, but increased reaction time on a stop-signal task (Palaus et al., 2020). TMS also improved d' on the 3-back task, suggesting the trainability of working memory and the regulatory role of DLPFC. Interestingly, within-group analysis of the anodal stimulation intervention group revealed that experienced gamers showed significantly greater improvement in 3-back d' after game training than novices (with no baseline differences), suggesting that prior gaming experience facilitated working memory improvement. This may be because early game training affected more general learning or transfer abilities, which mediated working memory enhancement (Zhang et al., 2021).

Regarding the central executive system of working memory, one intervention study developed a 3D game based on story scenarios where participants had to make go or stop responses based on briefly presented contextual cues such as a fairy pointing the way (go-signal) or an evil witch' s voice (stop-signal). The study also used transcranial direct current stimulation (tDCS) during gameplay, with anodal stimulation localized to the right DLPFC. Results showed decreased reaction time in the real stimulation group post-intervention but no change in the sham stimulation group (Friehs et al., 2021). These results differ from Palaus et al. (2020), who found increased stop-signal reaction time after game training. Wang et al. (2019) argued that executive functions are not easily improved through game training, and Bediou et al. (2018) also found no switching ability advantages in AVG players. Overall, brief game training may not enhance central executive abilities, while working memory capacity may be more readily improved through game training. These studies also identified the important role of DLPFC in working memory. The DLPFC is one of the core brain regions of the central executive network, and professional AVG players show stronger local functional connectivity between the central executive network and default mode network (Gong et al., 2019). Research has also found enhanced functional connectivity within and between the central executive network and salience network in professional AVG players (Gong et al., 2016). These neural findings suggest that professional players may have comprehensive advantages in information integration and executive control. Given inconsistent evidence regarding switching ability, more cognitive neural evidence is needed in this area.

In mathematical and reasoning abilities, one intervention study recruited 24 novices randomly assigned to 40 hours of AVG training with *Unreal Tournament 2004* or non-AVG training with *The Sims 2*. Results showed a marginally significant interaction between training duration and game type: the AVG training group showed greater improvement in mathematical ability post-training, with no main effects of training duration or game type (Libertus et al., 2017). This suggests that a certain duration of AVG training may be necessary to promote mathematical ability. Mathematical ability involves many subtasks, and more professional player cross-sectional studies and long-term intervention research are needed in this area.

In summary, AVG training induces neural plasticity in brain regions such as the superior parietal lobule, enhancing visual attention. AVG training can also improve working memory, primarily involving multiple neural networks centered on the hippocampus and DLPFC. Multiple-object tracking ability can also be improved through game training. Additionally, preliminary research suggests that mathematics-related abilities may be enhanced through AVG training, though the reliability of these results and the underlying neural mechanisms require more evidence.

It should be noted that game training is not always beneficial. One intervention study with novices revealed mechanisms of neural change from game training: participants were divided into an AVG training group (using CSGO) and a control group (using *Super Mario 64*), with each group further divided into two subgroups based on learning strategy—spatial strategy group (relying on external spatial landmarks) and response strategy group (relying on internal subjective counting or patterns without external spatial cues). All participants underwent 90 hours of game training. Results showed that when AVG training involved spatial strategies, players' left hippocampal gray matter increased; similarly, the control group using spatial strategies showed increased right entorhinal cortex after training. However, when using response strategies, both AVG training and control groups showed significant decreases in right hippocampal gray matter (West et al., 2018). This suggests that neural changes from game training are modulated by cognitive strategy. The entorhinal cortex serves as a bridge between primary sensory information and the hippocampus, with grid cells in the entorhinal cortex and place cells in the hippocampus playing important roles in spatial cognition (Epstein et al., 2017; Zhang et al., 2022). If cognitive strategies during game training engage corresponding neural structures such as the hippocampus or entorhinal cortex, they may jointly promote cognition; otherwise, they may cause damage. Clinical research has found that severe hippocampal damage and atrophy can significantly increase the incidence of various psychiatric disorders through disinhibition of the hypothalamic-pituitary-adrenal (HPA) axis, leading to HPA axis-related hormonal imbalances (McEwen & Magarinos, 1997). Under the influence of individual traits or environmental factors, once players reach the level of internet gaming disorder, abnormalities in dopaminergic and reward circuits further impair cognitive function (Chau et al., 2018; Aviv & Michel, 2020). Overall, cognitive damage or enhancement from game training may be mediated by multiple factors including game type, cognitive strategy, gaming duration, and addiction susceptibility (Weinstein & Lejoyeux 2020; Bavelier, Bediou & Green, 2018).

3.2 "Learning to Learn" Theory Explanation

Game training may enhance players' core ability to extract regularities, thereby improving multiple cognitive functions. The "Learning to Learn" theory provides partial explanations for general learning ability and game comprehension. Bavelier et al. (2012) proposed that action video games do not teach players any specific skill but rather increase their ability to extract patterns or regularities from the environment. This general learning ability enhanced through action video games is termed "Learning to Learn." One study examining players' learning rates for new games found positive effects of prior gaming experience on learning new action video games or strategy games (Smith et al., 2020). Another study using 45 hours of cumulative game intervention found that action video games promoted learning ability (Zhang et al., 2021). This study set up two novice groups for game training, with dependent measures being learning rates (learning curves) for core cognitive abilities—working memory and orientation learning tasks (the latter examining perceptual learning ability). The two novice groups showed no significant differences at baseline or final post-training performance. By comparing learning curves between the AVG training group and a control group receiving non-action video games, the AVG training group showed higher learning rates on both cognitive tasks. The AVG training group reached high task performance more quickly with game training, after which the curve plateaued, while the control group' s performance increased relatively slowly. AVG training may enhance players' learning rates for cognitive tasks rather than directly improving cognitive abilities themselves. This conclusion can partially explain Palaus et al.' s (2020) intervention results: compared to novices, AVG players showed greater working memory improvement after 15 hours of game training. Because players have higher learning rates, their cognitive abilities increase faster. In summary, AVG experience may promote individuals' "Learning to Learn" ability—that is, the capacity to comprehend and extract patterns. This theory focuses on explaining cognitive improvements after game training but cannot explain the divergence in players' gaming levels following training.

3.3 Comprehensive Discussion of Cross-Sectional and Longitudinal Studies

Bediou et al.' s (2018) meta-analysis examined cross-sectional cognitive differences between AVG players and novices as well as longitudinal intervention effects of AVGs on cognitive abilities. In cross-sectional cognitive differences, players overall scored 0.55 standard deviations higher than non-players. The cognitive differences between professional players and control groups in Table 2 range from 0.75 to 2.67 standard deviations. In attentional abilities, professional players show advantages across multiple domains. Intervention studies on attentional blink show that game training can significantly reduce the AB effect. Bediou et al.' s meta-analysis indicates that cognitive improvements from game training for abilities like multiple-object tracking are approximately 0.3 standard deviations, relatively modest. Although Benoit et al.' s (2020) study found that professionals and amateurs maintained significant differences in multiple-object tracking ability after training, current evidence shows that multiple-object tracking can be improved through game training (Green & Bavelier, 2006). Direct evidence for the relationship between sustained attention and game training is scarce and remains unclear. In working memory, professional AVG players show very prominent advantages, with effect sizes ranging from 0.8 to 1.3 (Hedges' s g) across studies. Bediou et al.' s meta-analysis shows that the effect size for spatial cognition differences (primarily spatial working memory and mental rotation) between AVG players and novices is 0.75 (Hedges' s g). These similar effect sizes confirm professional AVG players' advantages in visuospatial cognition. The meta-analysis shows that spatial cognition improves by 0.45 standard deviations after training, accounting for about half of the cross-sectional difference between professional players and control groups, suggesting positive effects of game training on players' spatial working memory. Regarding inhibition and switching abilities in the central executive system, results remain inconsistent in both cross-sectional and intervention studies. Currently, only one weak positive intervention evidence exists for the relationship between mathematical ability and game training.

Overall, assuming that key cognitive abilities of professional players are defined as at least 1.5 standard deviations above average (approximately the top 7%, matching the top 7% MMR criterion for professional players), the meta-analysis shows that AVG training produces an overall cognitive improvement effect of about 0.34 standard deviations (Bediou et al., 2018), leaving a considerable gap. This may be because current AVG intervention periods are relatively short, mostly less than 30 days, whereas recruited professional players typically have years of gaming experience. A recent longitudinal study collected IQ and average daily video game duration data from 9,851 children aged 9-10 (mostly under 1 hour daily), following up 5,169 participants two years later. The study found that video game duration significantly predicted IQ improvement in child and adolescent players (Sauce et al., 2022). Two years of gaming produced approximately 2.55 points of IQ improvement, with the magnitude increasing with gaming duration. This study counted total duration across various game types (including computer, mobile, and console games), not entirely matching the computer-based AVGs discussed in this paper, but it provides causal evidence for gaming experience promoting cognition. Nevertheless, the IQ improvement from two years of gaming experience was still modest. Additionally, the study found interesting results: without controlling for time spent watching videos and online social interaction, baseline IQ showed a significant but weak negative correlation with daily gaming duration (β = -0.07). However, when controlling for online video watching or social interaction, the correlation between baseline IQ and gaming duration became non-significant. Daily gaming duration reflects gaming preference to some extent. These results suggest that intelligence is not closely related to gaming preference. In summary, professional action video game players show outstanding performance in attention and working memory tasks, partially due to game training, but current game training cannot fully explain all differences between professional and amateur players. Future systematic long-term intervention studies are needed to explain the impact of game training on cognition.

4.1 Predictive Effect of Cognitive Abilities on Game Performance

Previous research has focused on the impact of games on cognition. In competitive sports psychology, the relationship between cognitive abilities and performance emphasizes cognition as the cause and performance as the outcome, using cognitive testing and training as talent selection or training methods to ensure competitive performance. From a psychological perspective, game performance prediction involves important factors including motivation, personality, emotion, and cognition. At the cognitive level, Large et al. (2019) tested 549 players and found that sustained attention ability predicted 1.2% of MMR variance after controlling for age, while multiple-object tracking quantity positively predicted 2.7% of MMR variance. In working memory, Large et al. also found that digit span significantly predicted 1.4% of MMR variance in AVG players. Kokkinakis et al. (2017) tested 56 players and found that spatial rotation span (remembering orientations of multiple arrows after an interfering task with rotating letters) significantly correlated with MMR ($r = 0.26$). However, Bonny and Castaneda (2017) used a similar spatial rotation span task to test 288 AVG players and found no correlation between working memory and MMR. Röhlcke et al. (2018) used comprehensive working memory performance (comprising operation span, spatial span, and digit span subtasks, where operation span requires remembering letters while completing calculation tasks) to predict MMR in 304 AVG players and found no significant predictive effect. These studies suggest that working memory and other cognitive abilities have poor predictive power for players' gaming performance.

In reasoning ability, Kokkinakis et al. (2017) used a matrix test similar to Raven' s Progressive Matrices to test 56 AVG players and found that reasoning ability showed a moderate positive correlation with MMR ($r = 0.44$). Large et al. (2019) used an odd-one-out task to test 549 AVG players; this task presents nine figures differing in color, shape, and detail count, requiring participants to identify the figure most different from the others. Results showed that odd-one-out task performance could predict 1.4% of MMR variance. Similarly, Bonny et al. (2020) used Raven' s Progressive Matrices to test 335 AVG players and found that reasoning ability positively predicted 4.5% of MMR variance, while numerical processing ability could positively predict 7.6% of MMR variance—potentially the highest predictive cognitive ability for MMR reported to date. A meta-analysis on chess found that mathematical ability had the highest explanatory power for chess skill (ranking), reaching 12%. The same meta-analysis found that fluid intelligence, processing speed, and short-term memory could explain 6% of ranking variance; comprehension ability could explain 5% of variance; however, full-scale IQ could not significantly predict ranking (Burgoyne et al., 2016). As an official Asian Games mental sport, cognitive abilities show low explanatory power for chess rankings. Overall, the direct effect of cognitive abilities on predicting game performance is minimal, which may be reasonable. Additionally, considering that game performance involves multiple factors beyond the psychological domain, these predictions still hold positive significance.

Compared to visual cognition, gaming technique shows higher predictive power for game performance. Cretenoud et al. (2021) tested 12 basic visual cognitive abilities in 94 CSGO players, including letter orientation discrimination, contrast sensitivity, multiple illusion patterns, 1-back task, orientation discrimination under masking, random dot motion judgment, simple reaction time, saccade tasks, visual masking tasks, visual acuity (static vision), and visual search tasks. The study also tested six in-game techniques and personality traits. In visual cognition, only saccade tasks and discrimination of two illusion patterns showed weak positive correlations with MMR, while most cognitive measures including simple reaction time and 1-back task were unrelated to MMR. Meanwhile, shooting and tracking techniques showed moderate to strong positive correlations with MMR. In prediction, all visual cognition, gaming techniques, and personality traits together predicted 69.6% of MMR variance; however, the six gaming techniques alone could independently predict 48% of MMR variance, indicating that gaming technique predicts game performance far better than basic visual cognitive abilities. However, this does not mean basic cognitive abilities are unimportant, as these visual cognitive abilities could predict 12.9-37.4% of variance in gaming techniques. Cognitive abilities may indirectly influence game performance through the acquisition of gaming techniques, resulting in low direct predictive effects on game performance.

Gaming duration can also stably predict game performance. In Röhlcke et al.' s (2018) study, no predictive effect of working memory on MMR was found, but a significant positive predictive effect of gaming duration on MMR was observed ($\beta = 0.73$). Cretenoud et al. (2021) found similar results, with total gaming duration showing strong positive correlations with both current and peak MMR, while weekly gaming duration showed weak positive correlations with MMR. Regarding weekly gaming duration, Gong et al. (2017) found a moderate positive correlation between MMR and average weekly gaming duration ($r = 0.53$) in professional AVG players. Number of matches also reflects gaming duration. Studies collecting DOTA2 players' match counts and MMR at multiple time points found significant positive correlations between matches and MMR, ranging from approximately 0.2 to 0.6 (Bonny & Castaneda, 2017; Bonny et al., 2020). Kokkinakis et al. (2017) collected match counts and MMR data from a large sample of players ($N > 17{,}000$) after they passed the initial learning phase and reached stable MMR, finding a significant but weak positive correlation ($r = 0.02$). These studies suggest that gaming duration has a stable and positive effect in predicting game performance. Additionally, players' MMR development may be nonlinear; future exploration of the gaming duration corresponding to MMR inflection points could help establish more accurate standards for professional player gaming duration.

4.2 Explanation of Domain-Specific vs. Domain-General Cognition

In competitive sports, a meta-analysis including 8,860 samples examined the relationship between cognitive abilities and sports performance (Kalen et al., 2021). Overall, high-level athletes showed higher cognitive abilities than lower-level athletes (Hedges' s g = 0.59). Regarding cognitive ability differences between high- and low-level athletes, decision-making ability (including anticipation) showed the largest effect size (Hedges' s g = 0.77), followed by higher-level cognitive abilities (working memory, switching ability, etc.; Hedges' s g = 0.44), while basic cognitive abilities (attention, short-term memory, etc.) showed the smallest effect size (Hedges' s g = 0.39). Based on whether cognitive materials were related to the sport—for example, examining differences in memory for meaningless color blocks versus climbing movements in rock climbers (Heilmann, 2021)—the meta-analysis divided cognitive abilities into domain-specific and domain-general categories. The closer the cognitive test presentation format is to real sports scenarios, the better the test results can distinguish athlete levels. The cognitive results of high-level athletes also suggest the reasonableness of better cognitive performance in professional AVG players. Currently, most cognitive tests in the professional AVG player domain do not incorporate gaming scenarios, which may be an important reason for their limited predictive power for game performance.

Notably, the meta-analysis did not include simple reaction time. The importance of simple reaction time in the AVG domain remains controversial. Large et al.' s (2019) study found that simple reaction time weakly predicted MMR ($R^2 = 0.049$), while other studies found that simple reaction time could not differentiate AVG player skill levels (Cretenoud et al., 2021; Ding et al., 2018). For complex team-based games, passive reaction speed may be less important than making accurate anticipations or decisions based on situational analysis, which are precisely the tests currently lacking in the AVG domain.

4.3 Explanation of Chunking Theory and Pattern Recognition

Accurate anticipation or decision-making requires deep "game sense." The chunking theory in expertise research posits that experts' extensive domain-specific knowledge clusters are stored in long-term memory as "chunks," which enable experts to quickly grasp the essence of current situations and make optimal decisions (Chase & Simon, 1973; Gobet & Simon, 1998). Chase and Simon had chess experts and novices view chessboards with either random piece placement or normal game positions, then reproduce the positions from memory on empty boards. If experts could reproduce more pieces from random positions, it would indicate an advantage in short-term memory ability. Results showed no significant differences between experts and novices in reproducing random positions, indicating that experts do not rely on short-term memory advantages. However, experts' ability to reproduce normal game positions far exceeded novices' . Additionally, experts often placed multiple pieces as a group (chunk) during reproduction, further validating the existence and importance of chunks. This study suggests that the core cognitive characteristic of chess experts lies not in basic cognitive advantages but in rich domain-specific chunk knowledge and experience. Chunking theory can explain the previously mentioned phenomenon of low predictive power of cognitive abilities for chess rankings (Burgoyne et al., 2016)—that is, structured knowledge or specific experience combined with the domain is the more important cognitive factor. The low explanatory power of cognitive abilities for game rankings may be similar to chess.

Building on chunking theory, research has found that soccer players' recognition of spatial topological patterns formed by team formations can effectively differentiate player levels, leading to the concept of "pattern recognition" in competitive sports (Williams & Davids, 1995; Williams et al., 2006). Pattern recognition emphasizes higher-dimensional pattern information underlying team sports, with understanding and recognition of such information being one of the core cognitive characteristics of high-level athletes. Go masters' memory of board positions, imaging experts' precise and rapid judgment of image patterns, and players' recognition of formation patterns all stem from long-accumulated chunk or pattern knowledge (Gobet & Simon, 1998; Krupinski, 2000). Chunks or patterns in professional AVG players may include memory of skill combinations, character matchups, team formations, and attack/defense rhythms, which may play key roles in players' game reading and anticipatory decision-making. In reality, e-sports involves more than mechanical skill; even in fighting games with less rich contextual information, understanding opponents' attack/defense rhythms or patterns is necessary for precise tactical judgment.

In summary, compared to gaming technique and gaming duration, cognitive abilities show low direct predictive power for players' game performance. On one hand, cognitive abilities may mediate game performance through gaming technique, resulting in low direct predictive effects. On the other hand, current cognitive tests do not involve core decision-making abilities, and experimental materials are not integrated with game projects. Furthermore, current research has not addressed higher-dimensional game patterns or chunk information.

From a competitive psychology perspective, this paper selected action video games, one of the main e-sports genres, with professional-level adult players as the primary research subjects. Discussing professional players' cognitive characteristics from a multi-cognitive perspective and connecting them with neural evidence leads to the following conclusions: First, professional action video game players have multiple visual attention advantages and prominent spatial working memory. Second, professional players' neural characteristics involve higher P3 amplitude during attentional processing, working memory performance related to plastic changes in the hippocampus and parietal regions, and enhanced functional connectivity in brain networks centered on the dorsolateral prefrontal cortex. Third, game training can improve some cognitive abilities, but short-term game training has limited cognitive benefits; overall, intervention studies still lack strong causal evidence. Fourth, current cognitive abilities have weak predictive effects on game performance; richer game chunk or pattern knowledge may be the key cognitive factor for predicting professional player performance. Finally, research on professional players in the action video game domain is still in its infancy, with inconsistencies and incomplete coverage. Professional and amateur players are not homogeneous, so caution should be exercised when generalizing research conclusions from professional players to the majority amateur population; positive results from adult studies should not be used as justification for encouraging children and adolescents to play games.

Research on the cognitive neuroscience of professional action video game players has gradually increased in recent years but remains limited. Evidence based on professional esports athletes is scarce, possibly because the industry does not sufficiently value professional players' cognitive abilities. Additionally, existing research results have limitations in guiding or predicting game performance. Most current study designs are small-sample quasi-experiments lacking strict variable control in controlled experiments, making them prone to Type I error inflation or publication bias. The stability of research findings needs systematic verification through larger sample sizes and intervention studies. Future research should strengthen the following three aspects.

6.1 Research Design: Limitations and Solutions for Cross-Sectional and Longitudinal Studies

Current cross-sectional studies comparing professional and novice players often fail to strictly balance control variables. Future research should strictly control participants' age, gender, education level, handedness, vision, and psychiatric history. In cross-sectional studies, the top 7% ranking criterion for professional players remains very broad, and differences within the top 7% may be substantial. Since current research in this field is limited, we have combined discussions for now; future studies should subdivide professional player levels based on specific indicators such as MMR, win rate, or professional player appearance rate (Kang et al., 2020). Additionally, there are few studies with amateur control groups matched for equivalent gaming duration (both weekly average and years). Since conducting long-term game intervention studies is difficult, future cross-sectional studies on professional AVG players should balance control group gaming duration as much as possible to clarify professional players' advantages. Future research should also specify participants' weekly gaming duration as precisely as possible, as professional players' weekly gaming duration may exceed amateurs, making it insufficient to only record gaming years. Furthermore, current AVG research mostly selects male participants; the cognitive factors underlying gender differences in game performance also require investigation.

Intervention studies can explain the causal relationship between professional players' cognition and game training. Current game training intervention studies are often too short, mostly less than 30 days, limiting their ability to explain the performance of professional players with years of gaming experience. Additionally, immediate post-tests are not suitable for game intervention studies; next-day post-tests with long-term follow-up are better choices. Moreover, given that cognitive strategies may moderate training outcomes (West et al., 2018), future intervention studies should consider the match between game content and training strategies when designing game training. Regarding the origins of professional players' cognitive characteristics, retrospective studies could investigate the relationship between individuals' metacognition of their abilities and gaming preferences. Alternatively, novices could be recruited and divided into groups with and without cognitive differences for game intervention studies to track and compare their game selection preferences, cognitive ability changes, and game performance.

6.2 Research Variables: Inclusion of More Perceptual and Domain-Specific Cognitive Tests

In general expertise research, expertise can be divided into perceptual expertise, cognitive expertise, and motor expertise (Bilali, 2017/2019). Professional AVG players' excellent performance in cognitive tasks may benefit from more fundamental perceptual advantages. One professional AVG player study used a global-local task with large letters composed of many small letters, comparing the degree of interference from incongruent trials between professional players and novices, and found no group differences. This suggests that professional AVG players' attentional advantages do not stem from perception but from attention itself (Wong & Chang, 2018). A meta-analysis on AVGs suggests that perceptual differences between players and novices may be the most prominent among all cognitive abilities (the largest difference between professional and amateur players may lie in higher-level cognition), while perceptual abilities are difficult to improve through intervention (Bediou et al., 2018). Unfortunately, current research on perceptual abilities in professional AVG players is limited. Some professional players are sensitive to subtle screen lag and network latency fluctuations, with network latency fluctuations involving time perception, yet there is minimal research on time perception in professional AVG players. Future research should deeply explore perceptual characteristics of professional AVG players, such as time perception, dynamic visual acuity (dynamic vision), auditory thresholds, spatial perception such as sound localization ability, and cross-modal information integration characteristics.

The core difference between professional and amateur players lies in domain-specific knowledge and experience. From this perspective, the next step in e-sports research could involve developing cognitive tests integrated with game-specific scenarios, incorporating variables such as game character spatial positions to examine players' recognition and judgment of chunks and patterns related to character positioning and attack/defense. Such domain-specific cognitive tests may better differentiate professional and amateur players and predict game performance. Additionally, cognitive tests should ideally provide metrics after speed-accuracy trade-off processing.

6.3 Research Directions: The G-Factor of Professional Players' Cognitive Characteristics

Cross-sport research has examined general cognitive abilities shared by team sport athletes and AVG players. For example, in a horizontal comparison among handball players, AVG players, and general college students, the three groups performed similarly in contextual learning, but in visual search, both AVG players and handball players outperformed college students (Schmidt et al., 2020). Such cross-sport studies provide preliminary evidence for important cognitive abilities related to competition. Different action video games have different mechanisms and may emphasize different cognitive structures. Both domestic and international professional scenes have seen players achieve outstanding results across different e-sports titles. This provides an opportunity to examine common cognitive characteristics of professional players successful across multiple projects, such as conducting case analyses of professional players who have achieved certain tournament rankings across multiple projects, or analyzing players who have reached professional levels in different games to extract their shared cognitive characteristics for systematic verification in intervention studies.

Furthermore, AVG competitive projects are rapidly evolving from computer to mobile platforms, and may even develop into metaverse-based e-sports projects using VR in the future. One study reported no cognitive ability differences between players using computers and mobile devices (Huang et al., 2017). Future research that can identify core cognitive characteristics and neural features of professional players across e-sports titles and device platforms can further advance our understanding of cognition.

References

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Note: Figure translations are in progress. See original paper for figures.