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Neural correlates of chess expertise: A systematic review of brain imaging studies comparing expert versus novice players

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ABSTRACT

Chess expertise involves a combination of advanced cognitive skills including strategic thinking, spatial reasoning, self-regulation of arousal/stress and memory, which are reflected in distinct neural processes. However, the precise neural mechanisms underlying these adaptations remain unclear. Understanding how chess expertise shapes brain function and structure across various brain imaging modalities will enhance our knowledge of expertise-related brain function. A systematic review of 18 neuroimaging studies using fMRI, fNRIS and EEG is presented here, highlighting the neural correlates of chess expertise versus those who have less experience of chess but who can play. Articles were selected based on their use of neuroimaging techniques and their focus on identifying brain regions linked to chess proficiency. It was found that expert chess players compared to novices exhibit greater activation in the bilateral fusiform gyrus and posterior middle temporal gyrus, which are associated with visual processing and spatial perception. In addition, experts demonstrate enhanced functional connectivity in networks underlying cognitive control and decision making, including the anterior cingulate cortex and the dorsolateral prefrontal cortex. Structural differences, such as reduced grey matter volume in the occipito-temporal junction and mediodorsal thalamus, suggest dynamic neurobiological changes that may reflect increased neural efficiency in chess experts. Studies show that chess expertise is associated with both structural and functional brain changes that reflect enhanced cognitive performance. These findings highlight the potential for chess training to improve cognitive abilities, such as impulse control and self-regulation, suggesting possible applications for cognitive interventions in clinical and other populations such as military or emergency services where cognitive performance needs to be optimal under pressure.

1. Introduction

Chess is a complex and cognitively demanding game that has fascinated researchers for decades due to its requirement for strategic thinking, attention and problem-solving. Originating in India during the 6th century, chess has become one of the most widely played games in the world, with millions of players ranging from novices (Elo score of 1500) to grandmasters (Elo score up to 2800, Dangauthier et al., 2007; Ericsson et al 2018). The Elo rating system in chess is a method to assess players' relative skill levels, developed by Hungarian physicist Arpad Elo, assigning each player a numerical rating based on their performance against other players. Chess relies on intricate cognitive processes, including memory, self-regulation, planning and visual-spatial reasoning, which has made it a valuable intervention for understanding human cognition (Burgoyne et al., 2016). Given the mental demands placed on players, chess has often been used to study expertise and cognitive adaptation, providing a window into how prolonged practice and experience can shape brain structure and function (Hänggi et al., 2014; Lane and Chang, 2018).

Cognitive research has identified several key processes that differentiate expert chess players from novices, these being: pattern recognition, memory, imagery, and decision making (Atherton et al., 2003; Lane and Chang, 2018; Villafaina Dominguez et al., 2019). Experts are known to have superior pattern recognition, the ability to chunk

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information and enhanced working memory when compared to novices or non-players (Chase and Simon, 1973; Gobet and Charness, 2006). For instance, expert chess players can recognise familiar patterns of pieces on a chessboard, which allows them to make faster and more accurate decisions under pressure (Gobet and Campitelli, 2007). These cognitive adaptations are thought to emerge from years of repetitive, persistent, deliberative, and increasingly complex practice, strengthening the mental processes associated with visual-spatial reasoning, self-regulation, decision-making and memory. However, while cognitive studies have provided insight into how experts outperform novices, the underlying neural mechanisms are still not fully understood.

Functional neuroimaging is an essential tool for exploring brain structure and functional networks that support chess expertise. Techniques such as structural and functional magnetic resonance imaging (s/fMRI), electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) allow researchers to observe real-time neural activity and corresponding longitudinal structural changes as people play chess. These methods have revealed significant differences between chess experts and novices (Bilalić et al., 2010; Hänggi et al., 2014; Wang et al., 2018), including altered functional connectivity and reduced cortical thickness (Ouellette et al., 2020).

Previous fMRI research has identified several key neural regions that appear to be specialised in expert chess playing. For example, Bilalic (2016) found that the fusiform face area (FFA) – which likely underpins the processing of complex 'patterns' that we typically see in faces – shows increased activation in expert chess players when viewing chess positions. Other studies have highlighted the role of the prefrontal cortex (PFC) in decision-making, self-regulation under pressure and future strategizing, with chess experts showing stronger functional connectivity between the PFC and subcortical areas compared to novices (Leong et al., 2024; Ouellette et al., 2020). Additionally, MRI has demonstrated that expert players have smaller grey matter volumes in the thalamus compared to novices (Wang et al., 2020), and the thalamus is a gateway region for multisensory processing and further, higher order cognition. In particular, the mediodorsal thalamus is involved in emotion regulation given its direct connectivity with prefrontal and anterior cingulate regions (Fang et al., 2024), and the mediodorsal thalamus ability to amplify prefrontal cortex function that modulates rule-based over impulsive responses (Halassa and Kastner, 2017). Moreover, Hänggi et al. (2014) reported reduced grey matter volume in experts in areas involved in visual-spatial reasoning, suggesting that expert players may develop neural efficiency and dynamic neural alterations through prolonged practice. Such findings point to a rich interplay between structural and functional brain adaptations in the development of chess expertise.

Despite a growing body of research, several gaps remain in the understanding of chess expertise from a neural perspective. Existing studies often employ different methodologies, making it difficult to compare findings across research. Sample sizes in functional neuroimaging studies are often small, which limits the generalisability of the findings. Finally, while neuroimaging has revealed specific brain areas involved in chess, the broader network dynamics that support expert performance, such as changes in white matter or long-term connectivity patterns, remain underexplored (Liang et al., 2022; Wang et al., 2020). Given these gaps and the lack of review examining brain imaging studies of chess players, this systematic review is a timely synthesis of the available neuroimaging evidence. Understanding the neural correlates of expert chess playing is not only important for clarifying the processes behind chess mastery but also as a contribution to broader theories of expertise, dynamic neural changes and skill acquisition (Gobet and Charness, 2006). By reviewing studies that use functional neuroimaging to examine the neural differences between chess experts and novices, this review will consolidate findings to identify patterns in brain activity that distinguish experts from novices. The review will also highlight areas for future research, with a focus on how long-term practice of chess might reshape the brain, and whether chess could be used as an engaging cognitive training intervention for those with mental health difficulties, or to enhance cognitive abilities in those who need to make decisions under pressure (e.g. military, emergency services etc).

2. Methodology

A systematic search was conducted via PubMed to identify relevant studies published between 01/01/2014 and 09/05/2024. The search used the term "Chess fMRI," OR "Chess EEG" OR "Chess SPECT" OR "Chess fNIRS", which yielded 76 results. A subsequent search with the term "Chess Brain" OR "Chess Neuro" returned 122 results. The search was limited to peer-reviewed articles published in English. No other databases were searched although reference lists of publications were examined, and the search was not restricted to any specific study design. To be included in the review, studies had to meet several criteria. First, they must have been published in the last decade between 01/01/2014 and 09/05/2024 and written in English. Importantly, studies were required to utilize functional neuroimaging techniques, specifically functional magnetic resonance imaging (fMRI), electroencephalography (EEG), Single Photon Emission Computed Tomography (SPECT). Positron Emission Tomography (PET) or functional near-infrared spectroscopy (fNIRS). Only studies that involved participants with significant experience in playing chess were considered, ensuring that the neuroimaging findings reflected chess expertise but with a comparison to those with little experience (but who could play).

Exclusion criteria were also applied. Studies that relied primarily on physiological measures such as heart rate or skin conductance were excluded, although these were referenced in the discussion. Additionally, studies focusing on board games such as Shogi, Checkers, or Onitama, were excluded but were mentioned in a broader discussion. Meta-analyses and review articles were not included in the final analysis but were cited in the text for context or background information.

In total, the searches yielded 178 results. Duplicates were removed, and the remaining studies underwent a three-step screening process. First, the titles were reviewed to identify potentially relevant articles. Abstracts of the remaining studies were then screened to ensure they met the inclusion and exclusion criteria. Finally, full-text reviews were conducted on the selected studies to confirm their eligibility for inclusion in the systematic review. For each included study, relevant data were extracted, including details about the study design, participant characteristics (e.g., level of chess expertise), neuroimaging techniques used, and key neural findings. The studies were categorized based on the neuroimaging method employed, allowing for a structured analysis of the neural correlates of chess expertise across different modalities. This process is demonstrated in Fig. 1, and included studies are summarised in Table 1.

3. Results

22 Papers were identified which reported using neuroimaging techniques to investigate the neural underpinnings of chess playing. One article implemented surface-based morphology (SBM) to examine cortical thickness from a raw public dataset and was therefore excluded (Ouellette et al., 2020). One article presented only a dataset and did not include any statistical analysis or discussion, so it was excluded as well (Li et al., 2015). 1 EEG study was removed because it looked at the Japanese board game shogi (which is often referred to as a Japanese version of chess) and not chess itself (Nakatani and Yamaguchi, 2014). Finally, one was removed as it was a protocol and contained no results (Gerhardt et al., 2022). These papers were removed from the analysis but may still be referred to in the discussion. This left 18 original research papers in which a group of participants' neural regions were examined in relation to chess playing/ training (See Table 1). The main task design identified in these papers was comparing brain regions in expert/ experienced chess players with novice/ beginner players ($N = 13$).

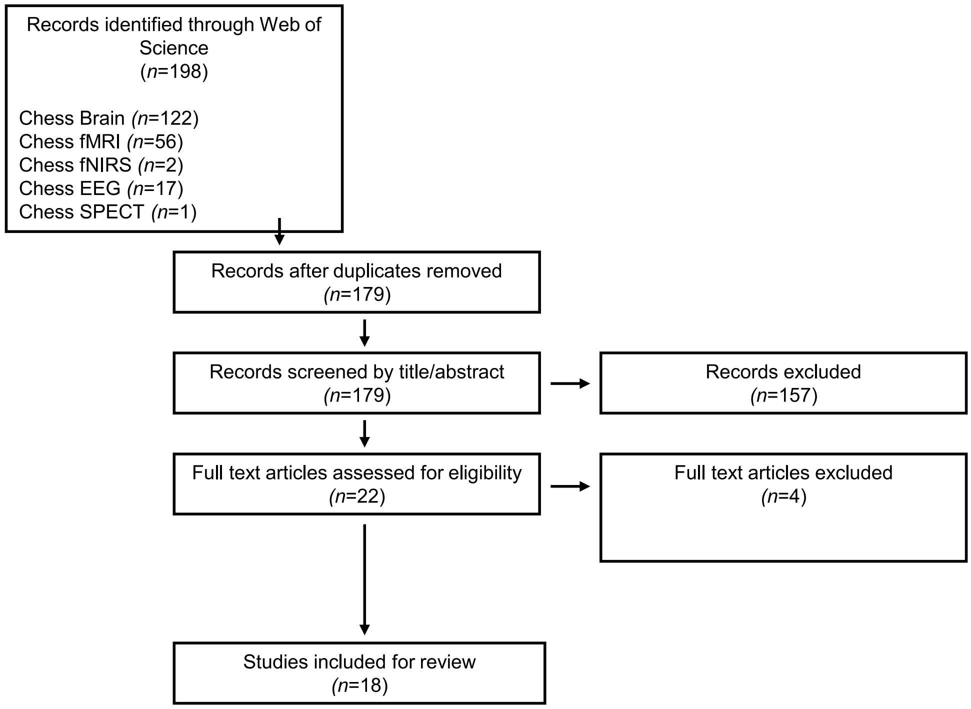

Fig. 1. CONSORT diagram to illustrate the search and inclusion process for studies included in the systematic review.

3.1. *Chess experimental conditions*

18 neuroimaging studies included 11 fMRI, 3 EEG, 2 MRI, and 2 fNIRS. Some studies were cross-sectional, examining brain structure and function of self-reported chess experts versus novices, though in these studies the experimental procedure did not involve playing chess but simply passive MRI (Hänggi et al., 2014; Wang et al., 2020), passive resting-state fMRI (Liang et al., 2022), passive structural and functional connectivity modelling (Regional Homogeneity, Grainger Causality, Seed-based Connectivity, Independent Component Analysis, Morphometric Connectivity, Functional Morphometric Similarity Connectome, Resting State Functional Connectivity, Functional Connectivity Strength) and comparing experts and novices with these connectivity models (Wang et al., 2018; Song et al., 2020; RaviPrakash et al., 2021; Song et al., 2022; Trevisan et al., 2022). Other studies of experts versus novices involved comparing brain activation when watching images of faces versus chess stimuli (Bilalić, 2016), while other studies engaged participants in deciding on the next move of a chess image (Powell et al., 2017), imagining chess moves of varying difficulty (meta-states, Premi et al., 2020), chess puzzles of varying difficulty (Pereira et al., 2020), playing chess end-games of varying difficulty (Villafaina et al., 2021), playing a full game of chess with players of different levels (better, worse, comparable), playing speed versus 15-minute chess (Villafaina et al., 2019; Leong et al., 2024) and analysis of playing chess comparing winners versus losers (Fuentes-García et al., 2020). See Table 1.

3.2. *Expert vs novice chess players*

Hanggi et al. (2014) measured grey matter volume and cortical thickness and reported reductions in expert chess players compared to a control group in both the occipito-temporal junction (OTJ) and precunei. There was a negative correlation between caudate nucleus volume and years of chess experience. Mean diffusivity was increased in experts compared to that of controls in the left superior longitudinal fasciculus, and chess tournament rankings (the Elo score) were inversely related to mean diffusivity within the right superior longitudinal fasciculus.

Bilalic (2016) used fMRI and found that the FFA in expert chess players showed greater activation when viewing chess positions compared to non-chess players, suggesting that the FFA in experts is more tuned to the visual complexity and relational aspects of chess positions. Multivariate pattern activation (MVPA) revealed that the FFA in experts could identify patterns in chess positions better than in novices, which suggests that the brains of chess experts are better at recognising and interpreting complex visual stimuli due to their extensive experience and practice. While novices show less differentiated neural responses, experts demonstrated significant neural specialisation, which likely underpins their superior visual and cognitive abilities in chess.

Wang et al. (2018) used fMRI to show higher functional connectivity homogeneity in the anterior middle temporal gyrus (aMTG) in professional chess players compared to novices.

Langner et al. (2019) measured chess expertise using fMRI to show enhanced functional connectivity between the posterior middle temporal gyrus (pMTG) and areas involved in action planning and visual processing, compared to novices. The collateral sulcus (CoS) in experts was also more connected with regions related to spatial perception and navigation, reflecting superior pattern recognition. Resting-state functional connectivity (RSFC) and meta-analytic connectivity modelling (MACM) revealed that experts compared to novices have enhanced activation in both hemispheres, but that the right pMTG appears to play a preferential role in linking object identity with potential actions.

Premi et al. (2020) used functional connectivity to show that chess players exhibit an increased dynamic fluidity when compared to beginner chess players. Chess playing may induce changes in brain activity through the modulation of the connectome.

Similarly, Song et al. (2020) used functional connectivity to show decreased functional connections in expert chess players between the right dorsal-anterior subregion and left angular gyrus and increased functional connections between the right ventral-anterior visual motion area subregion and right superior temporal gyrus. Moreover, they reported increased mutual interactions of the left angular gyrus and right dorsal-anterior subregion in chess experts compared to novices. This could suggest that professional chess playing enhances spatial perception and reconfiguration and semantic processing efficiency for superior

Table 1
Studies included in the systematic review (N = 18).

Author (Year)	Title	Participants M=male (n = 374), F=female (n = 178) 3 studies gender not available	Imaging modality	Main findings	Average Score (Elo rating) for the experts	Experimental design	Lateralisation
Bilalić (2016)	Revisiting the role of the fusiform face area in expertise	60 (28 experts M = 27, F = 1; 32 novices M = 20, F = 2)	fMRI	Chess expertise modulated FFA activation to presented stimuli	Above 2000 Elo* rating	Expert vs beginner chess players. Participants were either presented with facial or chess stimuli on a computer screen.	Right
Fuentes-García et al. (2020)	Chess players increase the theta power spectrum when the difficulty of the opponent increases: an EEG study	14 (All chess players but none were considered experts) M = 14	EEG	Participants who won their games were able to adapt to each chess game situation, increasing theta power when the opponent's difficulty increased	N/A	Conditions were based on winning or losing a chess game. Participants conducted three chess games of 3 min, plus 2 s of additional time per move. Chess games were played digitally. There were three difficulty levels: against their same Elo (100 % chess games), 25 % over their Elo (125 % chess games), and 25 % under their Elo (75 % chess games).	N/A
Hänggi et al. (2014)	The architecture of the chess player' s brain	40 (20 experts M = 20; 20 novices M = 20)	MRI	Reduced gray matter and corticol thickness volume in the occipito-temporal junction in chess players.	2366	Expert vs beginner chess players. Chess players and a group of controls both received MRI to examine the morphological differences in a network comprised by parietal and frontal areas and especially the occipito-temporal junction (OTJ), fusiform gyrus, and caudate nucleus.	Bilateral
Leong et al. (2024)	Distinct brain network organizations between club players and novices under different difficulty levels	40 (20 experts; 20 novices) Gender data not provided	fNIRS	Professional players illustrate significant frontal-parietal functional connectivity patterns and topological characteristics	1501.85	Expert vs beginner chess players. Participants were tasked with facing two opponents of differing skill levels The chess games took place online. The task had a time limit of 3 min, requiring players to complete a minimum of 15 moves within this timeframe.	Bilateral
Liang et al. (2022)	Training-specific changes in regional spontaneous neural activity among professional chinese chess players	43 (22 experts M = 4, F = 8; 21 novices M = 13, F = 8)	fMRI	Expert chess players show increased regional spontaneous activity in the posterior lobe of the left cerebellum, the left temporal pole, the right amygdala and the brainstem, but decreased regional homogeneity in the right precentral gyrus	2410	Expert vs beginner chess players Regional homogeneity analysis of resting state-fMRI was performed to determine local connectivity changes and their relation to profile changes.	Bilateral
Pereira et al. (2020)	Dynamics of the prefrontal cortex during chess-based problem-solving tasks in competition-experienced chess players: an fNIR study	30 (All had more than 4 years of continuous chess playing experience) M = 30	fNIRS	L-PFC increased its activation with the difficulty of the task in both adults and adolescents	N/A	Adult vs adolescent chess players. Participants had to complete chess puzzles at different difficulty levels. The puzzles were completed online. These chess problems consisted of three levels	Left

(*continued on next page*)

Table 1 (*continued*)

Author (Year)	Title	Participants M=male (n = 374), F=female (n = 178) 3 studies gender not available	Imaging modality	Main findings	Average Score (Elo rating) for the experts	Experimental design	Lateralisation
						of difficulty intended for chess players with an ELO rating of 1600–2400, with 1 being the lowest and 10 the highest level of difficulty: low-level (1), medium-level (5), and high-level (10) chess problems. Participants had two and a half minutes to solve each problem. Two moves for each problem were required.	
Powell et al. (2017)	The neural correlates of theory of mind and their role during empathy and the game of chess: A functional magnetic resonance imaging study	12 (All participants had a minimum of 4 years of experience playing chess) M = 12	fMRI	Neural overlap in the right temporal junction, left STG and posterior cingulate gyrus in chess, theory of mind and empathy tasks	N/A	Linked chess players' brains to theory of mind related neural structures. Participants looked at chess positions and had to choose what move they would do. This took place on a computer screen.	Bilateral
Premi et al. (2020)	Enhanced dynamic functional connectivity (whole-brain chronnectome) in chess experts	38 (18 experts M = 13, F = 5; 20 novices M = 7, F = 13)	fMRI	Expert chess players exhibit increased dynamic fluidity.	N/A	Expert vs beginner chess players. Dynamic connectivity parameters were evaluated applying spatial independent component analysis (sICA), sliding-time window correlation, and meta-state approaches to rs-fMRI data. Four indexes of meta-state dynamic fluidity were studied: *i)* the number of distinct meta-states a subject pass through, *ii)* the number of switches from one meta-state to another, *iii)* the span of the realized meta-states (the largest distance between two meta-states that subjects occupied), and *iv)* the total distance travelled in the state space.	N/A
RaviPrakash et al. (2021)	Morphometric and functional brain connectivity differentiates chess masters from amateur players	47 (24 experts M = 16, F = 8; 23 novices M = 8, F = 15)	fMRI	The saliency and ventral attention network of the brain are both functionally and anatomically different in professional chess players compared to amateurs.	N/A	Expert vs beginner chess players. This study looked at a dataset of amateur and professional chess players, the researchers utilized resting-state functional MRI to generate functional connectivity (FC). In addition, they utilized T1-weighted MRI to estimate morphometric connectivity (MC). The researchers combined functional and anatomical features into a new connectivity matrix, which they termed as *functional morphometric similarity connectome (FMSC)*.	Bilateral

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Table 1 (*continued*)

Author (Year)	Title	Participants M=male (n = 374), F=female (n = 178) 3 studies gender not available	Imaging modality	Main findings	Average Score (Elo rating) for the experts	Experimental design	Lateralisation
Song et al. (2020)	Altered intrinsic and casual functional connectivities of the middle temporal visual motion area subregions in chess experts	55 (28 experts M = 18, F = 10; 27 novices M = 12, F = 15)	fMRI	Decreased functional connections between right dorsal-anterior subregion and left angular gyrus in chess experts. Increased functional connections between right ventral-anterior visual motion area subregion and right superior temporal gyrus in chess experts.	N/A	Expert vs beginner chess players. This study used resting-state functional connectivity (RSFC) and Granger causality analysis (GCA) to study changed functional couplings of visual motor area subregions.	Bilateral
Song et al. (2020)	Changed hub and functional connectivity patterns of the posterior fusiform gyrus in chess experts	55 (28 experts M = 18, F = 10; 27 novices M = 12, F = 15)	fMRI	Increased functional connectivities between the right posterior fusiform gyrus and the visuospatial attention and motor networks in chess players.	2408.95	Expert vs beginner chess players. The researchers first mapped the whole-brain voxel-wise functional connectivity and calculated the functional connectivity strength (FCS) map in each of the chess players and novice players. Whole-brain resting-state functional connectivity analyses for the changed hub areas were conducted to further elucidate the corresponding changes of functional connectivity patterns in chess players.	Right
Song et al. (2022)	Professional chess expertise modulates whole brain functional connectivity pattern homogeneity and couplings	55 (28 experts M = 18, F = 10; 27 novices M = 12, F = 15)	fMRI	Increased whole brain functional connectivity pattern in ACC, aMTG, V1 and decreased functional pattern homogeneity in thalamus and precentural gyrus in chess players	N/A	Expert vs beginner chess players. This study employed whole brain functional connectivity pattern homogeneity (FcHo) method to identify the voxel-wise changes of functional connectivity patterns in 28 chess master players and 27 healthy novices. Seed-based functional connectivity analysis was used to identify the alteration of corresponding functional couplings.	Bilateral
Trevisan et al. (2022)	Surface-based cortical measures in multimodal association brain regions predict chess expertise	58 (29 experts M = 20, F = 9; 29 novices M = 14, F = 15)	fMRI	Chess expertise is based on the complex properties of the brain surface of a network of transmodal association areas important for flexible high-level cognitive functions.	2401.10	Expert vs beginner chess players. Fractional dimension (FD) and gyrification index (GI) for each brain region were compared between the groups. A multivariate model was used to identify surface-based brain measures that can predict chess expertise.	Bilateral
Villafaina et al. (2021)	Neurophysiological and autonomic responses of high and low level chess players during difficult and easy chess endgames–A quantitative EEG and HRV study	28 (15 high level players; 13 low level chess players) Gender data not available	EEG	High level chess players exhibit more alpha EEG power spectrums during difficulty chess endgames in the occipital area. High performance players showed a reduced autonomic modulation during the	1918.40	Easy vs difficult chess endgames. Participants randomly conducted four chess endgames divided into two levels using the computer as interface: 1) Easy level (two chess endgames), and 2)	N/A

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Table 1 (*continued*)

Author (Year)	Title	Participants M=male (n = 374), F=female (n = 178) 3 studies gender not available	Imaging modality	Main findings	Average Score (Elo rating) for the experts	Experimental design	Lateralisation
				difficult chess endgames which low performance players did not reach		Difficult level (two chess endgames). Participants had to accomplish checkmate using the fewest number of moves.	
Villafaina et al. (2019)	Electroencephalographic response of chess players in decision-making processes under time pressure	14 (All chess players) M = 14	EEG	Different brain electrical patterns were found between different game speeds. Under time pressure high values of theta power were found in posterior regions.	1921.07	Different time conditions. Participants conducted two chess games, a 1 min chess game (lightning) and 15 plus a 10 s increment for each movement (rapid). Chess games were completed online against an AI.	N/A
Wang et al. (2018)	Whole brain functional connectivity pattern homogeneity mapping	58 (29 experts; 29 novices) Gender data not available	fMRI	Higher functional connectivity homogeneity in the anterior MTG was observed in professional chess players compared to novices	N/A	Expert vs beginner chess players. Functional connectivity homogeneity was used to identify the differences of whole brain functional connectivity patterns between professional Chinese chess players and novices.	Bilateral
Wang et al. (2020)	Reduced thalamus volume and enhanced thalamus and fronto-parietal network integration in the chess experts	55 (22 experts M = 18, F = 4; 29 novices M = 14, F = 15)	MRI	Smaller gray matter volume regions in the thalami as well as strengthened integration between the thalamus and fronto-parietal network in expert players.	N/A	Expert vs beginner chess players. The researchers found smaller gray matter volume regions in the thalami of expert Chinese chess players in comparison with novice players. They then used these regions as seeds for resting-state functional connectivity analysis and observed significantly strengthened integration between the thalamus and fronto-parietal network.	Bilateral

[*] Elo rating system in chess is a method to assess players' relative skill levels. Developed by Hungarian physicist Arpad Elo, it assigns each player a numerical rating based on their performance against other players. A beginner usually starts with a rating of 1500, with game winners/losers winning/losing points. The number of points exchanged depends on the rating difference between the players and the expected outcome (e.g., a lower-rated player beating a higher-rated one earns more points). Expected Score = 1 / (1 + 10^((Opponent's Rating - Your Rating) / 400)). Ratings typically range from ~1000 (novice) to over 2800 (world-class grandmasters).

performance. This study also showed that chess experts have increased functional connectivity strength in the right posterior fusiform gyrus, the right posterior fusiform gyrus and the visuospatial attention and motor networks. This demonstrates that cognitive expertise has a positive influence on the functions of the brain regions associated with attention and motor control.

Using structural and functional imaging measures, Wang et al. (2020) compared experts with novice chess players and found that the volume of the thalamus in chess experts was significantly smaller, but the thalamus showed enhanced connections with the fronto-parietal network (FPN).

Furthermore, RaviPrakash et al. (2021) showed that the saliency and ventral attention networks were both functionally and anatomically different in professional chess players compared to amateurs.

More functional connectivity work by Liang et al. (2022) revealed that compared to novices, professional chess players showed increased regional spontaneous activity in the posterior lobe of the left cerebellum, the left temporal role, the right amygdala, and the brainstem, but decreased regional homogeneity in the right precentral gyrus. From a whole-brain point of view, local activity in regions such as the posterior lobe of the right cerebellum and the caudate correlated with enhanced training profiles.

Later work by Song et al. (2022) revealed that chess experts exhibit significantly increased whole brain functional connectivity pattern similarity in anterior cingulate cortex (ACC), anterior middle temporal gyrus (aMTG), primary visual cortex (V1), and decreased functional connectivity pattern homogeneity in the thalamus and precentral gyrus. Chess experts also show decreased functional connections between V1 and the precentral gyrus. The findings indicate that long-term professional chess playing may enhance coherence in brain networks, especially those related to semantic and episodic processing, efficiency of visual-motor transformation and cognitive control.

Structurally, Trevisan et al. (2022) showed that chess expertise predicts increasing fractional dimension in the left frontal operculum 5 (FOP5) and decreasing fractional dimension in the right temporal area and left caudal part of the dorsomedial prefrontal cortex. Chess expertise is associated with fractional dimension values in a set of association regions including the left fronto-opercular cortex, the right SPL/posterior cingulum and the lateral temporal cortex, and the fronto-medial cortex.

In a recent fNIRS study, Leong et al. (2024) showed that expert chess players exhibit distinct functional connectivity patterns and enhanced network characteristics compared to non-experts. These differences were particularly pronounced during high-difficulty chess games, highlighting the role of chunking processes in expert performance. The ability of chess experts to manage cognitive resources efficiently under pressure is supported by functional networks involving the frontopolar cortex (FPC), dorsolateral PFC (dlPFC), supramarginal gyrus (SMG) and subcentral gyrus (SCG), which are crucial for segmentation of cognition and emotion, pattern recognition and decision making in chess.

In summary, these studies have elucidated the difference in functional connectivity networks and related structural differences in the brains of expert chess players versus novices. Collectively, it appears that the neural architecture of expert chess players is significantly shaped by their extensive experience and practice.

3.3. Other experimental designs

Powell et al. (2017) used fMRI to examine the neural underpinnings of theory of mind (ToM), empathy and its relation to chess playing prowess. All participants had a minimum of 4 years of chess playing experience. Results revealed a neural overlap between ToM, empathy, and chess ability in the right-hemisphere temporo-parietal junction (TPJ), left-hemisphere superior temporal gyrus (STG), and posterior cingulate gyrus. Conversely, a network of cortical regions primarily within both hemispheres of the medial-frontal and parietal cortices, were selectively recruited while playing chess.

In an EEG study, Villafaina et al. (2019) examined neural electrical activity patterns of chess players in two different time pressures: rapid (15 min plus 10 s additional time) and rapid (1 min game). Results showed that increments in theta power during the lighting game were found in posterior brain regions (central and parietal). The right hemisphere was slightly more activated in both game conditions. Under time pressure, higher values of theta power were found in posterior regions. Finally, frontal area was more activated when further time to make a decision was allowed.

Fuentes-García et al. (2020) also used EEG to examine theta, alpha and beta power spectrum between participants who won and lost games in three different conditions: same skill, 25 % higher skill rating (Elo), 25 % lower skill rating. Results showed that the winning group had higher theta power in the frontal, central and posterior brain regions when difficulty increased. Alpha power showed higher levels in the condition where participants played against an opponent with a 25 % higher skill raring in C3, T3, T4, T5, and T6. The losing group showed a significant decrease in beta and alpha power spectrum in frontal, central, parietotemporal and occipital areas when the opponent's difficulty increased.

In an fNIRS study, Pereira et al. (2020) compared the dynamics of the PFC between adult and adolescent chess players, during chess-based problem-solving tasks of increasing difficulty levels. The left PFC increased in activity with the difficulty of the task in both adults and adolescents.

In a later EEG study, Villafaina et al. (2021) examined low vs high performance in chess players during easy and difficult chess endgames. All participants were chess players and were split into two groups (high level chess players and low-level chess players) based on Elo ratings. EEG responses did not show any differences between high- and low-level chess players. However, the EEG response in alpha power spectrum significantly changed between easy and difficult endgames in high performance chess players in the occipital area. This response was not observed in low performance chess players.

In summary, other experimental designs have provided additional insights into the neural mechanisms underlying chess performance under different conditions. Collectively the studies appear to suggest enhanced frontal and posterior crosstalk between regions when playing increasingly difficult chess games.

3.4. Lateralisation and gender

10 studies reported bilateral network activation and structural differences, whereas two reported right and one reported left lateralised activation, the remaining studies did not report lateralisation effects. The gender of the participants was significantly skewed towards male players, in total 374 male versus 178 female participants took part in the studies (3 studies did not report the gender of the participants).

4. Discussion

Across the 18 studies analysed in this systematic review, there is significant evidence that expert chess playing leads to distinct neural adaptations, broadly in line with the view that deliberative processing in left hemisphere top-down regions occurs in novices, whereas experts utilise right dominant or bilateral processing to achieve cognitive focus and complex pattern recognition under pressure – especially for difficult games. Expert chess players show functional differences compared to novices with notable changes in brain regions responsible for visual processing, cognitive control, memory, attention, and executive function. Specifically, visual and parietal cortex areas such as the fusiform gyrus and precuneus, and regions of the prefrontal cortex showed increased activation in chess experts, whereas bilateral thalamus, particularly the mediodorsal with direct connectivity to the prefrontal cortex showed reduced grey matter volume in experts. These findings indicate that prolonged chess training influences brain connectivity, leading to greater efficiency in spatial perception, pattern recognition, and decision-making abilities. Modalities like sMRI, fMRI, fNIRS, and EEG contribute diverse insights into these changes, allowing for a holistic understanding of the structural and functional neural basis of chess expertise.

sMRI studies consistently show that chess experts exhibit dynamic alterations in grey matter volume. For example, Hanggi et al. (2014) observed reduced grey matter volume and cortical thickness in expert compared to novice players, particularly in the occipito-temporal junction and precunei, suggesting that chess expertise leads to specific structural changes in visual attention areas. Additionally, they found a negative correlation between caudate nucleus volume and years of chess experience, which is also observed in those who engaged in adaptive working memory training and suggestive of greater neural efficiency – e.g. more efficient neural processes may be related to down regulation of receptor densities (Brooks et al., 2020). In terms of white matter structural alterations, Hanggi et al. found increased mean diffusivity in the left superior longitudinal fasciculus, with higher chess rankings inversely related to diffusivity in the right superior longitudinal fasciculus. This suggests that long-term chess experience influences neural connectivity and dynamic remodelling of white matter tracts over time, particularly in regions related to visuospatial processing and cognitive control. However, it is not yet clear how much time and how much improvement in chess playing is needed to effect these neural changes in grey (e.g. receptor densities, synaptogenesis etc) and white matter (tractography, novel connectivity in shape and size etc).

Similarly, Bilalic (2016) showed that expert chess players compared to novices exhibited greater activation in the fusiform face area (FFA) when passively viewing chess positions, highlighting the brain's adaptation to complex visual stimuli and pattern recognition. This finding aligns with Song et al., (2020, 2022), who demonstrated increased functional connectivity in regions such as the fusiform gyrus, anterior middle temporal gyrus and the anterior cingulate cortex in experts, indicating enhanced efficiency in visual-motor transformation and semantic processing. Functional connectivity also emerged as a key measure in Langner et al. (2019), who found that experts showed enhanced connectivity between the posterior medial temporal gyrus and regions involved in action planning and visual processing. In summary, the studies presented here collectively indicate that chess expertise leads to both structural and functional changes in the brain, enhancing connectivity in areas responsible for visuospatial processing, action planning, decision making and cognitive control.

fNIRS offers a promising alternative to fMRI due to its portability and higher tolerance to movement, and cost effectiveness, making it more suitable for naturalistic and dynamic task settings like chess playing in situ (as opposed to in a supine position in the fMRI scanner). However, fNIRS has lower spatial resolution – especially for subcortical regions - compared to fMRI, which limits the ability to accurately map global neural networks. Nevertheless, the fNIRS studies presented here collectively reinforce the role of the PFC in executive functioning and decision-making during chess, suggesting that fNIRS remains useful for understanding real-time cognitive processes and potential top-down control activations despite its limitations.

EEG studies provide valuable insights into the temporal dynamics of chess-related neural activity, which complement the spatial findings from fMRI and fNIRS. EEG has superior temporal resolution, allowing researchers to observe rapid changes in brain activity during chess tasks. Taken together, the EEG studies highlight how brainwave activity, particularly in the theta and alpha bands, varies with skill level, task difficulty, and time pressure in chess. Theta power seems to increase as cognitive load rises, while alpha activity is closely related to both performance level and the complexity of the task, particularly in more difficult situations for expert players who demonstrate superior cognitive flexibility, attentional control, and perceptual processing. Their brains seem to be more adaptable to both increased task difficulty and time pressure, enabling them to maintain higher performance levels. This heightened neural efficiency, particularly in the theta and alpha bands, likely underpins their superior problem-solving and decision-making abilities in chess.

Although the present study did not include any physiological or eye-tracking papers in the analysis, it is beneficial to discuss the insights these methods can provide, as some studies have included these. For example, some studies using heart rate variability (HRV) measures have consistently demonstrated that professional chess players exhibit better autonomic regulation compared to novices. Specifically, HRV tends to decrease during chess games as cognitive load increases, but professional players show more flexible HRV patterns, including superior autonomic control and cognitive resource management (Fuentes et al., 2018; Fuentes-García et al., 2020; Villafaina et al., 2021). This aligns with fMRI findings suggesting experts display more efficient functional connectivity in neural regions responsible for cognitive control of arousal (Leong et al., 2024). High-performance players tend to maintain higher HRV during chess tasks, suggesting better autonomic regulation is linked to superior cognitive performance under pressure (Villafaina et al., 2021). Eye-tracking research further illustrates the visual and attentional differences between experts and novices. Expert chess players can rapidly recognise and differentiate complex visual patterns on the chessboard, leading to faster reaction times compared to novices (Reingold et al., 2001; Sheridan and Reingold, 2017), as well as maintaining better focus and emotional regulation during problem-solving tasks, allowing them to allocate cognitive resources more effectively (Guntz et al., 2018). These visual processing advantages are supported by neuroimaging findings that show increased activity in regions associated with visual attention and pattern recognition, such as the fusiform face area (Bilalić, 2016).

Lateralisation of brain function during chess playing might hold further clues to the mechanism of becoming a chess expert. For example, previous fMRI and EEG research suggests a right-lateralised pattern of neural activation in chess experts in the visual attention, pattern recognition and cognitive control/executive functioning regions described above. For example, Bilalić (2016) found increased right FFA activation to chess stimuli in experts, and Song et al. (2020) found increased functional connectivity between the right posterior fusiform gyrus and the right visuospatial attention and motor networks in expert chess players. Other studies suggest that less expert chess players rely on left-hemisphere dominant neural functions, such as language-associated analytic skills, including planning and deliberative, effortful holding in mind of complex sequences as the game becomes more difficult (Pereira et al., 2020). However, most of the studies reviewed here reported bilateral structural and functional differences between novice and expert chess players, suggesting that during an experimental procedure at least (e.g. supine position in a dark and noisy brain scanner), chess playing incorporates a variety of cognitive functions linked to pattern recognition, spatial awareness and planning, across both hemispheres. In line with this, it has previously been suggested that during expert play, the right hemisphere is active for more holistic, intuitive processing, whereas people with less experience tend to utilise deliberative skills associated with the left hemisphere Bilalić (2011), both of which appear in this review of studies.

Chess playing is typically a male-dominated game, according to the World Chess Federation only 11 % of their rated members are female (FIDE, 2023). In professional tournaments, where female games are often played separately to the males at elite levels, the gender discrepancy in player gender is even starker, with only 5% being female participants in the Chess Olympiad or World Championships. As of 2025, no female has ever won the open World Chess Championship, and only Judit Polgar has competed at the highest levels, peaking at World ranked eighth position in 2005 twenty years' ago. In 2007 a brain imaging study conducted by Bilalić suggested that male chess players had significantly greater right hemisphere occipito-parietal activation for spatial processing and pattern recognition than females, whereas females showed greater bilateral activation suggesting different cognitive strategies. The gender discrepancy in chess playing was reflected in the number of total participants across all 18 studies of each gender in this review (374 males versus 178 females) preventing definitive conclusions about gender differences in neural structure and function in chess players. Greater access, support and encouragement should be given to female players of chess, not least due to the beneficial neural effects of playing chess highlighted in this review.

This review offers a comprehensive and multi-modal analysis of the neural correlates of chess expertise, synthesising findings across MRI, fMRI, fNIRS and EEG studies. The methodologies covered allow for a more integrated understanding of how chess expertise impacts both brain structure and function. Despite these strengths, there are several limitations that should be acknowledged. First, while there is a good cohort of findings that utilise fMRI, fNIRS and EEG, more advanced technologies such as magnetoencephalography (MEG) or multi-modal imaging approaches have not been utilised. These could offer more detailed insights into the temporal dynamics and neural network activity associated with expert chess performance. For example, techniques like MEG would allow for the precise timing of cognitive processes, which would deepen our understanding of how temporal resolution interacts with task performance. Additionally, many of the studies included in this review are limited by small sample sizes. For instance, studies like Liang et al. (2022) and Song et al. (2022) involve relatively small groups of participants, which limits the ability to apply these findings broadly. Future research could address this by encouraging meta-analytic approaches or collaborative multi-centre studies that pool data across research sites, thereby enhancing the robustness of conclusions. Another key limitation is the lack of longitudinal data in the reviewed studies, and so it is not known if gains of function persist. Most of the research, such as Premi et al. (2020) and Trevisan et al. (2022), relies on cross-sectional designs, comparing expert and novice players at a single time point. This provides only a snapshot of brain differences at one moment in time. Longitudinal studies tracking neural changes over the course of chess training and improved expertise would provide deeper insights into how brain plasticity unfolds and adapts over time as individuals transition from novice to expert. Additionally, there is a lack of cross-cultural considerations within the reviewed studies, most of which focus on participants from regions such as China and Europe. Cultural differences in chess training methods, cognitive strategies, and motivations for playing may lead to varied neural adaptations, and this gap in the literature limits the generalisability of findings across diverse populations.

The findings suggest that chess playing has potential to improve cognitive abilities with specific brain regions becoming more efficient due to regular chess play. However, the real potential of chess playing lies in its application to far-transfer effects, for example, chess-based cognitive training, where cognitive improvements extend beyond chess-specific tasks to broader areas of functioning. Research on other forms of cognitive training, such as working-memory training, has shown neural improvements corresponding to general cognitive abilities like self-regulation, impulse control, and planning (Brooks et al., 2020; Brooks et al., 2017; Brooks et al., 2016; Bürki et al., 2014; Jaeggi et al., 2011). Given the executive functioning demands of chess, it is plausible that regular chess training could foster similar far-transfer benefits, particularly in emotion regulation and impulse control, and might be more beneficial than other training interventions given that it might be more engaging and fun. For example, chess requires management of arousal and maintenance of focus during lengthy games, which could translate into the improved emotional resilience and self-regulation in other settings.

Clinical populations could particularly benefit from chess-training far-transfer effects. For example, cognitive deficits in disorders such as schizophrenia and bipolar disorder often include impaired executive functions like impulse control and planning (Carvalho et al., 2017). Similarly, anxiety and addiction disorders could see improvement in emotion regulation and impulse control through the strategic and cognitive demands of chess (Verdejo-García et al., 2019). Moreover, cognitive interventions that target self-regulation and emotional control have been shown to improve quality of life in individuals with other mental health disorders (Cella et al., 2017). Further research should investigate whether regular and increasingly difficult chess training could serve as an effective adjunctive intervention for improving cognitive deficits and emotional regulation in these populations.

The far-transfer potential of chess could extend beyond clinical populations. Chess might improve educational outcomes by enhancing students' problem-solving skills, strategic thinking, and attention control. Longitudinal studies could examine whether regular chess training can yield sustained improvements in academic performance or emotional well-being in student populations. Concomitantly, these far-transfer effects and executive function demands have shown to closely align within highly strategic sports, such as professional snooker (see Welsh et al., 2018, 2023), or young people who are susceptible to driving-related accidents (Walshe et al., 2017) or for occupations requiring a high degree of cognitive focus under pressure such as within the medical profession (Esmaili et al., 2023). Additionally, chess-based interventions could be tailored for older adults, where cognitive training has been associated with improved memory and executive functions (Lampit et al., 2014), potentially delaying cognitive decline associated with aging. Future research could prioritise exploring these far-transfer effects through longitudinal designs to track how chess expertise impacts broader cognitive abilities over time. Additionally, randomised controlled trials could be used to assess the efficacy of chess training as a cognitive intervention in both clinical and non-clinical populations.

5. Conclusion

This systematic review has highlighted the neural correlates of chess expertise, revealing distinct structural and functional differences between expert and novice players. Through various neuroimaging techniques, such as fMRI, fNIRS and EEG, it has been shown that chess expertise is associated with enhanced connectivity in brain regions responsible for visual processing, spatial reasoning, memory, and decision-making. This, in turn, opens intriguing questions about how and to what extent such chess-induced connectivity translates into performance in non-chess activities, such as operating drones, sport, multitasking and complex decision making against the clock, which would be particularly relevant to the military, medical services and to improve young people's impulse control. If such translation does occur and results in statistically significant improvement in performance, then incorporating chess play into military training, sport practices, education and for those in demanding employment will offer extraordinary value for money and time. These adaptations underline the potential of chess as a valuable cognitive training tool, especially with free software on the market that allows for shorter, daily games, with possible far-reaching applications for improving cognitive function in clinical populations and beyond. Future research could explore the long-term effects of chess training and its potential to improve cognitive abilities across different contexts, including sporting performance, mental health interventions and educational programs.

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Declaration of Competing Interest

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