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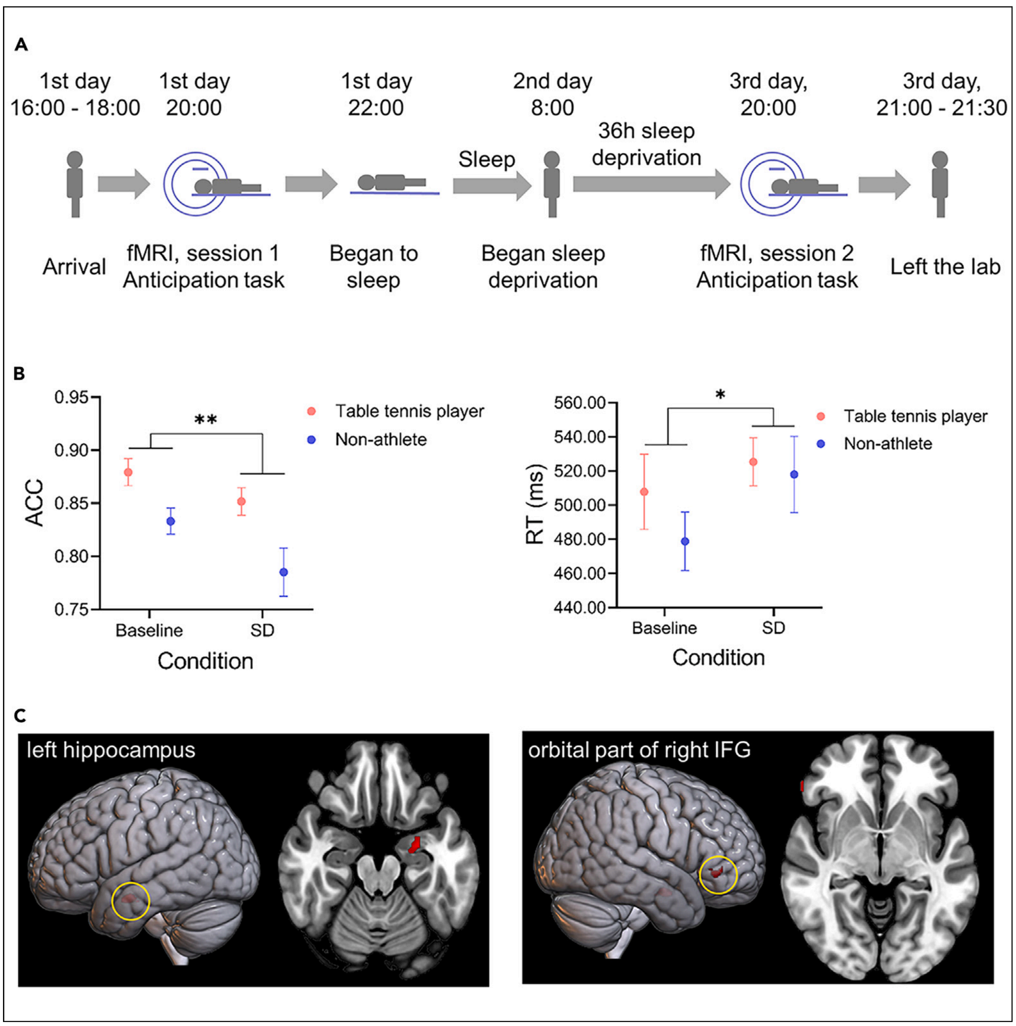

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Highlights

Table tennis players have higher neural efficiency than non-athletes

SD reduces sport-related anticipation performance

Compensatory activation occurs in the left hippocampus and right IFG after SD

Dai et al., iScience *26*, 107973
October 20, 2023
https://doi.org/10.1016/j.isci.2023.107973

Article

Total sleep deprivation reduces the table tennis anticipation performance of young men: A functional magnetic resonance imaging study

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SUMMARY

This study explored whether and how sleep deprivation (SD) affects sport-related anticipation. Twenty table tennis players and 28 non-athletes completed a table tennis anticipation task before and after 36 h SD. Functional magnetic resonance imaging (fMRI) data were acquired simultaneously. The results showed that, compared with the non-athletes, table tennis players had higher neural efficiency, manifested by their higher anticipation accuracy and lower frontal lobe activation. SD impaired anticipation performance, accompanied by decreased activation of the occipital and temporal lobes. Compensatory activation occurred in the left hippocampus and orbital part of the right inferior frontal gyrus (IFG) after SD in the table tennis player group, but not in the non-athlete group. The decreased accuracy of non-athletes was positively correlated with decreased activation of orbital part of the right IFG. This study's findings improve the understanding of the cognitive neuroscience mechanisms by which SD affects sport-related anticipation.

INTRODUCTION

Athletes often experience sleep deprivation (SD) or sleep restriction due to pre-competitive pressure, excitement after the game, jet lag, and increases in training load.[1,2] SD has a negative impact on sports performance and motor cognition.[3] Roberts et al. have found that vigor and endurance cycling performance decreased after 24 h SD and mood disturbance, confusion, and fatigue were higher after SD.[4] Similar results were found in running[5] and anaerobic exercise.[6] Cheikh et al. have found that adolescent karate athletes are slower on choice reaction time and maximal force time after one-night SD.[7] Taheri and Arabameri have also found that college student athletes' choice reaction time becomes longer after a one-night SD.[8] However, some studies have reported that SD has no significant impact on the simple selective reaction time but significantly influences the performance of more complex cognitive tasks, including the two-back working memory task, divided attention test and motor skill learning through mental training.[9] Saddoud et al. used a Kung-Fu fight decision task to explore the impact of 24-h SD on the 24 male Kung-Fu athletes' decision-making performance.[10] The results show that the accuracy of Kung-Fu athletes decreases and the reaction time becomes longer after SD. Although these studies have explored the effects of SD on exercise few have explored said effects on sport-related anticipation and its underlying cognitive neuroscience mechanisms.

Sport-related anticipation is the ability to predict others' subsequent sports movement or the coming result of sports movement.[11,12] It is an integrated expression across multiple systems, which includes sensory perception, proprioception, cognition, memory, motor control, and affection.[13] Some researchers believe that it is the excellent prediction ability of athletes that differentiates them from non-athletes.[13,14] Also, a great amount of evidence has indicated that, compared with novices, experts perform better in the anticipation tasks related to their sports.[15–20] In table tennis, the reaction time left for the player to receive the ball is short because the speed of the ball is fast and the trajectory of the ball is short. To receive the opponent's ball accurately and in time, the player needs to anticipate where the ball will land, making anticipation an indispensable cognitive ability for table tennis players.[18]

The mirror neuron system (MNS) and action observation network (AON) play an important role in anticipation.[12,17] The MNS is fundamental for action understanding, imitation and understanding,[21] and the core brain regions of the human MNS mainly include the inferior frontal gyrus (IFG), premotor cortex (PMC), inferior parietal lobule (IPL), and superior temporal sulcus (STS).[22,23] In contrast, the AON includes all brain regions involved in the process of action observation.[17] Caspers et al. have conducted an activation likelihood estimation meta-analysis and found that brain regions of the AON include the IFG, PMC, supplementary motor area (SMA), IPL, superior parietal lobe (SPL), posterior middle temporal gyrus (pMTG), intraparietal cortex, visual area V5, fusiform face area, and primary sensory cortex.[24] The terms MNS and AON are often used interchangeably in studies about sport-related anticipation and action observation.[19,25,26] However, some researchers believe that

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https://doi.org/10.1016/j.isci.2023.107973

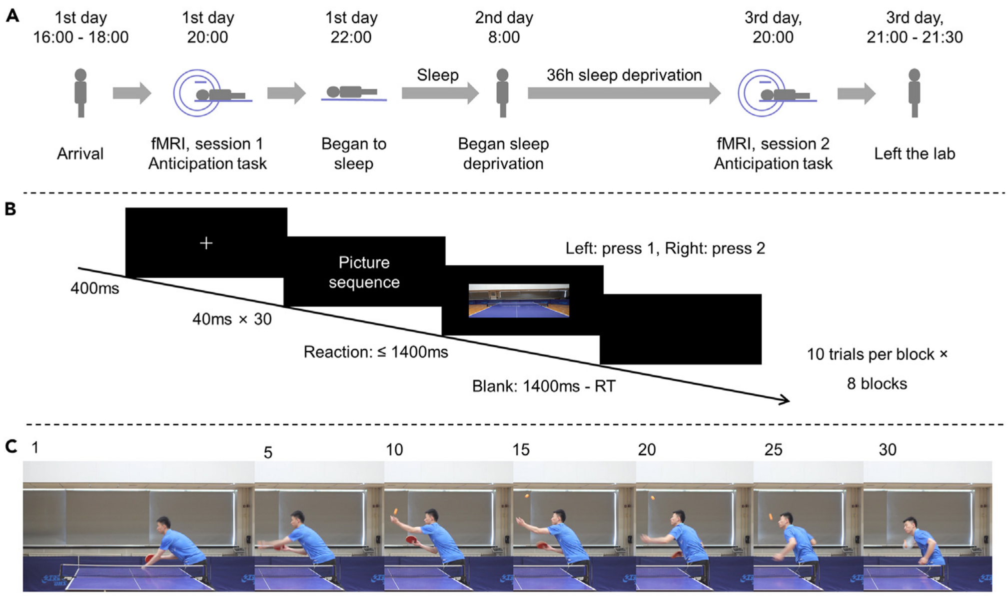

Figure 1. Experimental design

(A) Overall experimental arrangement.

(B) Presentation order of stimuli in one trial.

(C) Example of sequence of consecutive pictures output from the video of the table tennis service. Only the 1st, 5th, 10th, 15th, 20th, 25th, and 30th frames in a sequence are displayed in the figure. Thirty frames would be presented in the formal experiment. RT, reaction time.

AON contains more extensive brain regions than does MNS,[27,28] while others think that the concept of AON is more appropriate in humans than that of MNS.[29] In this research, we have used the term AON.

Several studies on the neural mechanisms of action observation and anticipation have been conducted. Balser et al. compared the prediction of expert and novice tennis players on the direction of ball flight, as well as that of subsequent movement reactions when watching tennis stroke videos,[17] and found that experts performed better than the novice in both tasks, with the AON-related activation of experts being more intense than that of novices, especially in the SPL, intraparietal sulcus (IPS), IFG, and cerebellum.[17] Bishop et al. asked participants to determine which direction their "opponent" would dribble the football and studied the activation in the cerebellum, inferior visual cortex, STG, and precuneus. They have found a distinctive difference in these activations between high- and low-skill players.[30]

Numerous studies have explored the cognitive neuroscience mechanisms by which SD affected cognitive function.[31] SD can lead to attention reduction with reductions in activation in the thalamus, dorsolateral prefrontal cortex (dlPFC), and IPS.[32,33] SD impairs memory which may relate to the activation in the frontoparietal areas, medial prefrontal cortex (mPFC), and hippocampus.[34–36] The increased risk-taking propensity of decision-making after SD is related to the left IFG and dlPFC, ventromedial prefrontal cortex (vmPFC).[37–40] These studies have documented the cognitive neuroscience mechanisms by which SD affects cognitive function in the general population; however, few studies evaluating the cognitive neuroscience mechanisms of SD affecting sports anticipation in athletes have existed.

Given the current divergences in research on the activation of AON in sport-related anticipation and the unclear cognitive neuroscience mechanisms underlying the impact of SD on sport-related anticipation, we decided to conduct research on the impact of SD on sport-related anticipation. A 36-h SD model was developed to explore how SD affected sport-related anticipation and its underlying brain mechanisms. All participants underwent fMRI scanning before and after SD while simultaneously completing an anticipation task, which required the participants to predict the placement of the table tennis serve from the perspective of the server's opponent. The experimental design diagram is shown in Figure 1 and is detailed in the STAR methods section. Our study hypothesized that: (1) AON would be activated in both groups when performing anticipation tasks; (2) anticipation task performance of the table tennis player group would be better than that of the non-athlete group, and greater activation in the AON would be observed; (3) SD would reduce anticipation task performance and the activation of AON; (4) the negative effect of SD on the non-athlete group would be more serious than that on the table tennis player group; this would be manifested by a greater decrease in accuracy and AON activation, as well as a greater increase in reaction time, in the non-athlete group after SD compared to the table tennis player group after SD.

RESULTS

Behavioral results

The Stanford Sleepiness Scale (SSS) was used to assess the sleepiness of participants at baseline and after SD. A 2 × 2 ANOVA with repeated measures for group (between-subject factor: the table tennis player group vs. non-athlete group) and condition (within-subject factor: baseline

Table 1. Demographic data ($M \pm sd$)

	Table tennis player group	Non-athlete group	p
Number	28	20	
Sex	Male	Male	
Ethnicity	Chinese	Chinese	
Age	20.55 ± 1.36	22.71 ± 2.21	[a]
Education	14.75 ± 0.72	14.93 ± 1.02	0.50
PSQI	4.70 ± 1.53	3.75 ± 1.84	0.07
SSS			
Baseline	1.80 ± 0.83	1.96 ± 0.84	[b]
SD	3.55 ± 1.43	4.21 ± 1.52	

PSQI, Pittsburgh sleep quality index; SSS, Stanford Sleepiness Scal; SD, sleep deprivation; $M \pm sd$, mean ± standard deviation.
[a]Comparison between groups p < 0.01.
[b]Main effect of condition p < 0.001.

vs. SD) was made. No significant group×condition interaction effect (F (1, 46) = 1.38, p = 0.25, partial η^2 = 0.03) and main effect of group (F (1, 46) = 2.16, p = 0.15, partial η^2 = 0.05) were found. The main effect of condition was significant (F (1, 46) = 88.52, p < 0.001, partial η^2 = 0.66). *Post hoc test* revealed that participants felt sleepier after SD ($MD \pm SE$ = 2.00 ± 0.21, p < 0.001, 95% CI: [1.57, 2.43], Table 1).

Twenty-seven non-athletes and eighteen table tennis players were included in the behavioral data analysis. A 2 × 2 ANOVA with repeated measures for group (between-subject factor: the table tennis player group vs. non-athlete group) and condition (within-subject factor: baseline vs. SD) found the existence of expert advantage and the negative effect of SD on sport-related anticipation. The reaction time and accuracy of the two groups at baseline and after SD were shown in Figure 2. The group × condition interaction effects were not significant for both accuracy (F (1, 43) = 0.75, p = 0.39, partial η^2 = 0.02) and reaction time (F (1, 43) = 0.61, p = 0.44, partial η^2 = 0.01). For accuracy, the main effect of the group (F (1, 43) = 6.62, p < 0.05, partial η^2 = 0.13) and the main effect of condition (F (1, 43) = 10.35, p < 0.01, partial η^2 = 0.19) was significant. *Post hoc tests* revealed that the accuracy of the table tennis player group was higher than that of the non-athlete group ($MD \pm SE$ = 0.06 ± 0.02, p < 0.05, 95% CI: [0.01, 0.1]), whereas that after SD was lower than that at baseline ($MD \pm SE$ = - 0.04 ± 0.01, p < 0.01, 95% CI: [-0.06, −0.01], Figure 2A). For reaction time, only the main effect of condition was significant (F (1, 43) = 4.17, p < 0.05, partial η^2 = 0.09). *Post hoc tests* revealed that the reaction time after SD was longer than the baseline reaction time ($MD \pm SE$ = 28.36 ± 13.88 ms, p < 0.05, 95% CI: [0.37, 56.35], Figure 2B). The main effect of group on reaction time was not significant (F (1, 43) = 0.52, p = 0.47, partial η^2 = 0.01).

Brain activation at baseline while performing the anticipation task

Two one-sample t-tests were used to explore brain activation in the table tennis player and non-athlete groups when they completed the anticipation task in ordinary circumstances (baseline) and to verify that the AON was activated in the sport-related anticipation task. The level of significance was defined as $p_{FWE} < 0.05$ with cluster size >20 (Family Wise Error, FWE). As shown in Figure 3, we found that the brain regions of AON, such as SPL, MTG and visual cortex, were activated during the anticipation task in both groups. This supported our first hypothesis. Detailed information of brain regions that were activated in the anticipation task can be seen in Tables S1 and S2.

Effect of SD on brain activation in different groups

Interaction between group and condition

Only activation of the left hippocampus (Brodmann area (BA) 28, 34) and orbital part of the right IFG (BA 47) showed a significant interaction between group and condition ($p_{uncorrected} < 0.0001$, cluster size >15; Figure 4A and Table 2). The simple effect test was made by SPSS26 (Figure 4B). The activation of the left hippocampus increased after SD compared to baseline in the table tennis player group ($MD \pm SE$ = 0.28 ± 0.06, p < 0.0001, 95% CI: [0.16, 0.40]), while no significant changes were observed in the non-athlete group ($MD \pm SE$ = −0.09 ± 0.06, p = 0.11, 95% CI: [-0.20, 0.02]). The activation of orbital part of the right IFG increased after SD compared to baseline in the table tennis player group ($MD \pm SE$ = 0.20 ± 0.07, p < 0.005, 95% CI: [0.06, 0.33]), and decreased in the non-athlete group ($MD \pm SE$ = −0.13 ± 0.06, p < 0.05, 95% CI: [-0.25, −0.00]).

Main effect of group

As shown in Table 2, there were five clusters with significant main effect of group ($p_{uncorrected} < 0.0001$, cluster size >15) and their peak coordinates were respectively located in the right SMA, right medial superior frontal gyrus (SFG), right SFG, left SFG, and right inferior temporal gyrus (ITG) (Figure 5A). After FWE correction, only the right SMA ($p_{FWE} < 0.01$), right medial SFG ($p_{FWE} < 0.05$), and right SFG ($p_{FWE} < 0.05$) were retained. As shown in Figure 5B, the activation of the non-athlete group was higher than that of the table tennis player group in the five clusters.

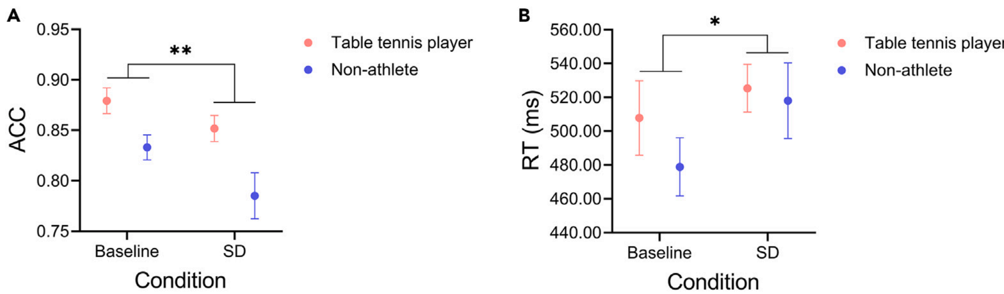

Figure 2. Accuracy and reaction time of the different groups under different conditions

(A) ACC of different groups under different conditions. The main effects of group and condition are significant. The ACC at baseline is higher than that after SD.
(B) The RT of different groups under different conditions. The RT at baseline is shorter than that after SD. ACC, accuracy; RT, reaction time; SD, sleep deprivation.
*p < 0.05, **p < 0.01, error bar: ± *SE*.

Main effect of condition

As shown in Table 2, there were three clusters with significant main effect of condition ($p_{uncorrected} < 0.0001$, cluster size >15). Peak coordinates were located in the right MTG (BA 37), right MTG (BA 21 & 22) and left middle occipital gyrus (MOG) (show in Figure 6A). After FWE correction, only the right MTG (BA 37) ($p_{FWE} < 0.05$) remained significant and the right MTG (BA 21 & 22) ($p_{FWE} = 0.06$) was marginally significant. Comparison between baseline and SD is shown in Figure 6B. Brain activation was reduced after SD in these three clusters.

Correlation between behavior and brain activation

The Pearson correlation coefficient between behavior and brain activation was calculated. The results showed that the reduced anticipation accuracy after SD was positively correlated with the reduced activation of the orbital part of the right IFG in the non-athlete group ($r = 0.55$, $p < 0.01$, $R^2 = 0.30$, 95% CI: [0.17, 0.79], Figure 7).

DISCUSSION

Our research is the first study to explore how SD influenced sport-related anticipation and its underlying cognitive neuroscience mechanisms. We found that the table tennis player group had better anticipation performance and lower frontal lobe activation. SD impaired anticipation performance and reduced activation in brain regions associated with visual perception. Most importantly, we found evidence of compensatory recruitment in the left hippocampus and orbital part of the right IFG after SD in the table tennis player group while completing the anticipation task.

AON in sport-related anticipation

Because of the interest in brain activation during the completion of the anticipation task in general, the brain activation in each group at baseline was analyzed. Consistent with the results of previous studies,[26,27,41] our study showed that both groups had positive activation in the AON,

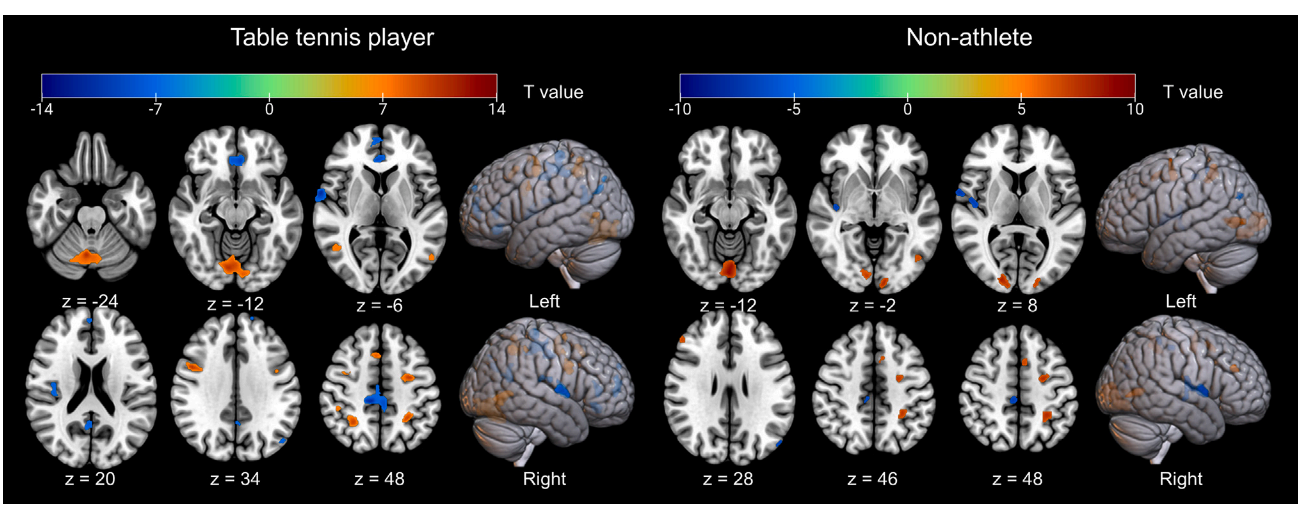

Figure 3. Brain activation in the table tennis player and non-athlete groups while completing the anticipation task at baseline.

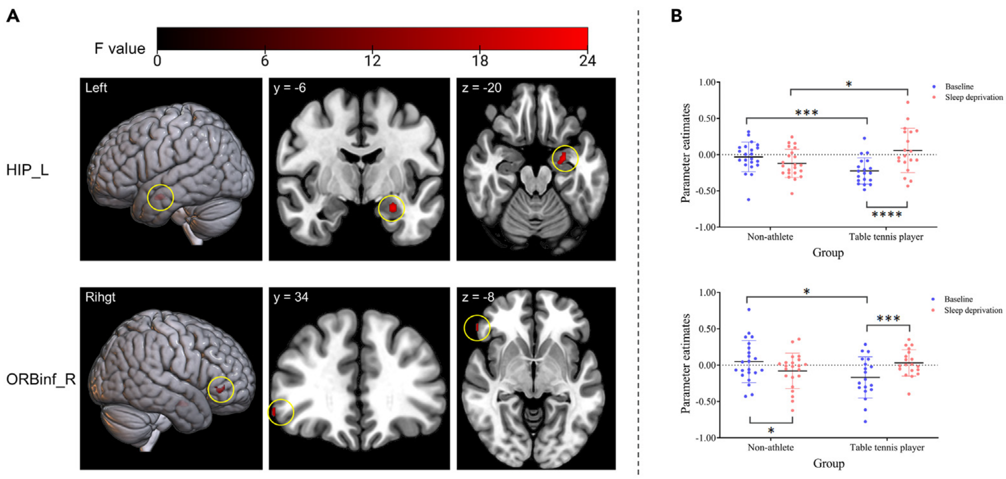

Figure 4. Differences between the table tennis player and non-athlete groups in the effects of SD on the left hippocampus and orbital part of the right inferior frontal gyrus

(A) Voxel-wise analysis: the interaction effect between group and condition.

(B) Diagram of simple effects. The round dots represent the mean parameter estimates for each group per condition. The black solid line represents the mean value, and the error bar represents ± *sd*. *$p < 0.05$, ***$p < 0.005$, ****$p < 0.0001$. HIP_L, left hippocampus; ORBinf_R, orbital part of the right inferior frontal gyrus.

such as the IPL, SPL, precentral gyrus, cerebellar, and visual cortex. The cerebellar and precentral gyrus, which were closely related to movement,[42,43] activated most voxels in the table tennis player group. In contrast, the calcarine cortex and MOG, which were closely related to visual perception,[44] activated most voxels in the non-athlete group. These findings may indicate that the table tennis player group used motion-related information on the anticipation task, whereas the serve video might be more of a visual stimulus for the non-athlete group.[45,46]

Compensatory activation of hippocampus and IFG in the table tennis player group after SD

The interaction effect of group and condition was found in the left hippocampus and the orbital part of the right IFG. The hippocampus and orbitofrontal complex are related to spatial representations and prediction of specific outcomes and are the neural bases of the

Table 2. Flexible factorial model result of fMRI data

Brain region	Cluster size	Brodmann area (BA)	Peak F value	Coordinate x	y	z
Interaction effect						
left hippocampus	40	BA 28, 34	23.57	−26	−6	−20
			17.28	−18	−12	−22
right inferior frontal gyrus, orbital part	16	BA 47	20.96	56	34	−8
Main effect of group						
right supplementary motor area	88	BA 6	33.48	10	20	56
right medial superior frontal gyrus	141	BA 8, 9	28.78	10	54	44
right superior frontal gyrus	78		26.81	14	56	26
			19.65	18	60	12
left superior frontal gyrus	118	BA 9	22.28	−12	54	34
			20.10	−14	42	40
right inferior temporal gyrus	33	BA 20, 21	22.15	62	−8	−28
Main effect of condition						
right middle temporal gyrus	125	BA 37	26.54	48	−64	0
right middle temporal gyrus	436	BA 21, 22	25.16	72	−32	−4
			22.07	46	−36	−2
			22.02	46	−28	−6
left middle occipital gyrus	85	BA 19	22.29	−44	−70	2

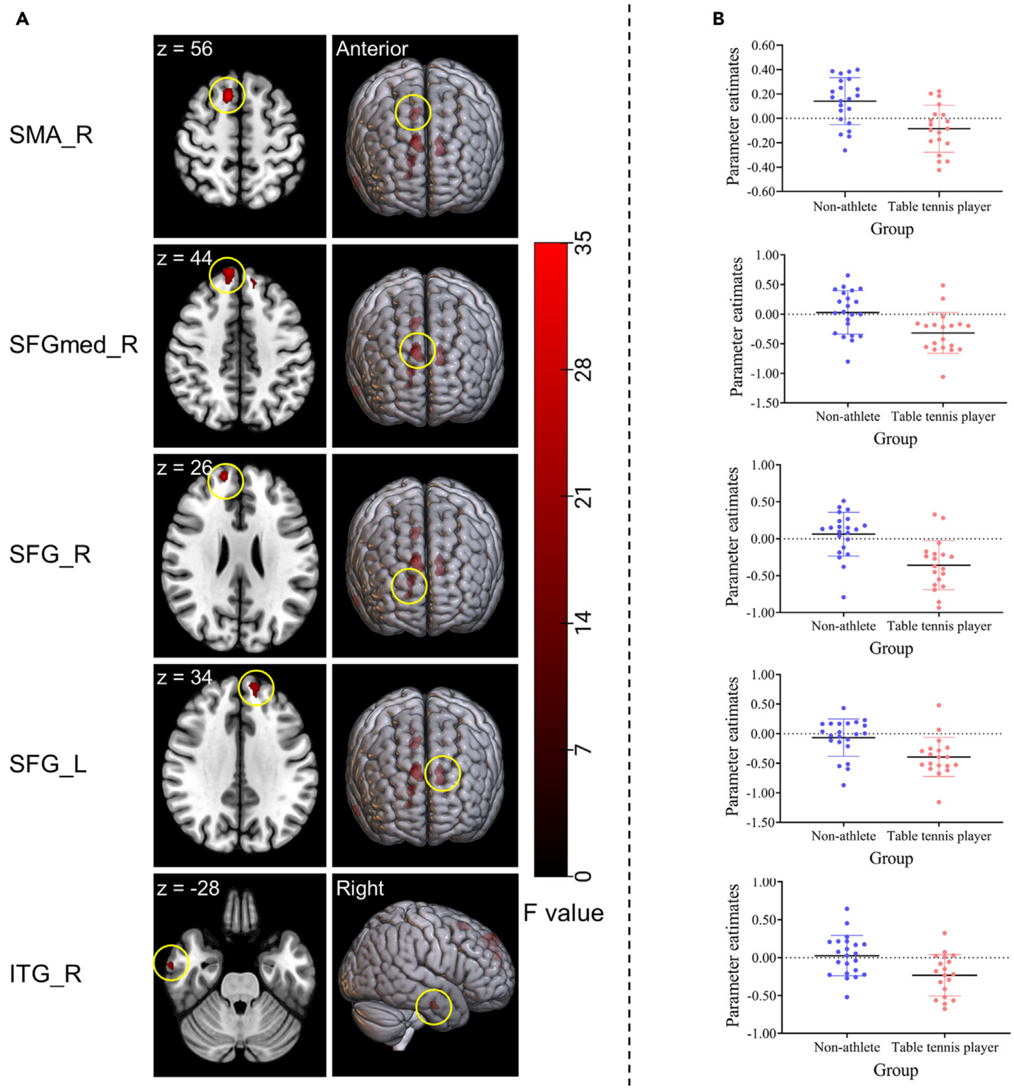

Figure 5. Brain regions with different activations between the table tennis player and non-athlete groups

(A) Voxel-wise analysis: the main effect of the group.

(B) Round dots represent the average of the parameter estimates at baseline and after sleep deprivation ((parameter estimates at baseline + parameter estimates after sleep deprivation)/2). The black solid line represents the mean, and the error bar represents $\pm$ *sd*. SMA_R, right supplementary motor area; SFGmed_R, right medial superior frontal gyrus; SFG_R, right superior frontal gyrus; SFG_L, left superior frontal gyrus; ITG_R, right inferior temporal gyrus.

cognitive map.[47] The orbitofrontal cortex (OFC) receives information from the hippocampus that contributes to the prediction of future outcomes.[48] This relationship between the hippocampus and OFC is also affected by sleep.[49] In this study, the left hippocampus activation increased in the table tennis player group after SD, whereas no significant change was evident in the non-athlete group. This could be a way for table tennis players to build a cognitive map of the serve and explore the distance between the current position and the location of landing. The hippocampus is known to be associated with long-term memory. Biderman et al. argued that the purpose of memory was not only to record the past but essentially to guide future decisions. Additionally, the hippocampus plays an important role in this process.[50] Balser et al. have found higher activation of the hippocampus in action anticipation than in action observation in a study of tennis players.[17] This finding might be due to the involvement of hippocampus in decision-making. Previous studies have found that SD-impaired memory was associated with the hippocampus.[35,36] Therefore, the reduced activation of the hippocampus in our research in the non-athlete group after SD occurred because SD damaged memory. In contrast, activation of the hippocampus was increased in the table tennis player group, possibly because the table tennis player group stored a large amount of episodic memory and abstract conceptual knowledge about table tennis. The table tennis player group might have tried to learn from past experience to improve their performance of anticipation in the context of reduced cognitive resources after SD.[51]

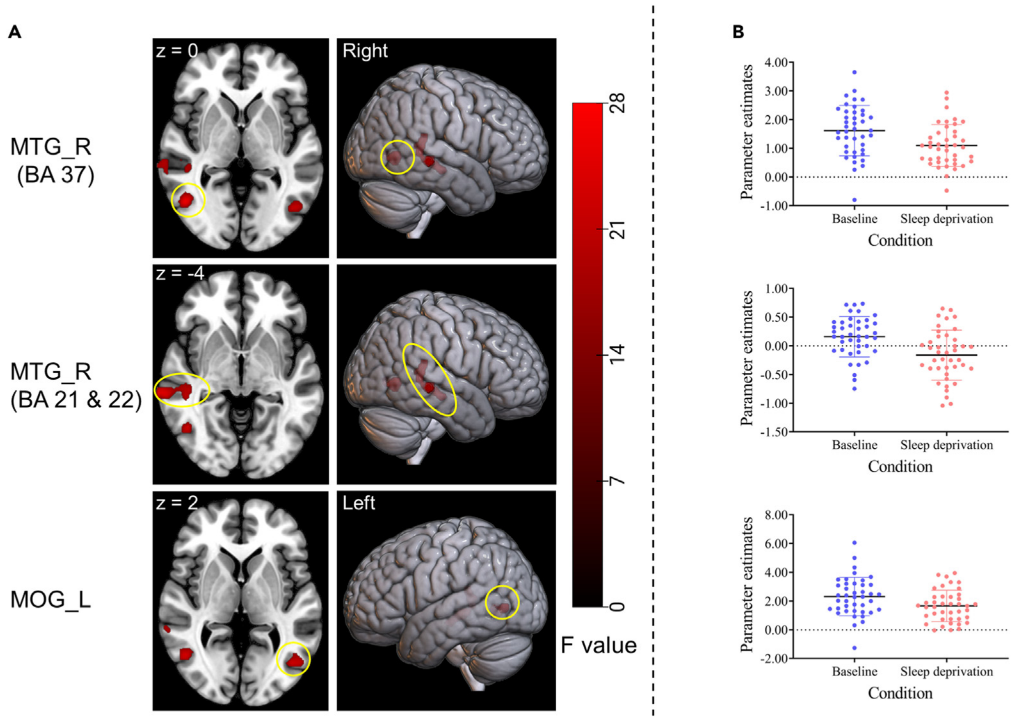

Figure 6. Brain regions with different activations between baseline and after SD

(A) Voxel-wise analysis: Main effect of condition.

(B) Round dots represent the mean parameter estimate for each subject per condition. The black solid line represents the mean, and the error bar represents ± *sd*. MTG_R (BA 37), right middle temporal gyrus; MTG_R (BA 21 & 22), right middle temporal gyrus; MOG_L, left middle occipital gyrus; BA, Brodmann area.

We also found increased activation in the orbital part of the right IFG in the table tennis player group and decreased activation in the orbital part of the right IFG in the non-athlete group after SD. IFG, one of the nodes of the AON,[27] was associated with various cognitive functions such as perceptual decision-making.[52] Abreu et al. found that when expert groups made errors in an anticipation task about basketball free throws, they showed higher activation in the bilateral IFG and anterior insula cortex, which may indicate that they were aware of their errors.[53] Sherman et al. also found that the IFG was involved in decision-making and was sensitive to the discrepancy between expectation and perceptual choice.[52] Lei et al. found that SD reduced the perception of risk in decision-making and suggested that this effect of SD may be related to IFG.[38] The reduced activation of the IFG after SD found in the non-athlete group might be because of impaired cognitive function after SD. In the Pearson correlation analysis of behavior and brain activation, we found that the decrease in the non-athletes' accuracy after SD was positively correlated with the decrease in orbital part of the right IFG. In contrast, compensatory activation of the IFG evident in the table tennis player group might be because of their attempt to compensate for the effects of SD with advanced cognitive functions. Of note, this explanation of compensatory activation of hippocampus and IFG is only an inference. The interpretation of the results in our study requires caution because the behavioral data pertaining to the effects of SD revealed no significant group×condition interaction effects on accuracy and reaction time.

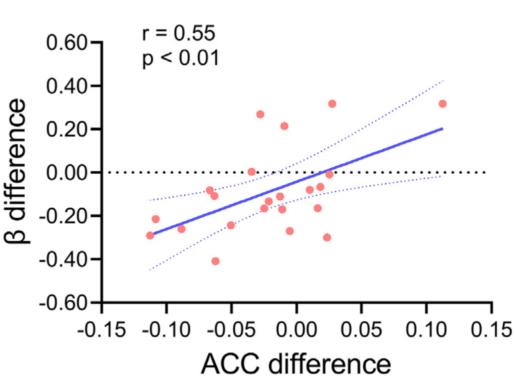

Figure 7. Correlation between the changes in ACC and the changes in ORBinf_R activation in the non-athlete group

β difference: ORBinf_R activation after SD minus the ORBinf_R activation at baseline in the non-athlete group. ACC difference: ACC after SD minus the ACC at baseline in the non-athlete group. ORBinf_R: orbital part of the right inferior frontal gyrus, ACC, accuracy, Curve line: 95% confidence interval of correlation coefficient.

Group difference in activation in the frontal lobe

Consistent with the results of previous studies,[18,19,54] the present study found that accuracy in the anticipation task was higher in the table tennis player group than in the non-athlete group, suggesting an expert advantage for table tennis players in predicting the drops of serves. The results of flexible factorial model analysis showed that activation was lower in the right SMA, right medial SFG, left and right SFG, and right ITG in the table tennis player group than in the non-athlete group. The SMA is part of the frontal motor cortex and is involved in motor planning.[24,55] Consistent with the results of previous studies,[17,56] the present study found lower activation of the SMA in the table tennis player group than in the non-athlete group while completing the anticipation task. According to the neural efficiency hypothesis, people with higher neural efficiency require less brain activation when they have same or better performance in cognitive tasks compared with individuals with low neural efficiency.[56,57] Our results implied that the table tennis player group was more efficient in processing motion-related information.

The SFG is located in the superior prefrontal lobe and is responsible for several higher cognitive functions such as working memory, decision-making, and motor control.[39,58,59] In a study on figure skating, Diersch et al. found that non-expert showed greater recruitment of the visual cortex and SFG.[45] The present study showed lower activation of the SFG in the table tennis player group than in the non-athlete group, which was consistent with the results of Diersch et al.[45] The higher activation of the SFG in the non-athlete group might imply that they were neurologically less efficient and needed to rely more on advanced cognitive functions of the prefrontal cortex to complete the anticipation task.[53]

The ITG is an important node of the ventral-stream of visual perception and played the central role in object recognition.[44,60] The ventral-stream of visual perception is distributed along the occipital and temporal lobes. Visual information is projected from the primary visual cortex (V1) and secondary visual cortex (V2) to the ITG through V4.[61] The primary function of the ITG is object recognition and is sensitive to the color,[62] shape,[63] and size[64] of objects. Cross et al. found that the ITG was sensitive to visual cues in a dance-learning paradigm.[28] In our study, the results showed that activation of the ITG in the table tennis player group was lower than in the non-athlete group. This implied that neural efficiency of the ITG was higher in the table tennis player group than in the non-athlete group.

Effects of SD on visual perception during anticipation

The behavioral data showed that SD reduced anticipation performance, as evidenced by decreased accuracy and increased reaction time. The flexible factorial model analysis of fMRI data showed that activation of the right MTG and left MOG decreased after SD. Both clusters—the right MTG (BA 37) and left MOG (BA 19)— span the temporal and occipital lobes. Both MTG and MOG play an important role in visual perception. The dorsal-stream of visual perception projects from the occipital visual cortex to the IPL through the middle temporal area (MT, V5).[61] The visual dorsal stream is involved in spatial position information recognition and motor control and is sensitive to features such as speed and direction of movement.[65] Our study found decreased activation of the right MTG and left MOG after SD, possibly indicating that SD impaired visual-spatial perception during action anticipation.

The MTG is also associated with semantic function.[66] Wang et al. found activation of semantic network in action anticipation.[19] Researchers have proposed common semantic representations, which would be active while understanding both actions and words, to explain the link between action and semantics.[67] The decrease in the activation of the MTG after SD may also imply that SD impaired the processing of action at the abstract concept level.

In addition, the cluster, the peak activation of which was located in the right MTG (BA 21 & 22), actually spanned the temporal and parietal lobes in this study. The temporo-parietal junction (TPJ) is a key brain region in the Theory of Mind network,[68,69] which is important for understanding the mental states of others.[70] Decreased activation in TPJ after SD suggested that the ability to speculate on the intention and to understand the mental state of the server was impaired after SD.

Sleep contributes to physical and mental health and cognitive functions.[71] A meta-analysis of sleep and mental health showed that improved sleep has small-to-medium-size effects on reducing negative emotions and increasing positive psychosis symptoms.[72] Another meta-analysis of sleep and memory showed that the benefits of sleep on prospective memory were in the small to medium range.[73] However, people are often sleep deprived for various reasons and experience negative effects of SD. Our study also revealed that SD would impair task performance, demonstrating that sleep health should be paid attention to. However, a meta-analysis of the effects of physical activity on sleep demonstrated that both acute and regular exercise can prolong total sleep time and improve sleep efficiency.[74] Exercise may be an effective means of preventing the negative effects of SD.

Limitations of the study

Our research facilitated a better understanding of the effects of SD on motor cognition. However, the limitations of our study should also be considered. First, we did not establish a control group that had normal sleep or counterbalance the session of baseline and SD between participants. Moreover, we cannot exclude the effect of the practice effect on our results. Second, we only recruited National Level II table tennis players because convincing higher-level athletes to participate in SD and obtaining the consent of their coaches were difficult to achieve. Third, only male participants were included in this study. Sex differences should be assessed in future studies as previous studies have showed that the effects of SD[75] and neural efficiency[76] were sex-specific. Fourth, participants were asked to respond only after seeing the response signal. However, higher-level athletes may be able to make the right decision before the end of stimulus. In future studies, researchers should consider allowing participants to respond during the stimulus presentation and collecting response times and accuracy.

Conclusion

Our study explored the effect of SD on sports-related anticipation. We found that the table tennis players had an expert advantage over non-athletes in the table tennis anticipation task and that SD attenuated anticipation performance. The AON was activated when completing the anticipation task in both the table tennis player and non-athlete groups. Differences in brain activation between the table tennis player and non-athlete groups were primarily evident in the frontal lobe, which was associated with advanced cognitive functions. By contrast, SD mainly affected the occipital and temporal lobes, which were closely related to visual perception. Compensatory activation in the hippocampus and the orbital part of the right IFG in the table tennis player group after SD suggested that table tennis players may try to work harder after SD to use their past experiences in facilitating their precognitive performance against the effects of SD. Our results suggested that table tennis players have higher neural efficiency in anticipation tasks than non-athletes. We expect this change in neuroplasticity in table tennis players compared to non-athletes to be a result of exercise rather than an inherent difference. Nevertheless, more research is needed to prove this point. In this study, SD altered neuroplasticity, which was primarily reflected through function. Our results suggested that sufficient sleep is essential to maintain adequate brain function and reminds indicates that athletes should pay attention to sleep health. Exercise may be able to counteract the effects of SD through a top-down approach implying that it may be an effective means to reduce the negative effects of SD.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.107973.

ACKNOWLEDGMENTS

This research was funded by the National Science Foundation of China (Grant Number 211-CXGC-M113-04-03-01). And we would like to thank Editage (www.editage.cn) for English language editing.

AUTHOR CONTRIBUTIONS

C.D. and Y.S. designed the study. C.D., Z.P., L.W., T.S., L.X., and M.X. contributed to the acquisition of data. C.D. conducted the analyses and wrote the first draft of the manuscript. C.D., Z.P., L.W., T.S., L.X., M.X., and Y.S. revised and approved the final version. Y.S. funded this study.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

Received: February 6, 2023
Revised: July 31, 2023
Accepted: September 15, 2023
Published: September 19, 2023

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Adobe Premiere Pro	Adobe	Version CS6
E-Prime	https://www.pstnet.com	Version 2.0
SPSS	IBM Statistical Product Service Solutions, Armonk, NY, USA	Version 26
MRICroGL	https://www.nitrc.org/frs/?group_id=889	Version 1.2.20220720
Marsbar	https://sourceforge.net/projects/marsbar/	Version 0.45
SPM	https://www.fil.ion.ucl.ac.uk/spm/software/download/	Version 12
MATLAB	Mathworks	Version R2018a

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the corresponding author, Yongcong Shao (budeshao@aliyun.com)

Materials availability

This study did not generate new unique reagents.

Data and code availability

The additional information is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

An *a priori* power analysis in G*Power revealed a minimum sample of 34 participants using the "ANOVA: Repeated measures, within-between interaction" ($f = 0.25$, $\alpha = 0.05$, $1 - \beta = 0.80$, number of groups = 2, number of measurements = 2, correlation among measures = 0.5).[77] We also referred to the sample size of previous studies on SD and sport-related anticipation.[78,79]

All participants were recruited through the recruitment advertisement published on the Internet. Inclusion criteria were as follows: (1) healthy males with normal naked or corrected visual acuity, (2) aged between 18 and 30 years (3) right hand, (4) normal sleep quality with Pittsburgh Sleep Quality Index (PSQI) score ≤ 8,[80] (5) no history of mental and neurological diseases, and (6) the non-athlete group was required to not exercise regularly and to not be proficient in any type of sports; the table tennis player group participants were recruited if they were at least a National Level II table tennis player. Finally, 28 participants in the non-athlete group were recruited and 20 participants in the table tennis player group. All the participants were within the limited age range, though the non-athlete group was older than the table tennis player group ($t = 3.88$, $p < 0.01$, mean difference (MD) $\pm$ standard error (SE) = 2.16 $\pm$ 0.56, 95% confidence interval (CI) = [1.04, 3.29]). And there was no significant difference between the two groups in the total score of the PSQI ($t = -1.89$, $p = 0.07$, $MD \pm SE = 0.95 \pm 0.50$, 95% CI = [-1.96, 0.06]). Detailed information is shown in Table 1. The experiment was approved by the Ethics Committee of Beijing University (Beijing, China).

Statement of ethics

This study protocol was reviewed and approved by Ethics Committee of Beijing University (Beijing, China), approval number (BM20180040). Written informed consent was obtained from the participants.

METHODS DETAILS

Stimuli

A male National Level I table tennis player was selected as the server. Forty service videos (resolution: 3840 × 2160, frames per second: 30) were recorded from the perspective of the server's opponent (receiver), of which twenty balls landed on the receiver's left half-court, and the others landed on the right. Thirty consecutive pictures (resolution: 1024 × 576) were outputted by Adobe Premiere Pro CS6 for each service taking the frame at the moment of contact between the ball and the racket as the last frame and the 29th frame ahead as the first frame. Therefore, the final experimental stimuli were forty groups of pictures. Each group of pictures appeared twice in the task.

Experimental procedure and paradigm

The overall experimental procedure is shown in Figure 1A. Each participant spent about 3 days in the experiment. The participants arrived at the laboratory at 16:00 on the first day of the formal experiment. Thereafter they could get familiar with the experimental environment, learn about the experimental process, and sign the written informed consent. The first fMRI scan (Session 1) was performed at about 20:00 on the first day. During scanning, participants completed a series of tasks including the anticipation task. Then, they would have one night's sleep in the laboratory from 22:00 on the first day to 8:00 on the second day. SD lasted for 36 h from 8:00 on the second day to 20:00 on the third day. Participants underwent their second fMRI scan (session 2) at about 20:00 on the third day. They were only allowed to stay in the laboratory during SD and carry out some simple activities, such as watching videos, listening to music, and reading to keep awake. Researchers took turns to supervise them during SD, in addition to medical staff on call.

The experimental paradigm was presented by E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA, USA). Each session contained only one run and lasted 400s. Each session contained 8 blocks. Before each block, a black blank lasting 20s was presented. During the blank presentation, participants were asked to open their eyes and look at the center of the screen. Each block lasted 30s, and trials were performed. Each trial was 3s. Trials were presented in the pseudo-random form. The presentation of the stimulus for a single trial in the "task" block was shown in Figure 1B. First, a fixation "+" was presented for 400 ms. Then a picture sequence containing 30 pictures (show in Figure 1C) was presented. Each picture was presented for 40 ms. A picture of a table-tennis table appeared on the screen when the picture sequence ended. The table-tennis table picture was presented for up to 1400 ms during which participants must make a response by pressing the button. Their work was to predict, as the receiver, which side the ball would land on. Participants were asked to press "1" if they believed that the ball would land on the left and "2" if they believe that the ball would land on the right. The picture disappeared immediately after pressing the button. A blank screen was used to fill the gap if the table-tennis table picture was presented for less than 1400 ms. Behavior tests and fMRI scanning were synchronized. Participants were told to keep their bodies still except for the fingers that pressed buttons during the entire session. The participants took practice before the formal scanning.

Image acquisition

MRI scans were acquired using a Siemens Magnetom Skyra 3.0 T Scanner (Siemens, Erlangen, Germany) with an 8-channel head coil in the Eighth Medical Center of the General Hospital of the Chinese People's Liberation Army (Beijing, China). The echoplanar imaging (EPI) sequence was applied to collect functional scans (flip angle = 90°, TR = 2000 ms, TE = 30 ms, slice thickness = 3.0 mm, slice number = 35, FOV = 225 × 225 mm^2, matrix size = 64 × 64, voxel size = 3.5 × 3.5 × 3.0 mm^3, number of volumes = 200). High-resolution structural images were acquired using the magnetization-prepared rapid gradient-echo sequence (flip angle = 8°, TR = 2200 ms, TE = 2.45 ms, slice thickness = 1.0 mm, slice number = 176, FOV = 270 × 270 mm^2, matrix size = 256 × 256, voxel size = 1.1 × 1.1 × 1.0 mm^3).

fMRI preprocessing

Preprocessing of the MRI data was done by SPM12 (Statistical Parametric Mapping software package; Wellcome Department of Cognitive Neurology, London, UK). The first 10 volumes were discarded. Thereafter slice-timing correction was done in an interpolation-based method. Next, head movement parameters were estimated and images were registered to the mean image. Data were excluded if the translation was > 2 mm and rotation >2°. After head movement correction, functional images were coregistered to the anatomical image which were normalized to the MNI space. Finally, an 8-mm full-width half-maximum (FWHM) Gaussian kernel was used to spatially smooth all volumes.

Four participants in the non-athlete group and one in the table tennis player group were excluded due to machine fault; moreover, two participants in the non-athlete group were excluded for head movement. Finally, 22 participants in the non-athlete group and 19 participants in the table tennis player group were included in the analysis.

QUANTIFICATION AND STATISTICAL ANALYSIS

Behavioral data analyses

After excluding the trials with reaction time less than 100ms[81] and participants with remaining trials less than half of the total, 27 non-athletes and 18 table tennis players remained. Then the accuracy and reaction time of the anticipation task were calculated. Two-factor ANOVA with repeated measures was conducted using SPSS 26.0 (IBM Corp, Armonk, NY, USA) separately for accuracy and reaction time with group (table tennis player group vs. non-athlete group) as the between-group factor and condition (baseline vs. SD) as the within-subject factor.

fMRI data analyses

In the first-level analysis, the "task" condition (corresponding to the 8 blocks) and "rest" condition (corresponding to the eight 20-s blanks) were determined for each session in the fMRI model specification. Six head motion parameters were also included in the model. A default high-pass filter was used and the cutoff was 128s. Gray-matter-mask was used as the explicit mask. After model evaluation, T-contrast was selected to create the contrast image for the "task" over "rest" of each subject in each session. These contrast images were used in group analysis.

In the 2nd-level analysis, two one-sample t-tests were first performed to explore the activation of the table tennis player group and non-athlete group when they complete the anticipation task at baseline. Thereafter the flexible factorial model was applied. The present study was a 2 × 2 factorial design with group (table tennis player group vs. non-athlete group) as the between-subject factor and condition (baseline vs.

SD) as the within-subject factor. Age was included as a covariate for a significant difference in age between the two groups. Three F-contrasts were used to test the main effect of group, the main effect of condition, and the interaction effect. Their weights matrices were made according to Gläscher and Gitelman.[82]

In order to show the differences between the two groups and differences between the two conditions more intuitively and conduct a simple-effect test for interaction effect, the average BOLD signals of significant clusters were extracted using Marsbar0.45. Thereafter analyses were made by SPSS26.0.