The impacts of Sleep Deprivation on Self-other Decision Making: An fMRI Study using Balloon Analog Risk Task (BART)

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Abstract

Background:
Sleep deprivation has been shown to affect cognitive function and decision-making, prompting interest in its impact on social interactions and risk assessment. Understanding how sleep deprivation influences self and other decision-making processes is crucial for elucidating its broader effects on social behavior and cognitive function.

Methods:
In this study, we utilized functional magnetic resonance imaging (fMRI) to investigate the effects of sleep deprivation on self and other decision-making. Eight participants underwent two fMRI scans before and after a period of sleep deprivation. Risk-taking behavior in self and other decision-making scenarios was assessed using the Balloon Analog Risk Task (BART).

Experimental Design:
Each fMRI scanning session consisted of four rounds of decision tasks, with task order randomly assigned to control for order effects. Participants were informed that another player required their assistance in making decisions.

Results:
fMRI data analysis revealed significant differences in brain activation patterns for different outcomes (win and lose) between sleep deprivation and control conditions. Reaction time under sleep deprive group was shorter than that under normal sleep group. Distinct activation patterns for risk were observed in self and other decision-making tasks. Notably, reduced brain activity in regions associated with risk assessment and reward processing was associated with sleep deprivation.

Conclusions:
Our findings indicate that sleep deprivation affects the neural processes involved in self and other decision-making, highlighting the importance of adequate sleep for cognitive function and risk assessment in social environments. These results contribute to our understanding of the neural mechanisms underlying the effects of sleep deprivation on decision-making processes, with implications for cognitive health and social behavior.

Keywords:
Balloon analogue risk task, Activation analysis, fMRI, insula, Risky decision-making, Sleep deprivation

1 | INTRODUCTION

1.1 Background

Decision making is a behavior that every human being engages in all the time. The cognitive view of decision making defines decision making as a process of information processing (Payne, Bittman, & Johnson, 1992). In essence, it is the process by which individuals monitor their own behavior through their own feelings and receive information feedback from the external world, to adjust and optimize their own behavior and make the correct or what-if response. Whether in daily life or at work, individuals will inevitably make many decisions for some people or some things every day. Some of these decisions may be simple choices of size, while others may require complex and sophisticated calculations. Decisions, big or small, make up our behavior and guide us in our lives, leading us to different futures.

Interestingly, people are not always rational in decision making. Individuals will react differently when faced with different decision-making information processing processes. Differences in ability or prior knowledge and experience, or simply small uncertainties, can lead to very different, rational, or irrational decisions in different environments and states of inspiration (Kahneman, 2003; Stanovich, 2013; Felin, Koenderink, & Krueger, 2017). The study of decision-making is one of the current meaningful and promising scientific topics (Defoe, Dubas, Figner, & van Aken, 2015). Psychologists have adopted some simple game paradigms to simulate individual decision-making using gambling games or choice judgements, thus facilitating the observation of people's behaviours in carrying out the decision-making process, and thus helping to provide a glimpse of those masked mental states in the decision-making process. Established studies have mainly focused on individuals' own self-decision-making when studying decision-making (Xiangyi Zhang, 2018; Fischhoff & Broomell, 2020), and considerable research has emerged in areas such as influences on decision-making, risk preferences, individual differences, etc. The prospect theory proposed by Kahneman and Tversky (1979) further elucidates the role in self-determination as the existence of irrationally different preferences in people. With in-depth research on decision-making, it can be deeply recognized that the environment in which an individual makes a decision, the cognitive assessment of the subject and object, and the inhibition and rethinking of one's own responses are all essential parts of the decision-making process.

In addition to making decisions for themselves, people in complex social relationships often participate in the decision-making behaviors of others, making suggestions and decisions for them (Ruff & Fehr, 2014). For example, people will buy desirable items for themselves and also select suitable gifts for their friends, people will choose a suitable elective course for themselves, and investment advisors will choose an exquisite financial plan for consumers. Self-decision making and decision making for others are important components of social decision making (Sanfey, 2007). Research on this issue takes the consistency between self-decision-making and decision-making for others as an entry point, which is also known as the "self-other" decision-making

difference (Liu, Y.F. et al., 2014; Lu, Xie, & Xu, 2012). In-depth exploration of "self-other" decision-making differences can help to further actualize and concretize decision-making research, which is more in line with the actual status quo of the social decision-making process, and more in line with the social nature of human beings as the sum of all social relations.

Current research on self-decision making versus decision making for others has focused on risk preferences and decision biases in behavioral research and on the differences that arise from various gain/loss scenarios and different priming effects in self-gaming and observing others' games. Researchers have interpreted such differences as being driven by interpersonal distance or differences in personal pro-social competence, but current research has not delved deeply into the different outcomes when the self receives different gain/loss conditions when acting as the duty-bearer in decision-making for others.

As previous research has found, interpersonal relationships moderate the difference between self and other decision making at both the behavioral and neurophysiological levels (Leng & Zhou, 2010, 2014; Lu et al., 2016; Shen et al., 2013; Xu & Xie, 2011). Studies have consistently shown that decisions made for others involve less risk taking (Laran, 2010) and omission bias (Lu et al., 2016) compared to decisions made for the self. Neurologically, self-decisions elicit more negative feedback-related negativity and larger P300 amplitudes than other-decisions (Shen et al., 2013). Furthermore, observing friends' decisions elicits a more positive P300 than observing strangers' decisions (Leng & Zhou, 2010). When gambling for friends, more negative FRN and larger P300 are observed compared to gambling for strangers (Leng & Zhou, 2014). While past research has investigated the role of interpersonal distance between strangers and acquaintances, no studies to date have examined self-decision making for others. Further research is needed to expand our understanding of how interpersonal relationships shape differences in self-versus-other perspectives across decision making contexts.

When it comes to decision-making tasks, researchers have found that once one is also involved in decision-making and gaming, the differences in FRN and P300 that were originally triggered by watching a friend lose vs. win disappear, even if the outcomes of the gains and losses with the friend are independent of each other (Yang et al., 2014; Leng & Zhou, 2010; Ma et al., 2011). For this phenomenon Ma (2011) attributed it to individuals' elevated self-focus after participating in the game, and the resulting social comparison psychology led to the neglect of friends' interests. Yue Tong and Huang Xiting et al. (2021) further found that the pattern of evaluating the outcome of friends is not fixed, but varies according to the individual's own situation of gain and loss through the game task. Current research has gradually begun to focus on the psychology of decision-making in different gain/loss situations through game tasks. By constructing decision-making tasks under different win-lose game conditions, researchers can help to further explore the differences between self-decision-making and others' decision-making. In particular, existing research prefers observing others' decision-making as a research model, and does not directly simulate the situations in which individuals make

decisions for others. This has led to some confusion between "making decisions for others" and "watching others make decisions" in related studies.

The present study aims to refine the current research on the differences between "self-other" decision-making, to advance the study of the different mental representations of self-play and other-play, and to focus on the psychological behavior and phenomena of decision-making for others under different gain and loss conditions. It has been demonstrated that people develop empathy, relative deprivation, and reference point effects in gaming tasks, and whether empathy for others or relative deprivation of one's own game occurs when the behavior is decided by the subject alone. It has also been demonstrated that there are different psychological states and risk preferences when deciding for oneself and deciding for others, so it is also possible to explore whether different psychological states arise in the same risky situation. The core of the study is to examine the status of empathy under conditions , where subjects made decisions for self and others copping with gains and losses.

The impact of sleep deprivation on cognitive functions, especially in decision-making, is a critical area of research. Studies consistently show that lack of sleep leads to slower decision-making and longer response times. This impairment is attributed to the adverse effects of sleep deprivation on attention, working memory, and executive functions, which are essential for efficient decision-making. Furthermore, there is robust evidence that sleep deprivation increases impulsivity and risk-taking behaviors. Individuals tend to favor immediate rewards over long-term benefits, leading to riskier and less considered decisions.

Additionally, sleep deprivation negatively impacts cognitive flexibility and creative problem-solving capabilities, which are crucial for complex decision-making tasks. The reduction in sleep quality is associated with diminished problem-solving abilities, negatively impacting the diversity and quality of decisions made. Moreover, the ability to regulate emotions, crucial for unbiased decision-making, is significantly impaired by sleep deprivation. This condition can lead to mood swings and emotional instability, which in turn can introduce biases and errors in judgment.

In a study further exploring the effects of sleep deprivation on risky decision-making, functional Magnetic Resonance Imaging (fMRI) was used to examine the impact of one night of total sleep deprivation (TSD) on the behavior and neural responses associated with risk in healthy adults. Participants (N=56) underwent fMRI scanning during a modified Balloon Analogue Risk Task (BART) after a night of total sleep deprivation and after a normal restful period, with the order of conditions counterbalanced across participants. The findings revealed no significant differences in risk propensity or risk-induced neural activation between rested wakefulness (RW) and TSD conditions. However, during TSD, there was a marked reduction in neural activity in the anterior cingulate cortex and bilateral insula during loss outcomes, and in the bilateral ventral striatum during gain outcomes.

These results suggest that sleep deprivation may affect risky decision-making by attenuating neural responses to decision outcomes and disrupting the brain-behavior

relationship that underpins decision-making processes. The importance of maintaining adequate sleep patterns is thus emphasized as crucial for optimal cognitive functioning and decision-making.

1.2 Research Hypothesis

Hypothesis 1: Sleep deprivation Group VS normal Group
Sleep deprivation Group will reduce neural activity in the reward-related regions for lose outcomes compared to rested wakefulness (RW).

Hypothesis 2: Self-decision Group VS Other decision Group
The reduction in neural activation for lose outcomes during sleep deprivation when making decisions for self is weaker than the reduction for lose outcomes when making decisions for others.

2 | METHOD

2.1 | Participants

Three participants (two females; one male) with a mean age of 25.3(25.3±3.6) years were recruited for this study. All three participants ensured two experiments before and after, one of which was in a situation of complete sleep deprivation (more than 24 hours without sleep, without taking coffee, tea and functional beverages, etc.), while the other was in a situation of more than three days of normal rest.

2.2 | Experimental design

In the experiment design, participants were randomized to undergo two scans before and after sleep deprivation. Each scan session comprised four rounds of decision-making tasks, with the order randomized to mitigate potential order effects. This design yielded a total of eight decision-making sessions for each participant, conducted both before and after sleep deprivation.

To ensure consistency in the sleep deprivation condition, participants were instructed to obtain 7-9 hours of sleep in the three days preceding the experiment and to refrain from sleeping for more than 18 hours prior to the MRI session.

To mitigate potential sequential effects, scans were conducted across two separate sessions, with participants undergoing the second session after altering their sleep patterns. Each experimental session commenced with a resting-state scan, followed by the decision-making tasks. Participants were informed that another player required their assistance in decision-making during the task. This sequential setup aimed to maintain participant alertness and engagement throughout the experiment.

2.3 | The balloon analog risk task

All participants were required to complete the modified version of the BART from the original paradigm (Lejuez et al., 2002) as a measure of their risk decision-making

behavior in the scanner. Participants were presented with a virtual balloon during the task and were asked to press a button to inflate the balloon which could either grow larger or explode. As the size of the balloon increased, the associated risk of explosion and the monetary reward increased. Participants had the option to continue or discontinue inflating the balloon by pressing two buttons with different colors. If participants stopped inflating the balloon, they would collect the wager for the current balloon, and the amount of the wager was added to the cumulative earnings as a reward. However, if participants continued to inflate the balloon and the balloon exploded, participants lost the wager of the current balloon, and the amount of the wager was subtracted from the cumulative earnings as a penalty. In this computerized task, participants can accumulate money each time they pump up a virtual balloon by pressing one button on the keyboard, but simultaneously, the risk of the balloon exploding will also increase. Thus, each pump conferred not only a greater potential reward but also greater uncertainty.

2.4 | Image data acquisition

MRI data acquisition. Imaging data were acquired using a 3 T Siemens Trio scanner equipped with a 32-channel head coil. High-resolution T1-weighted anatomical images were acquired using a gradient-echo (MPRAGE) sequence (TR = 2530 ms, TE = 2.26 ms, flip angle = 8°, 256 sagittal slices, slice thickness = 1 mm, 1.0 × 1.0 × 1.0 mm voxel, FOV = 256 mm, matrix size = 256 × 256). T2*-weighted functional images were acquired using a gradient-echo echo-planar imaging (EPI) sequence (TR = 1500 ms, TE = 30 ms, flip angle = 90°, 65 axial slices, slice thickness = 5 mm, voxel size 2.3 × 2.3 × 5mm, FOV = 220 mm, matrix size = 64 × 64).

Data analysis. Behavioral data analysis. We conducted separate repeated-measures ANOVA on the pro- portion of times that the participants chose the risky option (i.e., risk rate) and reaction times (RTs), with decision target (self vs. other) ,decision situation (gain vs. loss) and Sleep deprivation (RW vs. TSDs)within-subject factors.
fMRI data analysis. The fMRI data were preprocessed and analyzed using Statistical Parametric Mapping 12 (SPM12, Welcome Department of Cognitive Neurology, Institute of Neurology, London, UK). The first five volumes were discarded prior to analysis to allow for magnetic stabilization. Functional data were slice-time corrected to the middle slice. The functional images were then spatially realigned to the first volume to correct for head movement. Subsequently, the anatomical image was coregistered to the mean EPI image. The coregistered anatomical image was then segmented into gray matter, white matter, and cerebrospinal fluid using a unified segmentation algorithm. The realigned functional images were normalized to the Montreal Neurological Institute.

(MNI) EPI template and resampled to 3 × 3 × 3 mm^3. Finally, the normalized images were spatially smoothed using a Gaussian kernel with an 8 mm full width at half maximum. At the first level of analysis, we modeled three regressors of interest and convolved these with the canonical hemodynamic response function (HRF) on the basis

of the general linear model (GLM). In addition, six motion-correction parameters were included as regressors of no interest to account for motion-related artifacts. High-pass temporal filtering with a cut-off of 128 s was applied to remove low-frequency drifts in signal. The GLM also considered signal temporal autocorrelations with a first-order autoregressive model to improve noise estimation.

The three regressors were defined according to target (self vs. other) and situation (gain vs. loss) (1) balloon inflation (i.e. the onset of a larger balloon body started); (2) win outcome (i.e., the onset of the win feedback/collected the wager); (3) loss outcome (i.e., the onset of the loss feedback/balloon exploded). The six head motion parameters were included in the first level GLM model as a regressor to account for the head motion effects. The defined regressors are as follows: The probability of explosion for each balloon as the parametric risk level was entered into the model as a linear parametric modulation of the balloon win outcome regressor. We also added a parametric modulator to our GLM that scaled with reaction time (RT) with first order (linear) polynomial expansion.

At the second level analysis, the three first-level contrast images from each participant were then analyzed in a full factorial design with target (self vs. other), situation (gain vs. loss), and Sleep deprivation (RW vs. TSDs) as separate factors. All results were reported using whole-brain familywise error (FWE) corrected ($p < 0.05$) at the peak level.

Specifically, as described in the method section, for each balloon, the maximum inflation they can make was 70. From the 1st pump to the 70th pump, the probability of explosion increased monotonically and specifically ranged from 0% to 100.0%. In the 1st-level GLM, the probability of explosion was first orthogonalized and then incorporated in the model as parametric modulations associated with each inflation.

Three SPM t-contrast maps were obtained for each participant: (1) The contrast of risk was defined to examine brain activation that covaried with the parametric risk level; (2) The contrast of win was defined to examine brain activation in response to win outcomes; (3) The contrast of loss was defined to examine brain activation in response to loss outcomes. Next, the SPM t-contrast maps were entered in the second-level GLM for the group analyses. Paired t tests were conducted for each condition. The estimated brain activation values associated with the three contrasts (i.e., risk level, win events, loss events) in the key regions were extracted using XJview10 (https://www.alivelearn.net/xjview)

3 | RESULTS

3.1 | BART behavioral performance

RT. We performed a 2 (dcobject: self and other people) × 2(Sleep: deprive, normal sleep) analysis of variance after removing data whose response time was outside ±3SD

(the removed data accounted for 0.69% of the total number of trials). The reaction time of subjects under sleep deprivation conditions (M=3.80s, SD=2.90) was shorter than the reaction time under normal sleep conditions (M= 4.29s, SD=2.86). The results showed that the main effect of sleep deprivation was significant, $F(1, 854)= 6.234$, $p=0.013$, $\eta^2_p =0.007$. The reaction time under sleep deprive group was shorter than that under normal sleep group (see Figure 1). The main effect of decision object was not significant, $F(1, 854)=2.256$, $p=0.133$, $\eta^2_p=0.003$. The interaction between decision object and sleep deprivation was not significant $F(1, 854)=0.084$, $p=0772$, $\eta^2_p =0.000$ (Table 1).

Table 1a. ANOVA- RT for each trial.

Conditions	SS	df	MS	F	p value	η^2_p
dcobject	18.72173	1	18.72173	2.25610	0.13346	0.00263
Sleep	51.73342	1	51.73342	6.23423	0.01272	0.00725
dcobject ✻ Sleep	0.69844	1	0.69844	0.08417	0.77180	0.00010
Residual	7086.73368	854	8.29828			

Table 1b. RT (s)

Conditions	Self	Other
Deprive sleep	3.98 (2.75)	3.62 (3.04)
Normal sleep	4.41 (2.95)	4.17 (2.78)

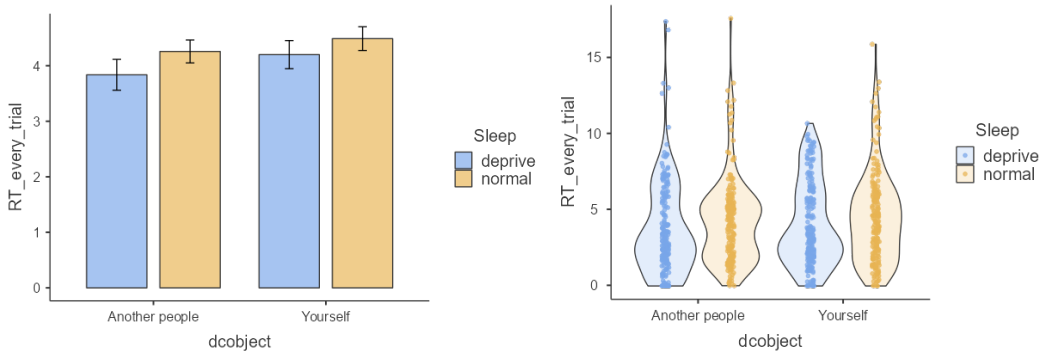

Figure 1. Distribution of variation in reaction times for decision-making for self and others under normal sleep and sleep-deprived conditions.

The violin plot (Figure 1B) illustrated the distribution and level of variation in reaction times for decision-making for self and others under normal sleep and sleep-deprived conditions. Reaction time variability was greater during sleep deprivation, indicating that sleep deprivation leads to inconsistent reaction speeds, whereas reaction times under normal sleep conditions were more consistent. This suggested a tendency for sleep quality to have a negative impact on reaction time stability.

Npumps. The results showed that the main effect of decision object was not significant ($F(1, 860) = 2.34919$, $p = 0.12572$, η^2_p=0.003), and the effect of sleep deprivation was close to significance ($F(1, 860) = 3.05704$, $p = 0.08074$, η^2_p=0.004). The interaction effect of was not significant at all ($F(1, 860) = 0.09832$, $p = 0.75393$, η^2_p=0.000). Furthermore, a biased effect size analysis showed that all effects were small (η^2_p values were all less than 0.005). Bar graph showed that sleep deprivation had no significant impact on the number of pumps, neither in self nor in others (Figure 2 A).

Table 2. ANOVA-nPumps.

Conditions	SS	df	MS	F	p value	η^2_p
dcobject	432.08449	1	432.08449	2.34919	0.12572	0.00272
Sleep	562.27894	1	562.27894	3.05704	0.08074	0.00354
dcobject ✻ Sleep	18.08449	1	18.08449	0.09832	0.75393	0.00011
Residual	158179.32870	860	183.92945			

Table 2b nPumps (times)

Conditions	Self	Other
Deprive sleep	21.48 (13.79)	20.35 (14.09)
Normal sleep	23.38 (14.00)	21.68 (12.29)

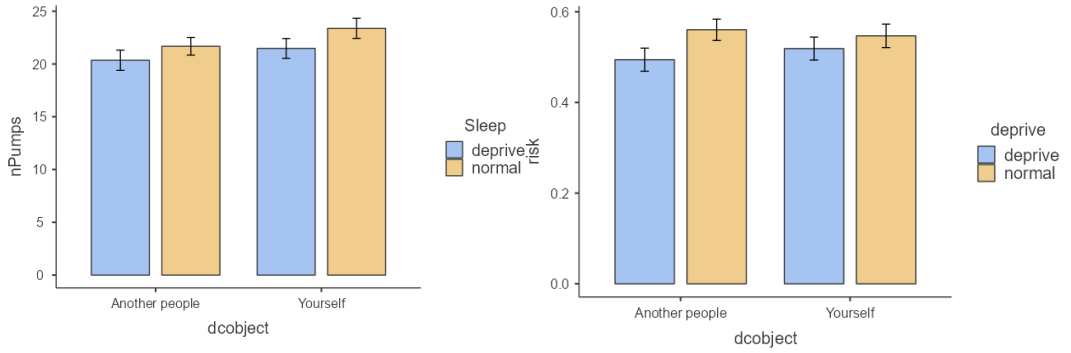

Figure 2. Distribution of variation in nPumps and Risks for decision-making for self and others under normal sleep and sleep-deprived conditions.

Risk .For the risk of decisions, we selected the data under the condition of receiving a reward (the balloon did not explode) (the removed data accounted for 37.62% of the total number of trials) and then conducted 2(dcobject: self, other people) × 2(Sleep: deprive, normal sleep) analysis of variance. The results showed that the main effect of sleep deprivation was marginally significant $F(1, 535)$=3.487 p=0.063, η^2_p =0.006. The main effect of decision object was not significant, $F(1, 535)$=0.049, p=0.825, η^2_p =0.000. The interaction between decision object and sleep deprivation was not significant $F(1, 535)$=0.566, p=0.452, η^2_p =0.001 (Figure 2 B, Table 3 **)**.

Table 3.ANOVA - Risk

Conditions	SS	df	MS	F	p value	η^2_p
dcobject	0.00417	1	0.00417	0.04915	0.82464	0.00009
SleepDeprive	0.29580	1	0.29580	3.48691	0.06240	0.00648
dcobject ✻ SleepDeprive	0.04800	1	0.04800	0.56583	0.45225	0.00106
Residual	45.38449	535	0.08483			

Earnings. We then analyzed the rewards subjects received in each trail. The results were shown in the Table 4. The main effect of decision-making object was not significant (F(1, 495)=0.183 p=0.669, η^2_p =0.000), and the main effect of sleep deprivation was not significant (F(1, 495)=0.032, p =0.857, η^2_p =0.000). The interaction between the two variables was not significant either. (F(1, 495)=2.291, p=0.131, η^2_p =0.005).

Table4.ANOVA- LastBalloonEarnings

Conditions	SS	df	MS	F	p value	η^2_p
dcobject	0.07659	1	0.07659	0.18321	0.66882	0.00037
SleepDeprive	0.01354	1	0.01354	0.03238	0.85727	0.00007
dcobject ✻ SleepDeprive	0.95761	1	0.95761	2.29066	0.13079	0.00461
Residual	206.93532	495	0.41805			

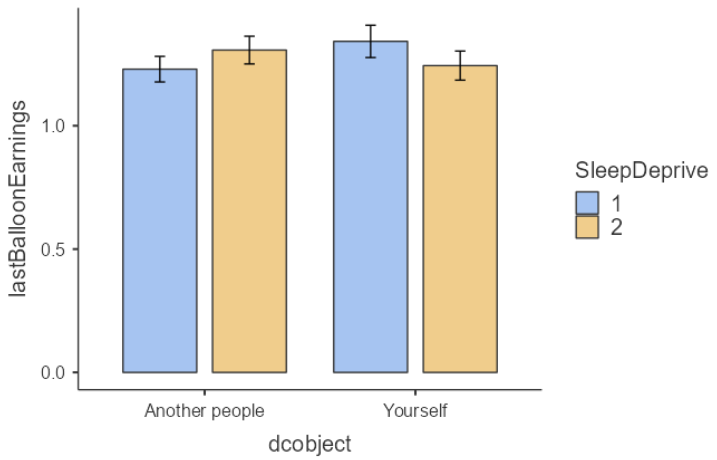

Figure 3. Distribution of variation in LastBalloonEarnings for decision-making for self and others under normal sleep and sleep-deprived conditions.

Winning numbers . We performed a 2 × 2 repeated measures ANOVA to analyze the frequency of rewards won. The findings indicated that the main effect of decision-

making object was not statistically significant. However, the main effect of sleep deprivation yielded a significant result. Interestingly, this suggests that sleep deprivation may not exert a substantial influence on subjects' behavioral decision-making outcomes. Furthermore, the interaction between decision-making object and sleep deprivation was found to be nonsignificant. Overall, these results imply that sleep deprivation may not significantly impact the behavioral outcomes of decision-making processes, as observed in our study.

Table 5.Within-group effect Note. Type 3 Sum of Squares.

Conditions	SS	df	MS	F	p value	η^2_p
dcobject	90.75000	1	90.75000	4.59494	0.16529	0.69674
Residual	39.50000	2	19.75000			
sleep	44.08333	1	44.08333	3.13018	0.21888	0.61015
Residual	28.16667	2	14.08333			
dcobject ✻ sleep	4.08333	1	4.08333	0.14286	0.74180	0.06667
Residual	57.16667	2	28.58333			

3.2 | Brain activation in response to the risk level

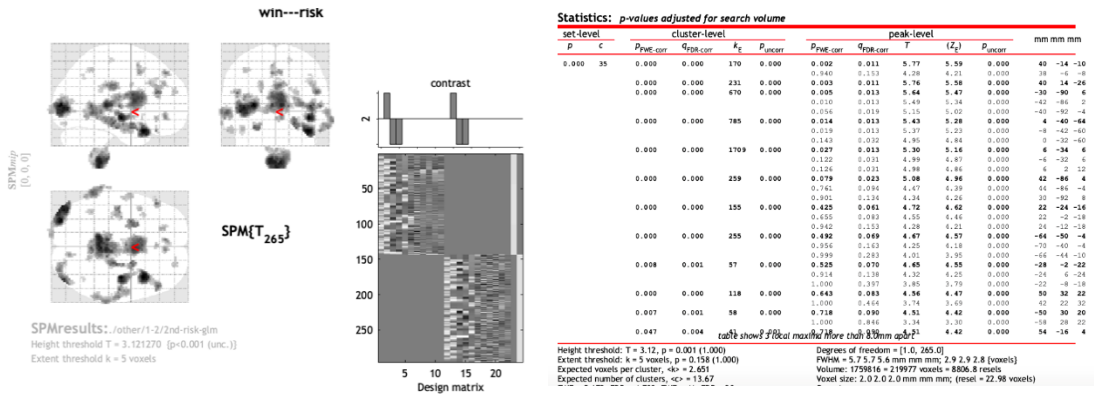

Figure4. Activation maps showing brain regions associated with Risk levels at win outcomes under sleep-deprivation (SD), P< 0.01.

The glm model represents the probability of explosion for each balloon, treated as the parametric risk level, entered into the model as a linear parametric modulation of the balloon inflation regressor, using a second-order polynomial expansion. The win event is defined as 1, and the explosion probability is included in the model as a parameter with a coefficient of -1.The effect of the win event on brain activation: A coefficient of 1 indicates that the occurrence of the win event positively impacts brain activation, meaning that the win event is positively correlated with activation. The contrast of risk is defined to examine brain activation that covaries with the parametric risk level (Figure 4).

Brain imaging results of the current study showed that during the risk processing stage, the activity of the neural dopamine network increased significantly with the increase in risk level in both RW and TSD. In the paired t-test comparing the risk levels of win outcomes, two activated clusters were observed at a significance level of p=0.01. Cluster 1 displayed activation in regions including the right cerebrum, parietal lobe, inferior parietal lobule, and temporal lobe, with a peak intensity of -8.212. Noteworthy structures within this cluster include the supramarginal gyrus and postcentral gyrus.

On the other hand, Cluster 2 exhibited activation in areas of the right cerebrum, limbic lobe, cingulate gyrus, and gray matter, with a peak intensity of 13.2085. This cluster encompasses structures such as the cingulate mid, Brodmann area 24, and corpus callosum. Despite their small voxel counts, these findings suggest involvement in diverse cognitive processes, underscoring the need for further exploration of their functional implications (Figure 5).

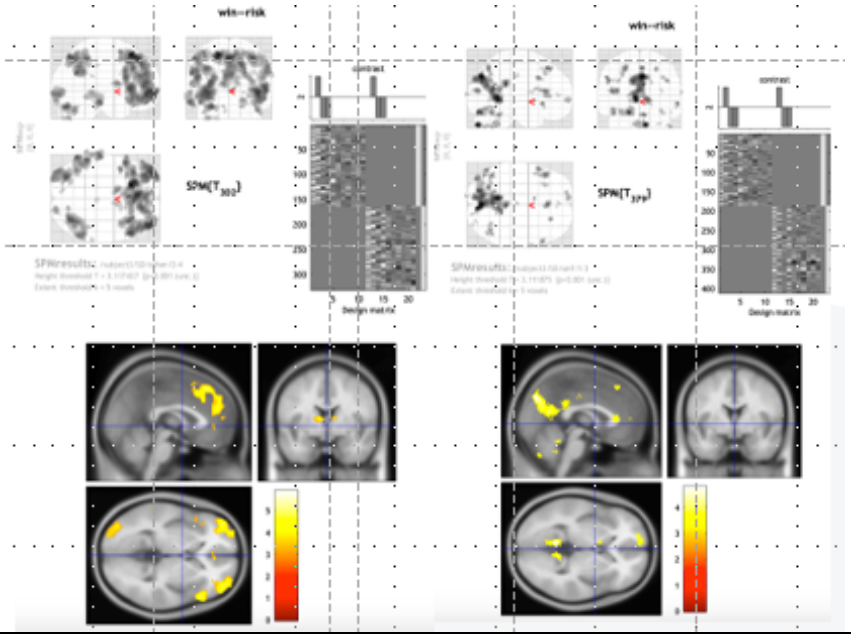

Figure5. The activation of brain regions during Subject 3's self-decision making under Risk condition for-self and for-other group , T1 brain map results. p value < 0.001.

The activation patterns in the brain regions during Subject 3's self-decision making under the Risk condition differed between the for-self and for-other groups, as depicted in the figure. However, despite this observed variation, no statistically significant differences in brain regions were found in the paired results, even when considering a significance level of $p < 0.05$. Therefore, the comparison between self and other conditions can only be evaluated against the original hypothesis in win and lose scenarios, as no significant differences were observed under the Risk condition.

3.3 | Brain activation in response to the outcome

At the specified threshold, the lose outcomes exhibited significant activation in the right parietal lobe and inferior parietal lobule, indicative of sensory information processing and spatial cognition functions during total sleep deprivation. Conversely, the win outcomes displayed significant activation in the Frontal Lobe, Precentral Gyrus, and

Occipital Lobe, with an FWE-corrected p-value of 0.05.

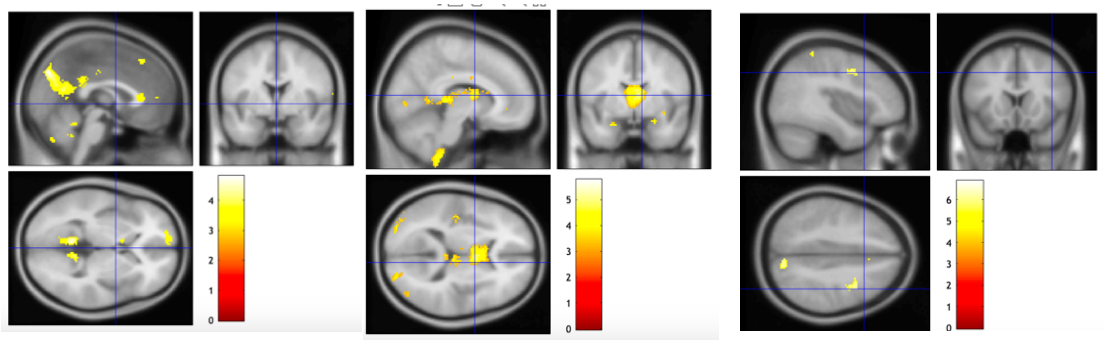

Figure6. The activation of brain regions during Subject 2's self-decision making under SD (Sleep Deprivation), including win-risk, win, and lose outcomes in the T1 brain map results.

The NSD brain activation under the lose outcome appears to be more active compared to the sleep deprivation condition, indicating a notable difference between SD and NSD at the single-subject level. However, no significant difference was observed in the win outcome between the SD and NSD situations(Figure 6).

Table 6: Activation Brain Regions Across varied outcome after Sleep deprivation (Subject 2).

Conditions			**Self-Decision-Making**	**Sleep deprivation**	
outcomes	**MNI**	**Voxels**	**Anatomical region**	**Cognitive Function**	**P-value**
Win-RISK	-20-84 -20	33	Left Occipital Lobe, Fusiform Gyrus, Brodmann Area 19	Visual Processing	**P=0.0001**
	-10 -52 4	148	Left Limbic Lobe, Posterior Cingulate Gyrus, Brodmann Area 29	memory, emotion regulation, or other limbic functions	
	2 -80 38	283	Right Parietal Lobe, Precuneus,Cuneus, Brodmann Area 7	visuospatial processing, attention, or other higher-order cognitive functions	
Lose	45 -45 52	63	right parietal lobe, inferior parietal lobule, and white matter region	sensory information processing and spatial cognition functions	**FWE P=0.05**
Win	-8 -86 14	9314	Occipital Lobe, Cuneus	Visual processing, spatial cognition	**FWE P=0.05**
	24 -50 -18	51	Right Cerebellum, Culmen	Motor coordination	
	-34 -12 66	3130	Frontal Lobe, Precentral Gyrus	Motor control, decision-making	
	-38 4 32	88	Frontal Lobe, Inferior Frontal Gyrus	Language processing	

-34 -22 42	150	Frontal Lobe, Postcentral Gyrus	Somatosensory processing
54 10 42	33	Frontal Lobe, Middle Frontal Gyrus	Motor planning
36 -58 54	70	Parietal Lobe, Superior Parietal Lobule	Spatial orientation

The paired t-test uncovered notable distinctions in brain activation between the sleep deprivation (SD) and non-sleep deprivation (NSD) conditions, with a significance level of $p < 0.01$, uncorrected. Particularly, under the NSD condition, heightened activation was evident in multiple brain regions linked to win outcomes, aligning with our hypothesis 1. (Table 6)

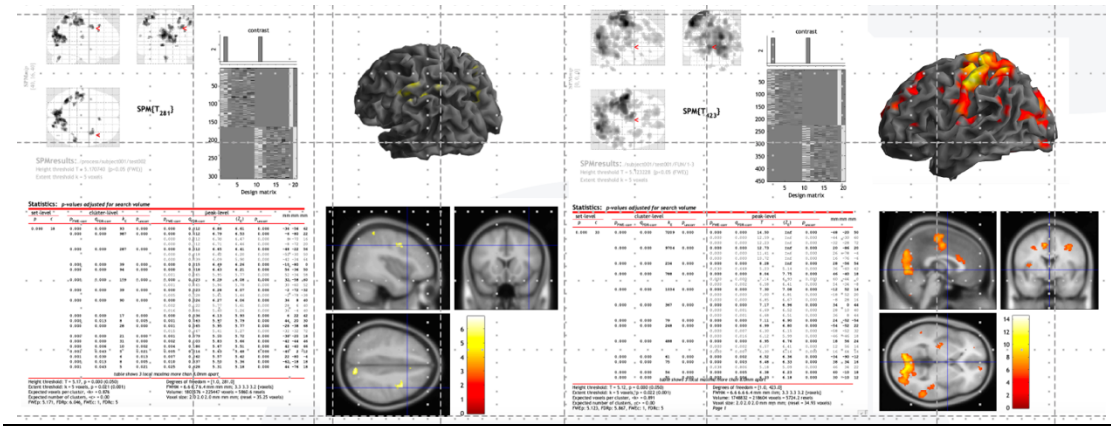

Figure7. Cortical activation maps showing brain regions associated with win outcomes in the sleep-deprivation (SD) and non-sleep-deprivation (NSD) conditions, corrected for family-wise error (FWE) at a significance level of < 0.05.

These regions included the temporal lobe, encompassing the superior and middle temporal gyrus, as well as the frontal lobe, including the inferior and middle frontal gyrus. Additionally, notable activation was found in the parietal lobe, particularly in the precuneus and superior parietal lobule, along with the posterior lobe of the cerebellum and the cuneus of the occipital lobe. Moreover, consistent activation patterns were identified in the insula, central sulcus involving the precentral and postcentral gyrus, and subgyral regions across multiple clusters. These findings suggest the significant involvement of these brain regions in the neurocognitive processes during win outcomes compared to the NSD condition. (Figure 7,Table 7)

Table 7: Main Effect of Win Outcome between SD and NSD

Peak MNI Coordinate	Brain Region	Voxel Count
-38 -62 -22	Left Cerebellum, Fusiform Gyrus, Brodmann Area 19	59
50 26 -10	Right Parietal Lobe, Precuneus, Cuneus, Brodmann Area 7	56
36 52 -14	Right Cerebrum, Frontal Lobe, Middle Frontal Gyrus, White Matter	37
-62 -20 -10	Left Cerebrum, Temporal Lobe, Middle Temporal Gyrus, White Matter	34

Peak MNI Coordinate	Brain Region	Voxel Count
38 10 16	Right Cerebrum, Sub-lobar, Insula, White Matter	74
-12 40 20	Left Cerebrum, Frontal Lobe, Medial Frontal Gyrus, Gray Matter	100
18 -78 32	Right Cerebrum, Occipital Lobe, Cuneus, Gray Matter	65
-30 -26 42	Left Cerebrum, Frontal Lobe, Sub-Gyral, White Matter	189
-20 -34 56	Left Cerebrum, Parietal Lobe, Postcentral Gyrus, Gray Matter	171

Table 7. Paired-t Contrast Test, all results reported are based on whole-brain analysis with a significance level of P < 0.05 at the peak level.

For the loss outcomes, heightened activation was observed during self-decision compared to decisions made for others. Subsequently, a second round of paired t-tests examined the disparities in brain activation between self and other decision-making under conditions of sleep deprivation. The analysis revealed activation in several brain regions, including the left corpus callosum, left precuneus, left anterior superior temporal gyrus, left fusiform gyrus, and left prefrontal cortex. Specifically, the left corpus callosum was implicated in interhemispheric communication and integration processes. The left precuneus showed involvement in various aspects of language processing, encompassing comprehension, memory, and production. The left anterior superior temporal gyrus demonstrated a close association with language comprehension and production, involving semantic processing and auditory language information processing. Additionally, the left fusiform gyrus was primarily engaged in visual information processing, encompassing visual perception and memory. Lastly, the left prefrontal cortex emerged as a pivotal region for executive functions, including decision-making, planning, working memory, and attentional control (Table 8).

Table 8: Main Effect of Lose Outcome between for-self and for-other.

Peak MNI Coordinate	Brain Region	Voxel Count
22 -56 -50	Right Crus I of Cerebellum	162
44 -74 0	Right Middle Temporal Gyrus (Brodmann Area 21)	252
-46 -66 -4	Left Middle Temporal Gyrus (Brodmann Area 21)	143
26 8 14	Right Middle Frontal Gyrus (Brodmann Area 9)	305
12 40 28	Right Middle Frontal Gyrus (Brodmann Area 46)	290
66 -42 36	Right Superior Temporal Gyrus (Brodmann Area 38)	261
-20 -60 26	Left Superior Temporal Gyrus (Brodmann Area 22)	1447

Table 8: Paired-t Contrast Test, all results reported are based on whole-brain analysis with a significance level of P < 0.05 at the peak level.

4 | DISCUSSION

4.1 | Effects of sleep deprivation on reaction time

In our statistical results, we found that the reaction times of subjects under sleep deprivation conditions were lower than those under normal sleep conditions. This result and trend were consistent with our hypothesis. Participants took shorter time to make decisions when they were sleep deprived. This finding was consistent with previous studies.

Harrison and Home (2000) noted that sleep deprivation may lead to a decrease in decision-making quality and an increase in risk preference. Subjects' cognitive abilities may decline under sleep deprivation, which could have a negative impact on attention and working memory. Telzer et al. (2013) revealed that teenagers with poor sleep quality are more likely to engage in risky conduct, potentially due to an imbalance between affective and cognitive regulation. Therefore, they had difficulty making rational choices and tend to make hasty decisions, which explained why subjects under sleep deprivation conditions had shorter reaction times per trial than subjects under normal sleep conditions. In addition, according to the subjects' verbal reports, the subjects under the deprivation condition may have rested to end the experiment faster, thus speeding up their responses. Due to the small sample size selected in this study, it is difficult to be highly convincing. The sample size can be increased for further exploration in the future.

4.2 | The effect of risky decision between sleep deprivation and normal sleep

Risk was calculated by dividing the number of key presses the subject made by the maximum number of key presses allowed for that trial without the balloon exploding. The maximum risk value is 1, and the larger the value, the higher the apparent risk. The statistical chart showed that the sleep deprivation group had lower risk than the normal sleep group. This result is inconsistent with our expectations. However, due to the small sample size, this result is not convincing.

Previous research (Fraser et al., 2013; MacDonald & Cote, 2021) pointed out that sleep deprivation may cause people to be more inclined to accept high-risk options rather than rationally weigh the pros and cons. This means that sleep-deprived individuals are more likely to be biased toward taking risks, even if this may lead to adverse outcomes. This increased risk preference may be due to factors such as cognitive decline, mood swings, and poor concentration caused by sleep deprivation. In general, sleep deprivation is often thought to negatively impact cognitive function, including decision-making. However, Mao et al. (2023) also used functional magnetic resonance imaging (fMRI) and a modified balloon simulated risk task (BART) to study the effects of one night of total sleep deprivation (TSD) compared with resting wakefulness (RW) on decision-making. Effects on behavior and neural activity. They found that although sleep deprivation may have affected some neural mechanisms, it did not have a significant impact on participants' decision-making tendencies overall. Combining the results of this study (including fMRI results) with previous research, sleep deprivation may affect risk-taking decision-making by attenuating neural responses to decision outcomes, rather than directly changing risk-taking behavior.

4.3 | Self–other discrepancies did not affect brain activation to outcomes

The current study investigated the impact of one night of total sleep deprivation (TSD) on risk-taking behavior and brain activity in three healthy adults using a modified Balloon Analog Risk Task (BART) in a tightly controlled block-design study. Contrary to our expectations, no significant differences in risk-taking behavior were observed between the rested wakefulness (RW) and TSD conditions in the self-other study. However, neuroimaging data revealed a notable reduction in regional neural activity for both win and loss outcomes during TSD compared to RW. The study's primary strength lies in its meticulous and comprehensive experimental design, which incorporates the reliable BART paradigm. Furthermore, the combination of behavioral experiments and fMRI techniques in investigating the effects of TSD on risk-taking decisions under stringent sleep laboratory conditions holds considerable promise.

In hypothesis 2, we proposed that the reduction in neural activation for lose outcomes during sleep deprivation would be weaker when making decisions for-self compared to decisions for-others. However, due to the lack of significant differences found in brain regions between self and other conditions in the paired t-tests, we were unable to further analyze the differential impact of sleep deprivation on the two scenarios. The limited number of participants may have hindered the effectiveness of the secondary analysis. Additionally, our experimental design involved block designs, with a considerable time gap between decisions made for self and for others, making direct comparisons challenging and reducing the interpretability of the results.

4.4 | TSD did not affect brain activation in response to risk

The significance of Risk activation is lower compared to other outcomes such as win and lose. The results of paired t-tests also reveal a smaller number of voxels, limiting further investigation into the regions of interest. Contradictions have been persistent in past studies. In the study of (Salfi et al., 2020),robust activation was seen in the anterior cingulate cortex/me- dial frontal cortex (ACC/MFC), bilateral dorsal lateral prefrontal cortex (DLPFC), bilateral insular cortices, bilateral striatum, thalamus/midbrain, and a posterior network of bilateral visual pathway areas in the occipital region during both RW and TSD.

Safil et al. showed that inadequate sleep influenced risk-taking depending on the habitual individual response during deliberative decision-making(Salfi et al., 2020). In addition, some researchers have further divided the behavioral measurement of risky decision-making into experience-based measures (e.g., IGT, BART) and description-based measures (e. g., CGT), and found that there may be differences between these two different measures, such as age(Frey et al., 2017). One review suggested that a possible mediator of the relationship between sleep loss and risk-taking behavior was reduced functioning of the vmPFC(Womack et al., 2013), which is not found in our results, even the duration of TSD was also 24 hr, the same as our study. It is possible that higher risk is accompanied by higher reward and thus modulates striatum activation,

not just by risk itself. Compared to our findings of activation in the precuneus, insula, and middle frontal gyrus, there is only intersection in the activation of the bilateral insular cortices.

4.5 | Limitations and Futural Plans

Using functional magnetic resonance imaging (fMRI) and the cups task, wherein participants were tasked with choosing between risky and sure options for themselves and others in both gain and loss scenarios,(Xu, 2021) discovered that individuals exhibited greater risk-taking tendencies when making decisions for themselves in loss situations compared to decisions made for others. Interestingly, no significant difference in risk aversion was observed between self and other decisions in gain situations. Moreover, stronger activations in the dorsomedial prefrontal cortex (dmPFC) and anterior insula (AI) were noted when individuals made decisions for themselves in loss scenarios, but not in gain contexts. However, contrary to our hypothesis, our study did not observe differences in activations associated with dmPFC and AI. This could be attributed to the relatively small sample size and the use of a self-other decision paradigm based on block cycles, which might have compromised the validity of multiple comparison results. Additionally, our definition of risk differed slightly, as the maximum number of pumps for our balloons was set at 70, yet the average maximum number of pumps for participants was only 50. This resulted in more button presses, leading to participant fatigue and weariness, which may have contributed significantly to the activation of the motor cortex.

Improvements to the experimental paradigm, such as increasing the sample size, rigorously controlling experimental conditions, and incorporating well-matched control groups, would enhance the reliability of the findings. Additionally, refining the analytical strategies to reduce errors and increase sensitivity could provide more robust results. Furthermore, conducting functional connectivity analyses on the regions of interest would offer deeper insights into the underlying neural mechanisms involved in the observed effects.

By addressing these limitations and implementing improvement strategies, future research can provide a more comprehensive understanding of the neurobiological mechanisms underlying decision-making impairments in sleep-deprived individuals.

5 | CONCLUSION

In conclusion, our study sheds light on the impact of sleep deprivation on decision-making processes, particularly in the context of self and other considerations. Through neuroimaging techniques, we identified differences in brain activation patterns associated with self and other decision-making under sleep deprivation conditions.

As we wrap up our report, we extend our heartfelt gratitude to the participants for their invaluable contributions and trust in our research. We also express our appreciation to the fMRI laboratory operators for their technical support and guidance, as well as to our mentor for encouragement and guidance.

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