Memory of Navigation in Individuals with Varying Social Anxiety: A Virtual Reality EEG Study

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Abstract

While social exploration and spatial navigation share overlapping cognitive processes, how social anxiety influences navigation behavior, memory, and neural activity in immersive VR environments with social feedback remains unclear. This study combines VR and EEG to examine how individuals with varying social anxiety levels navigate virtual spaces under socially rewarding (e.g., positive facial feedback) or punishing conditions. Participants searched for landmarks in VR while receiving token rewards/punishments and feedback from strangers. Analysis of navigation paths, curiosity, and anxiety revealed correlations, and EEG data showed improved memory performance over time. Notably, high socially anxious individuals displayed altered hippocampal-prefrontal connectivity and frontal alpha asymmetry during social threat exposure. These findings advance understanding of socio-spatial neural mechanisms and potential therapies for social anxiety.

Keywords: Spatial Navigation; Social Interaction; Social Anxiety Disorder; Memory; EEG

Introduction

Spatial navigation is fundamental to human behavior, enabling us to reach destinations, explore new environments, and return to familiar places. This cognitive skill depends on processing spatial information, forming cognitive maps, and making navigational decisions. Neuroscience has identified key brain regions such as the hippocampus (O'Keefe & Dostrovsky, 1971), parietal cortex, and prefrontal cortex (Baumann & Mattingley, 2021), alongside neuronal cell types like place cells (O'Keefe & Dostrovsky, 1971) and grid cells (Hafting, Fyhn, Molden, Moser, & Moser, 2005), which together form the spatial navigation system. Beyond physical navigation, humans also navigate complex social environments—a skill termed social navigation—that involves understanding and anticipating the actions of others (Riedl & St. Amant, 2003; Tavares et al., 2015). This ability relies on additional neural mechanisms in areas like the prefrontal cortex and temporoparietal junction (Tavares et al., 2015; Nejati et al., 2023). Social anxiety can significantly impact cognitive functions, potentially affecting both spatial and social navigation abilities (Wong & Rapee, 2016; Kállai, Karádi, & Feldmann, 2009). Individuals with high social anxiety often exhibit heightened sensitivity to social cues and may experience difficulties in spatial memory and attention, especially under social circumstances (Schofield, Johnson, Inhoff, & Coles, 2012).

Recent studies, combined with advances in neuroimaging and virtual reality (VR), have driven progress in both spatial and social navigation research. Despite a growing understanding of these domains, the impact of social anxiety on navigation patterns, memory, and the underlying neural mechanisms—particularly in the context of social interactions and feedback in navigational tasks—remains vital for further investigation. Therefore, this research focuses on exploring differences in navigation patterns among individuals with varying levels of social anxiety (Kállai et al., 2009), examining how rewards and punishments during spatial exploration shape navigation strategies and motivation (Garvert, Saanum, Schulz, Schuck, & Doeller, 2023), and investigating how positive or negative social feedback during social navigation influences an individual's ability and willingness to navigate and memorize, as well as their cognitive and neural responses (Tavares et al., 2015; Wagner et al., 2023; Liang et al., 2024). By employing VR and potentially EEG, the study aims to deepen our understanding of how social interactions affect navigation, cognitive abilities, and neural signals, potentially paving the way for innovative clinical treatments for social anxiety and related conditions.

Methods

In conjunction with the content shown in the figure (see1), a total of 60 participants were recruited for the experiment (ages 18 to 36, with a mean age of approximately 22.6 years). All participants were right-handed, had normal or corrected-to-normal vision, and reported no cognitive impairments. Prior to the experiment, participants completed standardized questionnaires to assess spatial ability and anxiety levels (e.g., SAS, LSAS, SBSOD), and resting-state EEG data were collected (sampling rate: 500 Hz) using a 32-channel mbt Smarting PRO system, with electrodes placed according to the international 10–20 system.

Before the formal experiment, participants underwent a pretesting phase designed to familiarize them with the use of physical manipulatives and the Memory Sorting Test. This phase also included training on joystick-based navigation within an immersive virtual environment to help participants adapt to the control method.

In the subsequent formal testing phase, participants entered an immersive virtual environment that integrated spatial memory formation and social feedback. The environment was divided into six blocks, each consisting of six trials, with an equal number of spatial and social tasks. However, the task setups differed: in the spatial task, the interaction target was a box (with a flower as the target item), whereas in the social task, the interaction target was a virtual character. Both types of tasks included reward and punishment conditions. Participants were instructed to obtain as many rewards as possible and reach the navigation goal in the shortest possible time.

During the experiment, derived behavioral metrics such as navigation trajectory, instantaneous speed, pause behavior, and trajectory entropy were automatically recorded. In addition, participants' self-reported anxiety and willingness scores were collected. EEG data, recorded continuously throughout the experiment, underwent standard preprocessing procedures including noise and artifact removal. The data were then segmented into task-specific epochs corresponding to different navigation phases (approaching, interacting, and leaving the field), and categorized based on task type (spatial vs. social) and reward/punishment conditions. Time-frequency analysis was performed using the Morlet wavelet transform, focusing on the oscillatory activity of alpha (8–12 Hz) and theta (4–7 Hz) frequency bands.

After finishing the navigation session, participants completed an arrangement task to assess their construction of virtual spatial memories where they needed to re-arrange the right position of specific object on the 2D map based on the VR task. On the second day, they completed an online arrangement task and a subjective rating task assessing the arousal and valence of the interactive objects. Additional questionnaires on anxiety and perceived spatial ability were also completed.

Results

In the ERP analysis, three task-related epochs (approach, interaction, and leave) were examined across four conditions (reward/punishment × spatial/social tasks), revealing a significant main effect on social and spatial conditions during the approach phase ($p < 0.05$, Figure 2c1, 2c2), though no significant results were observed in the left and right temporoparietal junctions (lTPJ: CP5, P7, P3; rTPJ: CP6, P4, P8) or prefrontal cortex (lFC: F3, F7, FC5; rFC: F4, F8, FC6). Time-frequency analysis (TFA) using Morlet wavelet transform on the same epochs and conditions identified significant neural activity in Delta (0.5–4 Hz), Alpha (8–13 Hz), and Beta (13–30 Hz) bands, with notable Beta wave activation across reward conditions and Theta wave activation at 1–4 seconds in interaction phases (Figure 2d, graphs A1, A2, C4), highlighting differences in neural responses to reward/punishment and spatial/social stimuli (Figure 2a, 2b).

In memory-related results(see figure3), participants' recognition accuracy of scene stimuli (e.g., buildings, cases, passers-by) improved across experimental blocks, accompanied by faster self-evaluation reaction times and increased confidence ratings.Correlation analysis revealed a significant negative relationship between LSAS anxiety scores and confidence self-ratings during memory recall (ρ= -0.41, p = 0.0013) and a positive relationship with rating time (ρ= 0.37, p = 0.0037), suggesting that socially anxious individuals were less confident and more hesitant.

During the recognition task, we found that the accuracy of participants' memory for cases was negatively correlated with theta band power in the left frontal cortex during interactions with reward-associated cases in the navigation session (ρ= -0.57, p = 0.004) and positively correlated with alpha band power in the same region during interactions with punishment-associated boxes (ρ= 0.38, p = 0.0236), which might indicate functional specificity of different frequency bands of prefrontal activity in motivational learning.

Further, self-confidence ratings after memory tasks were negatively correlated with alpha-band power in the left frontal cortex across conditions involving spatial punishment (ρ= -0.55, p = 0.0043), implicating left frontal alpha power as a neural marker of confidence in memory retrieval.

Discussion

This study utilized a spatial pathfinding task with virtual interactions (cases or pedestrians) to administer rewards, aiming to explore the relationship between anxiety, memory, navigation behavior, and neural activity via EEG. Social anxiety, measured by the Liebowitz Social Anxiety Scale (LSAS), impairs spatial navigation by diverting cognitive resources, leading to longer pause times and slower speeds, especially in social contexts (Geer, Barroso, Conlon, Dasher, & Ganley, 2024; Kállai et al., 2009). This cautious behavior extends from social decision-making to navigation tasks (Saul, He, Black, & Charles, 2022). Unlike other anxiety scales, LSAS uniquely correlates with navigation outcomes, suggesting specific aspects like fear of evaluation play a key role (Amir, Elias, Klumpp, & Przeworski, 2003; Baker, Heinrichs, Kim, & Hofmann, 2002). In contrast, the Santa Barbara Sense of Direction Scale (SBSOD) better predicts spatial abilities in object recognition, indicating distinct cognitive processes (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Farran et al., 2022), though LSAS links to self-rated memory, reflecting self-evaluation biases (Holas, Kowalczyk, Krejtz, Wisiecka, & Jankowski, 2023).

EEG results suggest that heightened theta oscillations may reflect cognitive effort directed toward reward-driven strategy adjustment (e.g., resolving prediction errors or updating reward expectations), which could compete with neural resources required for memory encoding. While enhanced inhibitory may control mechanisms (e.g., suppressing distractors or emotional interference) that facilitate focused attention on spatial details, thereby improving memory consolidation. These insights clarify social anxiety's impact on spatial behavior and propose future interventions, like reducing social cue interference in navigation.

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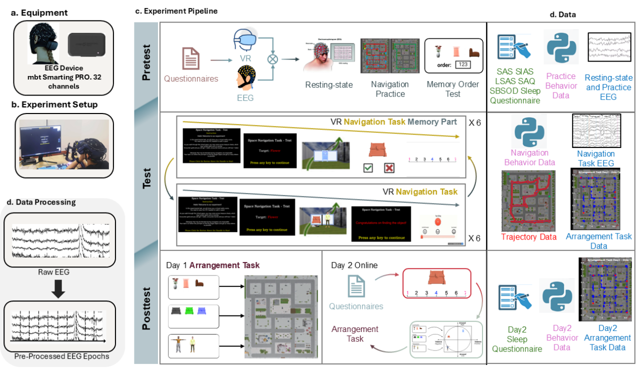

Figure 1: This figure provides an overview of the experiment pipeline, outlining the different phases and data collection methods involved. The experiment is divided into three main stages: Pretest, Test, and Posttest, with data processing integrated throughout. (a) The equipment used includes the mbt Smarting PRO device and a 32-channel EEG system for data acquisition. (b) In the Pretest phase, participants first complete questionnaires, followed by a resting-state task and practice VR navigation tasks. (c) The Test phase includes the VR navigation task and memory test, with EEG recordings taken during these tasks. (d) In the Posttest phase, participants engage in an arrangement task and provide additional data, including behavioral, EEG, and trajectory data. The figure also highlights the data processing steps, from raw EEG to pre-processed EEG epochs, as well as the various types of data collected throughout the experiment, including questionnaire, behavioral, and task-related data.

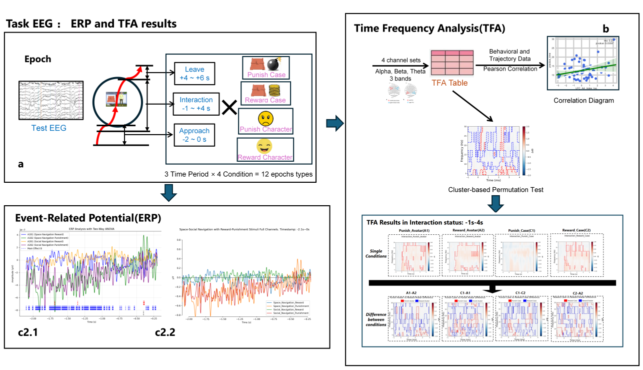

Figure 2: The overall process of validating EEG data using ERP and TFA is illustrated. Different time periods (e.g., Leave, Approach, Interaction) were paired with experimental conditions (spatial/social × Punish/Reward) to form 12 Epoch types. Subsequently, brainwaves from three bands of interest—*Alpha*, *Beta*, and *theta*—were extracted and analyzed via time-frequency analysis. Correlation tests incorporating behavioral and movement data were then conducted, and differences among conditions were statistically evaluated using the cluster-based Permutation Test (CbPT). The figure displays TFA visualizations for the interaction period alongside ERP waveforms comparing temporal EEG changes across conditions for further validation.

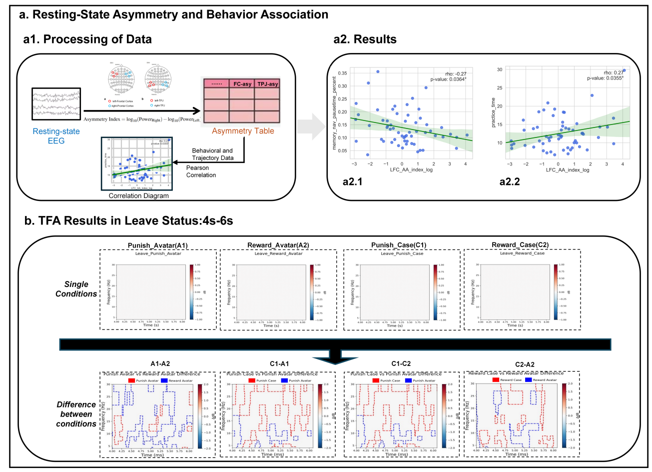

Figure 3: Resting-state and Task EEG analyse. (a) Resting-state asymmetry and behavior association analysis: Resting-state EEG data were processed to compute the asymmetry index, which was then used to generate an asymmetry table. Correlation analysis was performed between the asymmetry index and behavioral/trajectory data, with results visualized through scatter plots. (b) Time-frequency analysis (TFA) results in the Leave status (4s-6s). The top row shows the TFA results for individual conditions (Punish Avatar, Reward Avatar, Punish Case, and Reward Case). The bottom row presents the differences between conditions, highlighting statistically significant contrasts.

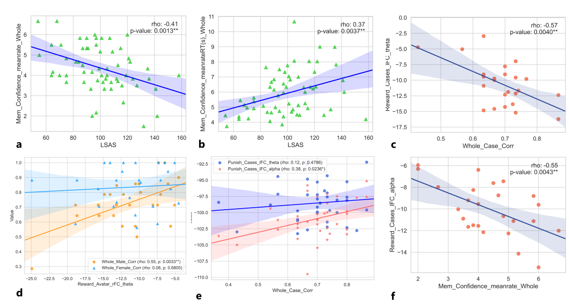

Figure 4: Behavioral performance correlates with brain activity. (a) Participants' self-rated memory confidence decreases with LSAS anxiety scores ($\rho = -0.41$, $p = 0.0013$), whereas their memory self-evaluation reaction times increase with LSAS ($\rho = 0.37$, $p = 0.0037$). (b) During the recognition task, the accuracy of memory for cases is negatively correlated with theta band power in the left frontal cortex during interactions with reward-associated cases ($\rho = -0.57$, $p = 0.004$) and positively correlated with alpha band power in the same region during interactions with punishment-associated boxes ($\rho = 0.38$, $p = 0.0236$). (c) Furthermore, self-confidence ratings after memory tasks are negatively correlated with left frontal alpha-band power under spatial punishment conditions ($\rho = -0.55$, $p = 0.0043$)