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Intuitive virtual reality based frontal-midline theta neurofeedback: a feasibility study in young ages

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Background: Neurofeedback is a method to modulate neural activity, such as frontal-midline theta oscillations. Given the emerging role of pathologically disrupted neuronal oscillations in psychiatric disorders, neurofeedback has potential as a novel therapeutic intervention. Participant immersion in the neurofeedback paradigm is critical to its efficacy. Here, we tested whether virtual reality enabled immersion and rapid acquisition of the ability to intentionally modulate frontal-midline theta oscillations.

Methods: We developed a neurofeedback task in which participants were instructed to clean up trash in a virtual underwater environment with their own thoughts. Unbeknownst to the participant, the amount of trash was updated as a function of frontal-midline theta power estimated from real-time electroencephalography recording. The neurofeedback blocks were interleaved with a working memory task, which is known to increase frontal-midline theta oscillations.

Results: The study involved 29 participants (Mean age = 24.62 years, SD = 9.31). By the end of the first block, 70% of participants successfully increased and sustained their frontal-midline theta oscillations. The amplitude of frontal-midline theta during neurofeedback was greater than rest but not as strong as during the working memory task.

Conclusion: We suggest that virtual-reality-based neurofeedback is highly immersive, causes minimal discomfort and increases theta oscillations with a brief learning period. Neurofeedback is a feasible method of increasing neural activity similar to working memory tasks and a promising method for training individuals to increase endogenous theta oscillations. Future research should investigate potential transfer effects into cognitive domains to increase cognitive control and top-down control.

KEYWORDS

neurofeedback, working memory, virtual reality, theta oscillations, frontal-midline

1 Introduction

Mental illnesses such as anxiety, depression, and substance use disorders are highly prevalent, affect one out of five adults, and are associated with disruption to executive functions such as working memory (WM) (Steel et al., 2014). Thus, interventions that aim at increasing cognitive control and associated neural activity patterns offer a promising avenue for prevention and treatment (Nikolin et al., 2021). Frontal-midline theta (FMT) oscillations are recruited in a variety of cognitive control tasks that require the prioritization of relevant information or the maintenance of information over time (Hsieh and Ranganath, 2014; Riddle et al., 2020a). Interventions that increase the amplitude of FMT oscillations might serve as a novel strategy to enhance cognitive control. One such approach that garnered interest but has yet to reach the level of evidence required for regulatory approval or inclusion in treatment guidelines is neurofeedback (NF). Nonetheless, studies indicate that FMT NF training can improve attention and working memory (Wang and Hsieh, 2013; Enriquez-Geppert et al., 2014; Pfeiffer et al., 2024).

NF represents a type of biofeedback where the goal is to recondition, retrain, or learn different neural activity patterns by presenting real-time perceptual feedback derived from ongoing brain signals using a closed loop system (Marzbani et al., 2016). The most common form of NF is based on measuring neural activity with electroencephalography (EEG) or functional magnetic resonance imaging (Sitaram et al., 2017). Despite the lack of comprehensive evidence of efficacy, especially in terms of the potential for creating lasting changes in neural activity that result in clinically significant improvements, clinical applications in attention deficit hyperactivity disorder, stroke rehabilitation, and anxiety have been proposed (Hammond, 2007; Sitaram et al., 2017; Van Doren et al., 2019).

One hurdle for the adoption of NF is that the rate of responders typically varies between fifty to eighty percent. Critically, the degree to which participants feel immersed within the task plays an important mediating factor in the efficacy of NF (Su et al., 2021). One approach to improve immersion is virtual reality, which presents virtual objects to the entire visual field of the individual and is more akin to natural experience (Székely and Satava, 1999). Previous work demonstrated that immersive virtual reality (iVR) using a head-mounted display does not significantly corrupt the signal quality of EEG, making the use of iVR with EEG-based NF feasible (Wood et al., 2021; Kerick et al., 2023). Additionally, there is evidence that the learning curve and responder rate are higher in iVR compared to a classical NF task on a computer screen (Berger and Davelaar, 2018). Overall, iVR with EEG NF is a promising methodology that may lead to novel circuit-based interventions, but significant work is required to improve the efficacy of this technique (Pinheiro et al., 2021). To date, studies specifically targeting FMT using iVR-NF remain limited, as noted in a recent systematic review (Kober et al., 2024).

In the present feasibility study, we hypothesized that iVR-NF for FMT oscillations would result in first a high acceptance and comfort (i.e., usability score), second a high responder rate (i.e., higher than fifty percent), third a rapid learning rate (i.e., higher than fifty percent), and fourth a spatially precise increase in the power of theta oscillations over the frontal-midline in healthy participants. Finally, in an exploratory analysis, we investigated the potential for transfer learning between elevated FMT power from neurofeedback and increased FMT power during a working memory task.

2 Materials and methods

2.1 Participants

The Intuitional Review Board of the University of North Carolina at Chapel Hill approved this feasibility study. All 29 recruited participants provided written informed consent. Inclusion criteria were age > 18 years and no history of psychosis, neurological conditions, or seizures. Participants were recruited by flyer and word-of-mouth in the broader area of Chapel Hill, NC, United States, between April 2022 and August 2022.

2.2 Experimental design

The single experimental session lasted approximately 2 hours. First, participants were briefed on the details of the experiment and provided demographic information. The EEG was applied, and the participants familiarized themselves with the head-mounted display and the virtual underwater world that served as the immersive environment. Participants were informed that this underwater environment would be constant throughout the study and were encouraged to visually explore the space. In subsequent experimental blocks, the participants were instructed to maintain fixation on a cross-shaped anchor and this acclimation to the underwater environment was used to reduce distraction and curiosity. Next, participants engaged in a 2-min resting-state recording while maintaining fixation on an anchor at the center of their visual field. A forward fast Fourier transform was run on 30 s (sample on request) of data from each of the frontal-midline electrodes. These power spectra were manually inspected at the beginning of the experiment. If an electrode displayed poor contact with the scalp (flat spectrum), then the channel was manually selected and flagged for removal. The mean and standard deviation of FMT power was calculated from this resting-state period and used in the NF algorithm in subsequent blocks. During NF, participants needed to generate frontal-midline theta power greater than their resting-state theta power. Participants performed the 5-min NF task in which they were given the instruction: "Let your mind wander and try to figure out how to remove the trash in the ocean with just your thoughts. You do not have to literally clean the ocean in your mind, but some of your thoughts will remove the trash." After the initial NF task block, participants performed four blocks of the N-back WM task and NF task in an alternating pattern. Before the first WM block and after the initial NF task, participants performed the WM task at three different difficulty levels for titration to the individual's WM capacity. This ensured that in the main experimental blocks the participants performed above chance but below ceiling. Altogether, there were five total blocks of the NF task and four blocks of WM task. Participants were able to take breaks as needed in between blocks. Each block of the WM task was 30 trials and was the same duration of 5 min as the NF task for direct comparison between the

TABLE 1 The questionnaire iVR NF consisted of questions about discomfort, immersion, usability, enjoyment, difficulty and performance. (SSQ: Simulator Sickness Questionnaire, IPQ: Igroup Presence Questionnaire, SUS: System Usability Scale).

Num	Question (anchors)	Sub-domain	Scale	Source
1	Did you experience sickness or nausea while wearing the head-mounted display?	Discomfort	4-Item Likert Scale	SSQ
2	Did you experience discomfort while wearing the head-mounted display?		4-Item Likert Scale	SSQ
3	Did you experience a headache while wearing the head-mounted display?		4-Item Likert Scale	SSQ
4	How real did the virtual world seem to you?	Immersion	7-Item Likert Scale	IPQ
5	How aware were you of the real-world surrounding while being in the virtual world? (i.e., sounds, room temperature, other people, etc.)		7-Item Likert Scale	IPQ
6	In the virtual world, I had a sense of "being there."?		7-Item Likert Scale	IPQ
7	Somehow I felt that the virtual world surrounded me?		7-Item Likert Scale	IPQ
8	If there was a treatment available using this system, would you use such a system for therapy regularly?		5-Item Likert Scale	SUS
9	Did you enjoy the virtual ocean environment?	Enjoyment	5-Item Likert Scale	None
10	Were you motivated to clean the ocean?		5-Item Likert Scale	None
11	How difficult was it to clean the ocean?	Difficulty	5-Item Likert Scale	None
12	How tiring was it to clean the ocean?		5-Item Likert Scale	None
13	Was it frustrating to clean the ocean?		5-Item Likert Scale	None
14	Did it get easier over time to clean the ocean?		5-Item Likert Scale	None
15	Did you enter into a flow state when cleaning the ocean?	Performance	5-Item Likert Scale	None
16	Were you able to clean the ocean?		Slider 0–100	None

tasks. At the end of the session, the participants were queried about the acceptance and comfort of the iVR-NF with the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), the Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001), the System Usability Scale (SUS) (Brooke, 1996) and with additional study-specific questions (Table 1).

2.3 Immersive virtual reality neuro feedback (iVR-NF)

The NF setup consisted of two main systems (Figure 1A). The first system was a head-mounted display (HTC Vive Pro, HTC, Xindian, Taiwan) powered by a high-performance VR computer (Intel i7-3.61 GHz, RAM 64GB, Nvidia GeForce RTX 3080Ti) running the NF application (iVR-NF system). The second system was a 128-Channel EEG system (HydroCel Geodesic Sensor Net with NetAmps 410 amplifier, Electrical Geodesics Inc., OR, United States). The EEG system streamed the data via the user datagram protocol (UPD) of a local 5 GHz network to the iVR-NF system with a frequency of 750 Hz. The iVR-NF task was developed in Unity Version 2020.3.26f1 (Unity, 2022).

The goal of the NF task was to clean a polluted ocean of trash (Figure 1B). The virtual underwater environment consisted of animated fish swimming in arbitrarily generated paths around the field of view with underwater sounds. The primary feedback stimuli were the number of trash objects that were presented bobbing in the ocean scene (e.g., pizza box and toilet paper roll, i.e., slow update rate). Participants were instructed to remove the trash from the ocean. We also provided second, more immediate feedback by adjusting the tint of the ocean (i.e., fast update rate). A toxic green color corresponded to low FMT power, and a clear blue ocean color depicted an increase in FMT power. In total, there were a maximum of 50 randomly located floating trash objects and 10 different color levels of the water, from blue to green. At the beginning of each NF task, the trash level was set to 50 percent, and

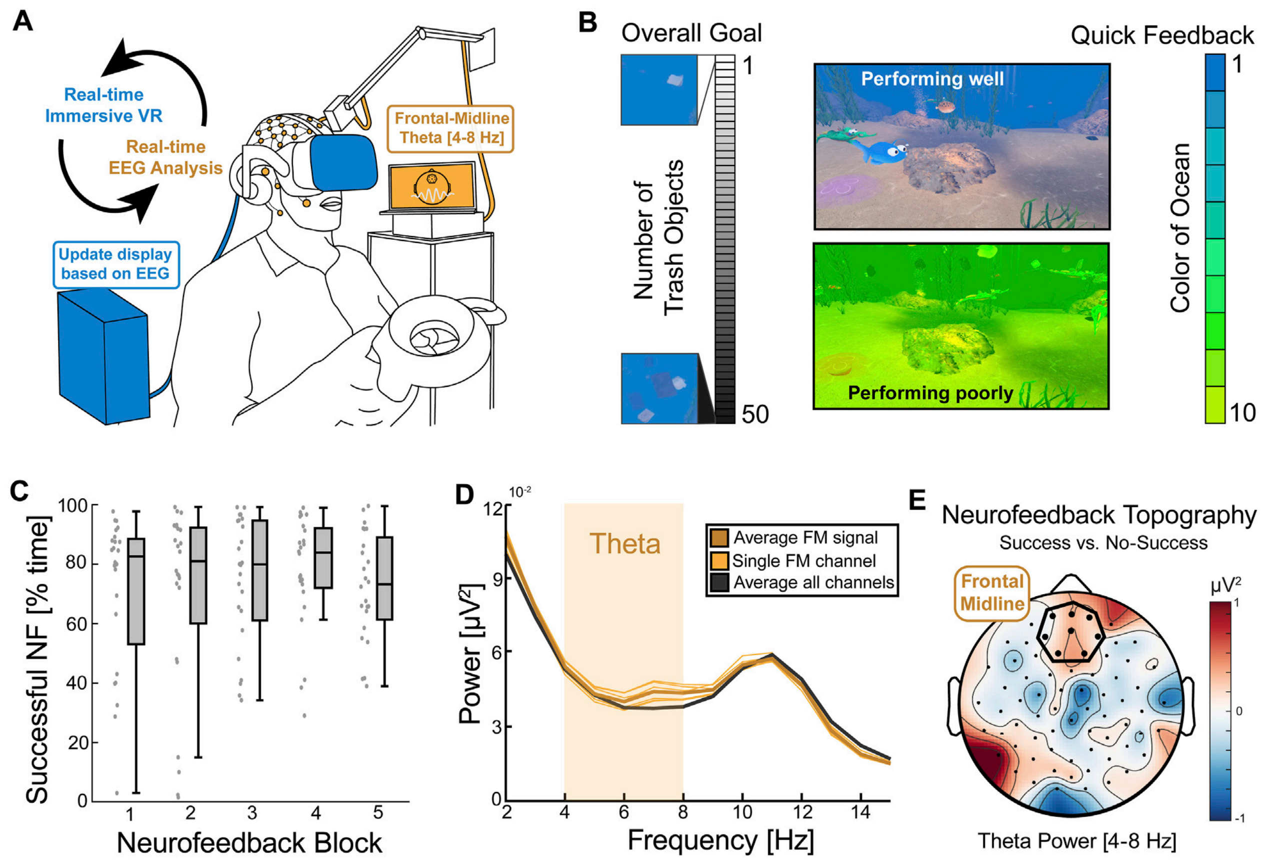

FIGURE 1
(A) The immersive virtual reality neurofeedback (iVR-NF) system. In blue, the iVR-NF system, and in orange, the EEG system is shown. **(B)** The overall goal was to clean the ocean of trash by reducing the number of trash objects present in the ocean (LEFT). We provided rapid feedback via the color of the ocean ranging from blue to toxic green (10 levels). Two examples of low and high performance are shown. **(C)** Participants were able to clean the ocean of trash using NF. The amount of time at which the participant displayed frontal midline (FM) theta power greater than that of resting-state is depicted on the Y-axis for each NF task block on the X-axis. **(D)** Frequency spectrum and normalized power of the frontal-midline electrodes during the NF task. Each FM refers to a single EEG channel, whereas the average FM is the mean of all single EEG channels shown. **(E)** The topography of theta power for the first NF task block as a difference between successful versus non-successful NF performance (median split) revealed a spatially specific increase in the FM theta. The region of interest depicts the frontal midline electrodes centered on Fz and including the seven surrounding electrodes (depicted as thicker black dots).

thus the underwater environment had 25 trash objects present, and the color level was set to five.

The EEG data was streamed from the EEG computer to the VR computer. Every 250 milliseconds, the system calculated FMT power from the data from the last 4 seconds and updated the pollution level and ocean color level. A 4-s window was chosen to detect state-level theta power, as opposed to more transient changes that can be detected with a shorter window. The frontal-midline was defined as Fz and the surrounding seven electrodes on the EGI 128-net. Our preprocessing steps at each update were as follows. Data with artefacts from eye blinks, eye movements, and head movements were rejected by deviation from the mean signal. We ran a z-transformation over time and removed data greater than 3 standard deviations from the mean. We used a buffer of 25 milliseconds on either side of the data that met these criteria and removed this data from our FMT estimation. When data was flagged for deletion in one channel, this period of time was also deleted in the other channels. Next, EEG data in each channel were normalized by z-transformation across time and bandpass filtered (FIR-filter, order = 250) in the theta band (4–8 Hz). Theta power was then calculated for each channel using the median of the band-pass filtered signal to reduce the influence of outliers and noise, yielding a single theta power value for the window. To calculate the update, we normalized the resulting theta value using the resting-state FMT power mean and standard deviation for that participant to account for nonlinear day-to-day signal variations caused by changing electrode impedances. This value was then multiplied by a scaling parameter and then added to a global pollution score. The level of trash and color depicted was based on the pollution score (i.e., adding removing randomly trash objects or changing the color of the ocean). We used a greater scaling parameter for the watercolor level such that the watercolor changed faster than the number of trash objects.

Quantification of the power of FMT oscillations during the tasks was performed in two ways: based on the real-time calculated FMT power and with more extensive data preprocessing steps applied post-hoc. The post-hoc EEG data were preprocessed by first high and low pass filtering, downsampling to 200 Hz, rejecting bad

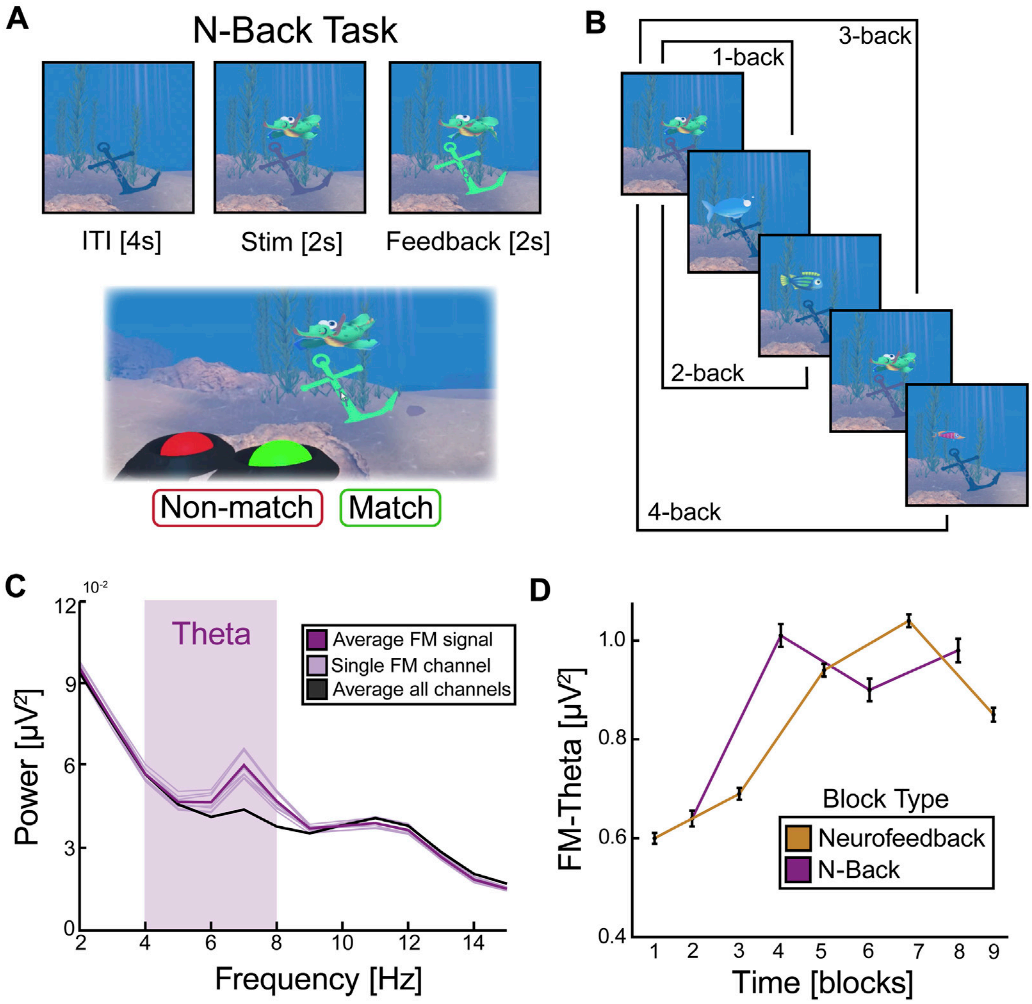

FIGURE 2
(A) N-Back WM task in the immersive virtual reality neurofeedback environment. **(B)** Based on a series of shorter blocks, the difficulty of the N-Back was titrated to be between one and four for each person. **(C)** Frequency spectrum and normalized power of the frontal-midline electrodes during the N-Back task. Each FM refers to the single EEG channel, whereas Average FM is the mean of all single EEG channels shown. **(D)** Frontal-midline theta (FMT) power increased over blocks for both the N-Back WM task and the NF task. The x-axis depicts time in blocks, and the NF and WM tasks alternated. Throughout this alternation, there is a temporal dependence where theta was elevated in both tasks following the second NF task (block 3).

channels and time points with artefacts, referencing to the global average, and rejecting artefacts using Independent Component Analysis with the open-source toolbox EEGLAB (Delorme and Makeig, 2004). The frontal midline was defined as Fz and the surrounding channels. The data were analyzed with MATLAB MATLAB. (2022) and R for statistics (Team, 2022). While the present study used a 128 channel EEG system, the use of a high-density system was used out of availability. The neurofeedback would likely be similar using a lower channel system with only a couple redundant channels over the frontal midline. The use of a 128-channel system allowed us to run an analysis of the spatial specificity of changes in theta power following frontal-midline neurofeedback. In addition, we compared the theta power derived from our real-time system and from the recorded data which were processed using a canonical preprocessing pipeline that accounted for additional source of noise. We draw the conclusion that our real-time preprocessing system was effective and similar to the high-density recording with more extensive preprocessing.

2.4 The N-Back WM task

We used an N-back WM task that consisted of three epochs (Figure 2A). First, an animated fish was presented at fixation for 4 seconds, and participants were asked to remember the type of fish presented (of five possible fish). At the start of the WM task block, the participant was told how many stimuli into the past they were to compare the fish in their visual field. During the titration of the task, the fish was either a match or a non-match to a fish presented two-back, three-back, or four-back (Figure 2B), with 10 trials for each. A difficulty level was chosen where the percentage correct was approximately between 60 and 80 percent. If the participant performed above 60% on the 4-back, then 4-back was selected. If they performed above 60% on 3-back, then the 3-back was selected. Otherwise, 2-back was selected. Then, on the four subsequent WM task blocks, the number of items that had to be held in mind was kept constant. Participants held a video game controller in each hand that was depicted in the virtual reality scene. Each of these controllers was indicated as red or green. Participants were instructed to respond during the 2 seconds that each fish was presented on the screen by pressing the button on the green game for a match or the red controller for a non-match. For practice trials, visual feedback of whether the answer was correct was provided by changing the color of the anchor in the background (red for incorrect and green for correct). Between trials, there was a 4-s interval with no fish present.

2.5 Statistical analysis and post-hoc EEG processing

To investigate our first hypothesis that iVR-NF for FMT would result in high acceptance and comfort, we used t-tests to check whether each assessment was above or below the midpoint of the rating scale, normalized to a range from zero to one. We corrected for multiple comparisons using Bonferroni correction. Our second hypothesis was that we would see a rapid response rate (overall ability to perform NF) due to the immersive VR environment and our utilization of two simultaneous forms of NF, one rapid (ocean color) and one gradual (number of trash items). For this outcome, we simply quantified the response rate and qualitatively compared this rate to those reported in the field. We ran a single Pearsons correlation to assess the relationship between the subjectively perceived performance and their neurofeedback success. In addition, we quantified how many participants were able to sustain elevated FMT power for 20 s, 1 min, and 2 min. Our third hypothesis was that participants would rapidly learn neurofeedback with the immersive environment. We quantified how many participants were able to reach maximal clean state within the first block and how many were able to by the final block. We performed a single Pearsons correlation between the subjective experience of ability (Likert scale) with overall NF performance.

Our fourth hypothesis was that we would find a spatially precise increase in FMT power. We used a Students t-tests to investigate the mean FMT power for NF versus resting-state. In addition, we performed a median split on participants based on successful NF rate, and performed a paired t-test in FMT power between groups. For this analysis, we ran a t-tests for each electrode with a median split of participants by NF success. If successful neurofeedback recruited scalp wide theta power, then there would be no local maximum over the frontal-midline.

For our exploratory, we investigated FMT power during the WM task and investigated the correlation between FMT power during WM and during NF. First, we assessed FMT power at baseline between WM and resting-state using a Students' t-test. Then, we investigated FMT power between those with high WM performance and those with low using a median split (Students' t-test). We investigated the impact of time on FMT power during WM using a one-way ANOVA with time. The difference in overall FMT power was investigated between NF and WM using a Students' t-test. Finally, we ran an analysis of individual difference of overall FMT power during WM and NF using a Pearson's correlation.

Finally, we investigated whether the real-time FMT power and the retrospective post-hoc calculated FMT power were significantly different from each other using a Students' t-test on mean power over all NF blocks.

2.6 Data and code availability

All relevant data supporting the results are presented in this manuscript. Raw data is available upon request.

3 Results

3.1 Task and participants

We developed a NF task where participants were able to clean the ocean by exploring different patterns of thought until a strategy was developed (Figure 1B). In total, five blocks of the NF task were completed that were interleaved with four WM blocks. A total of 29 healthy participants completed the study, and 24 were used for the final analysis. The five participants that were dropped from the analysis were removed due to low-quality EEG recordings, which were not related to the NF task. We speculate that for these participants, there was excessive physical jostling of the VR system on top of the EEG such that data had excessive noise, which precluded its analysis. Of the participants included in the analysis, the mean age was 24.62 years (SD = 9.31), 12 participants were male, 11 were female, and one was nonbinary. None of the participants had hearing problems. Seven participants required visual correction and did so via contact lenses. Past experience with iVR was low, rated as an average of 1.5 (SD = 1.18) on a scale of zero to four.

3.2 Acceptance and comfort—Hypothesis 1

Questionnaire findings revealed that participants experienced a low level of discomfort and low level of sickness, as shown in a mean score of 0.23 (range 0–1; SD = 0.18; comparison to midpoint: $t(23) = -7.22$, $p < 0.001$). In detail, the sickness or nausea mean score was 0.10 (SD = 0.18), discomfort 0.33 (SD = 0.26), and headache 0.26 (SD = 0.28). Furthermore, participants generally felt immersed in the iVR environment 0.55 (range 0–1; SD = 0.13; comparison to midpoint: $t(23) = 1.78$, $p < 0.044$; not-significant after correction for six comparisons: $p = 0.26$), enjoyed the NF task 0.63 (range 0–1; SD = 0.17; comparison to midpoint: $t(23) = 3.80$, $p < 0.001$), rated the difficulty from easy to moderate 0.39 (range 0–1; SD = 0.21; comparison to midpoint: $t(23) = 3.79$, $p < 0.001$), and had a high subjective feeling to be able to clean the ocean, i.e., successful neurofeedback performance, mean of 0.65 (range 0–1; SD = 0.21, $t(23) = 3.79$, $p < 0.001$). Overall, the usability of the NF task was rated high at 0.69 (range 0–1; SD = 0.24, $t(23) = 3.89$, $p < 0.001$).

3.3 Successful performance of the neurofeedback task—Hypothesis 2 & 3

In the NF task, the vast majority of participants demonstrated the ability to sustain FMT power above resting state levels for 50% of

TABLE 2 Frontal-midline theta power for each block and task.

Block	Neurofeedback (NF)		Working memory (WM)	
	Mean [μV^2]	SD	Mean [μV^2]	SD
1	0.60	1.80	0.64	1.98
2	0.69	1.98	1.01	2.73
3	0.94	2.10	0.90	2.90
4	1.04	2.16	0.98	2.94
5	0.85	2.25		

the time, which was sufficient to remove the trash and clean the ocean. On average, participants successfully cleaned the ocean for 71.49% (NF-1, SD = 25.87) of the time in the first block, 69.90% (NF-2, SD = 31.64) in the second block, 74.49% (NF-3, SD = 21.64) in the third block, 77.73% (NF-4, SD = 19.19) in the fourth block and 72.39% (NF-5, SD = 18.10) in the fifth block (Figure 1C). In a post-hoc analysis, we were interested in how long in time participants were able to sustain FMT power. Thus, we analyzed how many participants were able to maintain elevated FMT power for 20 s, 1 minute, and 2 minutes, with only 2 s of interruption in the task block. We found that every participant could sustain FMT power for 20 s, nine participants (37.50%) for 1 min, and two participants (8.33%) for 2 min. Thus, we found supporting evidence for our second hypothesis that iVR-NF would result in a high responder rate. In support of our third hypothesis that participants would demonstrate a high learning rate, we found that 18 (75%) of the participants were able to clean the ocean via NF in the first block (NF-1) more than 50% of the time. This already high learning rate was further increased to 21 out of 24 (87.50%) participants in the fifth block (NF-5). Participants were able to accurately assess their own performance success, as evidenced from a significant correlation between their subjectively perceived performance and their objectively assessed performance (r (22) = 0.542, p = 0.006).

3.4 NF increased frontal-midline theta power—Hypothesis 4

We investigated frontal-midline theta power during neurofeedback and during WM relative to resting-state (Table 2). Consistent with our fourth hypothesis, there was a significant increase in FMT power relative to the resting-state baseline during neurofeedback (mean increase from rest = 0.821 μV^2, SD = 0.847, t (23) = 4.74, $p < 0.001$, d = 0.97). This increase in power was specific to the theta band (Figures 1D, 2C). There was a significant increase in FMT power in the best-performing versus the worst-performing participants in the first block of neurofeedback (median split; t (22) = 2.228, p = 0.031, d = 0.45) (Figure 1E). There was no significant effect of time on FMT power for NF (F (1,23) = 3.749, p = 0.065, η_p^2 = 0.14). However, this effect was trending, suggesting that there was a numeric increase in theta power over time. The highest FMT power was in the fourth block of NF at 1.04 μV^2 (SD = 2.16), and the lowest was in the first block at 0.60 μV^2 (SD = 1.80) (Figure 2D).

3.5 Individual differences in theta power for WM and NF—Exploratory analysis

The number of items in the WM task was titrated for each participant to be greater than chance but to be experienced as difficult: 22 participants were allocated to the 4-Back, one to the 3-Back, and one to the 2-Back. The accuracy of the WM task in the first block was 56.94% (WM-1, SD = 18.39%), in the second block was 68.47% (WM-2, SD = 13.55), in the third block was 70.42% (WM-3, SD = 10.74%) and in the fourth block was 73.75% (WM-4, SD = 10.56%). FMT power was also increased during WM relative to the resting-state baseline (mean = 3.183, SD = 1.754, t (23) = 8.89, $p < 0.001$, d = 1.81). FMT power was increased in participants with greater performance during the WM task in the first block of WM (median split, t (22) = 2.388, p = 0.020, d = 0.49). A one-way ANOVA revealed a main effect of time on FMT power (F (1,23) = 62.49, $p < 0.001$, η_p^2 = 0.73), such that FMT power increased over WM blocks. The highest FMT power during WM was in the second block at 1.01 μV^2 (SD = 2.73), and the lowest was in the first block at 0.64 μV^2 (SD = 1.98). FMT power was increased in participants with greater performance during the WM task in the first block of WM (median split, t (22) = 2.388, p = 0.020, d = 0.49). Across participants, FMT power was greater during the WM task than during NF (mean = 2.36, SD = 1.57, t (23) = 7.38, $p < 0.001$, d = 1.51) and there was a significant individual differences correlation between FMT power during WM and during NF (r (22) = 0.45, p = 0.028) such that participants with greater FMT power during WM also demonstrated greater FMT power during NF.

3.6 Real-time approach versus canonical preprocessing on a high-density system

We investigated the effectiveness of a low channel count with minimal preprocessing in real-time and the fully preprocessed data from the high-density recording. There was a significant difference between real-time FTM power and the retrospective post-hoc calculated power (t (23) = 2.117, p = 0.035, d = 0.43) which suggested that there might be additional corrections performed in the offline analysis. Notably, the real-time FTM power was greater than the post-hoc calculated power with a small to medium effect size, which suggests that there may be additional source of noise in the theta estimate during real-time that were removed during the computationally intensive post-processing.

4 Discussion

Consistent with our first hypothesis, our results indicate that iVR-NF was pleasant and evoked low discomfort and thus had a high acceptance. After multiple comparisons correction, the immersion into the underwater environment was not significantly high, which may be due to the use of an underwater environment. Second, all participants were able to perform NF for a minimum of 20 seconds, indicating a high responder rate. Third, the iVR-NF enabled a brief learning-period, with three-fourths of participants successfully using the NF in the first block despite having no prior experience. However, there was little further improvement in the subsequent session. Fourth, FMT power measured during the NF task was significantly elevated compared to rest, and this increase was spatially specific to the frontal-midline. Finally, in our exploratory analyses we found that FMT power was even greater during the WM task and those participants that showed the greatest ability to engage FMT power during NF also showed the greatest increase in FMT power during the WM task. It is unclear whether these participants are more readily able to engage FMT power or whether there was genuine transfer learning between NF to WM.

4.1 Frontal-midline theta and cognitive control

FMT is generally considered a cognitive control signal (Cavanagh & Frank 2014) as it is shown to increase in a variety of task such as WM (Jensen and Tesche, 2002), attention (Fiebelkorn and Kastner, 2019), hierarchical rule use (Riddle et al., 2020b), and the manipulation of internally maintained information (Albouy et al., 2017; Riddle et al., 2020a). However, there is also evidence that FMT oscillations might reflect the cognitive effort exerted for a cognitive control task rather than reflect the degree of successfully engaged cognitive control (McFerren et al., 2021). Future research is required to adjudicate between whether the theta power generated in our NF paradigm reflects increased cognitive control or increased cognitive effort to maintain cognitive control. Future research could deplete cognitive resources, which would drive an increased amount of cognitive effort while maintaining a fixed level of cognitive control. For example, using the cognitive expenditure of effort for reward task, individual differences in willingness to exert cognitive effort can be systematically assessed (Lopez-Gamundi and Wardle, 2018).

Previous research also demonstrated that deficits in cognitive control that arise with various psychiatric illnesses may correspond to a reduction in FMT power as well (McLoughlin et al., 2022). In our study, we conducted exploratory analyses to investigate whether was any transfer in theta power between NF and a cognitive control task. We found some evidence that those that engaged more FMT during NF also showed greater theta power during WM. However, it is unclear whether these individuals have a stronger endogenous theta rhythm overall or whether the NF itself was responsible for increasing the theta power. Future studies should run a double-blinded placebo-controlled randomized clinical trial to investigate whether NF training is able to increase theta power and whether these effects transfer to additional cognitive domains. Critically, our study did not include a placebo condition with random neurofeedback as a control and so precludes our ability to draw these conclusions. Furthermore, it is unclear whether people with disease-related deficit in theta power will respond to our iVR-NF environment in the first place. However, we report a high response rate and fast learning rate, which suggests that perhaps people with cognitive control deficits might have a greater chance of responding than with less immersive approaches.

4.2 Acceptance and comfort

In line with the literature, the iVR did not evoke any negative reactions (Gerber et al., 2019; Saredakis et al., 2020) and was highly accepted, reflected in the high usability score. Furthermore, immersion was high, indicating that participants were able to forget about their surroundings and focus on the task. This suggests that the virtual environment was fascinating and did not evoke negative emotions. Overall, the high immersion, acceptance and comfort could be one reason why participants were able to perform the NF task with a high responder rate (Checa and Bustillo, 2020). This is further supported by the good balance between high-scored subjective performance and moderate difficulty rating of the NF task, which aligns with Power J. et al., where difficulty in gamified tasks was linked to increased self-efficacy, engagement and performance (Power et al., 2020).

4.3 Performance

All participants were able to perform the NF task successfully for 20 seconds. However, around one-fourth of participants were not able to successfully perform the task even after five blocks. Either these participants were able to perform the NF for brief periods but could not sustain the effect due to cognitive fatigue, or they simply were unable to figure out a successful strategy. We speculate that one successful strategy could entail performing cognitive work akin to that required for WM. Other NF tasks demonstrated a lower responder rate of around fifty percent, but there are others that have found comparable success around 80% as reported here (Su et al., 2021). In line with the literature that suggests iVR increases the learning rate for NF (Berger and Davelaar, 2018), our results showed that three-fourths of the participants were able to clean the ocean in the first block of the series without prior iVR experience. In addition, in this feasibility study, two modes of NF feedback were used (i.e., a fast change in the color of the ocean and a slower trash update mode), which is an innovation beyond traditional NF tasks. In our NF design, participants potentially realized faster if their strategy was working and thus were able to finetune their strategy. Furthermore, the ocean is a positive-valence natural scenery and, therefore, could be calming, which would perhaps enhance rapid learning (Nan et al., 2012). It should be noted that there was only a moderate increase in success rate with 71% and 70% in the first two blocks and 78% and 72% in the fourth and fifth blocks. Thus, while there was an increase over time this increase was moderate.

4.4 Power

The FMT power measured and processed in real-time during the NF task differed from the FMT power retrospectively analyzed post-hoc, indicating that the eye blinks, head-turning, and other artefacts may have inflated theta estimations during live processing of the NF task performance. This effect was only moderate to small and any systematically missed artifacts would likely drive a much larger difference between the processing pipelines. The analysis provided evidence that the FMT power of individual participants in the NF task increased numerically over time, indicating that the strategy could be finetuned and improved. Alternatively, some previous work suggests that FMT power tracks linearly with the amount of cognitive effort that is exerted (Castro-Meneses et al., 2020; McFerren et al., 2021). Under this interpretation, participants must exert greater levels of cognitive effort with each subsequent block. FMT power increases with time were markedly greater for the WM task, which suggests that cognitive resources were depleted over time, however, there was only a small increase in FMT power during the NF. Thus, future iterations of the NF might change the difficulty of cleaning the ocean over subsequent blocks to further drive an increase in FMT power.

4.5 Limitations

This study assessed healthy young participants, but it remains unclear if our findings would generalize to patients with psychiatric or neurological illnesses. A fundamental limitation of the present study was the lack of a control condition. Future studies could include a condition wherein the trash appears or disappears randomly and is not related to FMT power but is instead a recording from another participants or some other predetermined sequence of events. With placebo NF, we expect that participants would develop suboptimal strategies that do not increase genuine FMT power and thus would not show any transfer learning to a cognitive control task. Future studies should investigate the lasting impact of this training on FMT power to assess whether training paradigms with NF could be used in a therapeutic setting. For systematic results, future iVR-NF studies should follow the consensus on how to report and design NF (Ros et al., 2020). The window length used to detect state-level theta power was chosen based on piloting sessions conducted by the authors on themselves and requires validation through future studies. The selected time window of 4 seconds resulted in a more gradual and sensible change in the virtual scene; however, the exploration of additional time windows was outside the scope of this feasibility study. Similarly, the initial cognitive load titration and EEG artefact filtering methods require further validation. This study did not assess whether FMT during NF predicts subsequent WM performance or neural activity, this should be explored in future research. Additionally, the free exploration period could be further standardized to ensure that all participants are more equally accustomed to the virtual reality environment prior to the start of the initial experimental recordings. There is a possibility of non-linear changes in signal due to changes in impedance which could theoretically inflate the estimation of FMT power. Future studies could more rigorously monitor impedance and hardware level calibration to the reference electrode. Finally, there was a difference in signal between theta power as estimated real-time and the post-processed theta power. This could be due to more extensive artifact cleaning during computationally intensive preprocessing pipelines that are not accessible during real-time theta power estimation.

4.6 Conclusion

Our results indicated that iVR-NF was highly accepted and did not elicit discomfort. The NF was successfully utilized in the majority of participants in the first NF session. Furthermore, FMT iVR-NF is feasible and increases neural activity in a similar manner to WM tasks. Therefore, iVR-NF designed to enhance FMT power is feasible and future research should investigate potential transfer learning effects into cognitive domains, such as working memory or cognitive control. People suffering from neurological or psychiatric illness that impacts FMT oscillations might see benefits from techniques designed to increase FMT power although future research is required to translate the findings presented here into clinical application.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by IRB University of North Carolina - Chapel Hill. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SG: Conceptualization, Investigation, Writing – original draft, Writing – review and editing, Formal Analysis, Methodology, Software, Visualization. JR: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review and editing, Visualization. HL: Writing – original draft, Writing – review and editing, Investigation. MZ: Writing – original draft, Writing – review and editing, Conceptualization. FF: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review and editing, Funding acquisition, Project administration, Resources.

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Conflict of interest

FF is a full-time employee of the University of North Carolina - Chapel Hill. FF is the lead inventor of IP issued to UNC and licensed to Electromedical Products International (EPI). In the last twelve months, FF has received consulting honoraria from the following entities: EPI and Insel Spital. FF is a shareholder of EPI. In the last twelve months, FF has received royalties from Academic Press and the University of North Carolina at Chapel Hill.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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