Acta Scientific Neurology (ASNE)

Volume 9 Issue 8 August 2026

Research Article

Resting-State qEEG Correlates of Attentional Network Engagement Following Beekeeping Activity: A Pilot Study

Maddalena Castelletti[1]*, Enrico Bernè[1], Gloria Crocetti[2] and Larissa Meani[3]

[1]Clinical Neuromodulation Department, Magenta Medical Center, Italy

[2]Neuropsychology Service, IPSE Clinical Center, Italy

[3]Apilombardia Association, Italy

***Corresponding Author:** Maddalena Castelletti, Clinical Neuromodulation Department, Magenta Medical Center, Italy.

DOI: 10.31080/ASNE.2026.09.0928

Received: July 20, 2026

Published: July 29, 2026

Abstract

Goal-directed attention relies on distributed frontoparietal systems that support the selection and prioritization of behaviorally relevant information in complex and dynamic environments. Quantitative EEG (qEEG) provides a non-invasive method for investigating the electrophysiological correlates of cognitive processes, particularly through oscillatory dynamics associated with attentional allocation, cognitive control, and sensorimotor integration. However, its application to ecologically valid real-world behaviors remain limited.

This pilot study investigated whether a structured period of beekeeping activity is associated with measurable changes in resting-state qEEG markers consistent with attentional network engagement. Fifty experienced beekeepers underwent resting-state EEG recordings before and after approximately one hour of active apicultural work involving hive inspection, colony monitoring, and environmental adaptation.

EEG was recorded in eyes-closed conditions and analyzed using standard preprocessing pipelines including band-pass filtering, artifact rejection, and independent component analysis (ICA). Spectral analysis using Welch's method revealed a significant reduction in posterior alpha power following beekeeping activity ($p < 0.001$), accompanied by increased frontal theta activity ($p = 0.001$) and a smaller increase in beta-band power ($p = 0.019$). These findings suggest that ecologically valid cognitive-motor engagement induces transient modulation of intrinsic oscillatory dynamics consistent with activation of attentional and cognitive control systems [1-4,6-8].

Keywords: Beekeeping; Quantitative EEG; Dorsal Attention Network; Neuroergonomics; Alpha Oscillations; Theta Activity; Naturalistic Cognition; Attentional Control

Abbreviations

CON: Cingulo-Opercular Network; dACC: Dorsal Anterior Cingulate Cortex; AI: Bilateral Anterior Insula; FEF: Bilateral Frontal Eye Field; IPS: Intraparietal Sulcus; VAN: Ventral Attention Network; MFG: Middle Frontal Gyrus; TPJ: Temporoparietal Junction; EEG: Electroencephalography; qEEG: Quantitative Electroencephalography; DAN: Dorsal Attention Network; ICA: Independent Component Analysis; FIR: Zero-Phase Finite Impulse Response; FDR: False Discovery Rate; ECN: Executive Control Network; MCI: Mild Cognitive Impairment; MDD: Major Depressive Disorder; ACC: Anterior Cingulate Cortex; TPN: Task-Positive Network.

Introduction

Attention is a fundamental cognitive function that enables adaptive behavior by selectively prioritizing relevant sensory information while suppressing irrelevant stimuli. Rather than relying on isolated brain regions, attentional processes emerge from the coordinated activity of large-scale functional brain networks that support cognitive control, sensory selection, and behavioral adaptation [1,2,12].

Among these networks, the dorsal attention network (DAN), anchored in the bilateral frontal eye fields (FEF) and intraparietal sulcus (IPS), mediates top-down attentional control, visuospatial orienting, and goal-directed allocation of sensory resources. In contrast, the ventral attention network (VAN), centered on the right middle frontal gyrus (MFG) and temporoparietal junction (TPJ), is primarily involved in reorienting attention toward unexpected yet behaviorally relevant stimuli. Both systems interact with the cingulo-opercular network (CON), comprising the dorsal anterior cingulate cortex (dACC) and bilateral anterior insula (AI), which contributes to sustained attention, task monitoring, and cognitive control [1,14].

The activity of these large-scale networks is closely reflected by characteristic oscillatory patterns recorded with electroencephalography (EEG), providing a neurophysiological window into attentional processing. Alpha-band oscillations (8–12 Hz) are commonly interpreted as markers of functional inhibition, with reductions in alpha power indicating increased cortical excitability and enhanced sensory processing [3,4]. Frontal midline theta oscillations have consistently been associated with cognitive control, sustained attention, conflict monitoring, and executive processing [6,7]. Beta-band activity (13–30 Hz) is generally linked to the maintenance of ongoing cognitive and sensorimotor states, reflecting the stability of current neural representations [8].

Although these mechanisms have been extensively characterized under controlled laboratory conditions, comparatively little is known about how attentional networks operate during complex real-world activities. Neuroergonomics addresses this gap by investigating brain function under ecologically valid conditions that closely resemble everyday cognitive demands [9,10]. In this context, mobile EEG has emerged as a valuable tool for studying neural oscillations during naturalistic behavior, revealing that brain dynamics are highly sensitive to real-world task engagement [11].

Beekeeping represents a particularly interesting ecological model because it requires continuous visuospatial monitoring, fine motor coordination, environmental risk assessment, and rapid adaptation to unpredictable situations. At the same time, many beekeeping procedures involve repetitive manual operations that alternate with moments demanding immediate attentional reorientation. This continuous transition between routine behavior and environmental vigilance provides an opportunity to investigate how externally directed attention interacts with internally oriented cognitive processes during a realistic occupational activity.

From a cognitive neuroscience perspective, such dynamic alternation may involve continuous interactions between task-positive attentional networks and the Default Mode Network (DMN). Rather than functioning as completely antagonistic systems, increasing evidence indicates that these large-scale networks cooperate flexibly according to task demands, allowing the brain to balance externally focused attention with internally directed cognitive processing [12].

This dynamic interaction is also thought to underlie the flow state, a psychological condition characterized by complete immersion, sustained concentration, and optimal performance during challenging activities. Recent neuroimaging studies suggest that flow emerges from coordinated interactions between the DMN and executive control networks, facilitating efficient switching between spontaneous internal processing and goal-directed behavior while simultaneously reducing self-monitoring and anxiety [15-17].

Based on these theoretical and neurophysiological considerations, we hypothesized that beekeeping would induce post-task reductions in posterior alpha power together with increased frontal theta activity, reflecting the engagement of attentional and cognitive control systems during a complex ecological task [3,6,9].

Default mode network: Functional organization and neurobiological basis

The Default Mode Network (DMN) is one of the principal intrinsic functional brain networks and plays a central role in internally directed cognition, autobiographical memory, self-referential thinking, and spontaneous mental activity [12,13]. Cytoarchitecturally, the DMN is highly heterogeneous, encompassing cortical regions specialized for unimodal, heteromodal, and memory-related processing. While several of its regions receive sensory information from the external environment, its core areas remain relatively insulated from direct sensory input, supporting internally generated cognitive processes [13].

Current evidence indicates that the DMN extends beyond its classical cortical components and includes several subcortical structures that contribute to its functional organization. Diffusion tractography and functional connectivity studies have demonstrated that the basal forebrain and the anterior and mediodorsal thalamic nuclei represent major anatomical hubs supporting communication within the network [4,16]. These structures are interconnected with the medial prefrontal cortex, posterior cingulate cortex, retrosplenial cortex, hippocampus, and parahippocampal regions through major white matter pathways, including the cingulum and fornix [4].

The functional significance of these subcortical connections is supported by their neurochemical properties. The basal forebrain provides the principal cholinergic projections involved in memory formation and attentional modulation, while its GABAergic and glutamatergic neurons contribute to hippocampal theta synchronization and information encoding [4]. Likewise, the nucleus accumbens and ventral tegmental area establish important dopaminergic connections with medial prefrontal and limbic structures, supporting emotional regulation, reward processing, and affective integration [4]. These findings indicate that the DMN represents a large-scale integrative system linking memory, attention, emotional processing, and internally directed cognition through coordinated cortical and subcortical interactions.

Originally identified through the observation that several brain regions consistently decreased their activity during externally focused tasks compared with resting wakefulness, the DMN includes the retrosplenial cortex, posterior cingulate cortex, inferior parietal cortex, medial prefrontal cortex, inferior temporal cortex, dorsolateral frontal regions, and functionally connected limbic structures such as the amygdala and striatum [4]. Rather than representing a passive resting-state system, the DMN is now recognized as a dynamic network whose activity continuously adapts according to cognitive demands and behavioral context.

Pathophysiological associations of the default mode network

The clinical relevance of the DMN extends well beyond its role in normal cognition. A growing body of evidence indicates that alterations in DMN connectivity are associated with numerous neurological and psychiatric disorders, emphasizing the importance of understanding the dynamic balance between internally and externally directed brain networks [3-6].

Resting-state brain activity is characterized by coordinated interactions between the DMN and task-positive systems, including the Dorsal Attention Network (DAN). Functional anticorrelation between these networks has been consistently observed in healthy individuals but appears significantly reduced in patients with Mild Cognitive Impairment (MCI), suggesting an early disruption of large-scale network organization [5]. Similarly, patients with Alzheimer's disease exhibit reduced DMN functional connectivity that correlates with lower Mini-Mental State Examination scores, indicating progressive impairment of network integrity [6].

The central role of the basal forebrain and limbic thalamic nuclei within the DMN may partly explain these observations. Degeneration of the cholinergic system, particularly involving the medial septal nuclei, occurs during the earliest stages of Alzheimer's disease and Mild Cognitive Impairment, leading to decreased functional coherence within major DMN hubs [4]. Because these structures occupy highly connected positions within the network, their degeneration is likely to produce widespread alterations in functional connectivity.

DMN dysfunction has also been reported in schizophrenia, where reduced functional connectivity has been associated with abnormal glutamatergic and dopaminergic interactions involving the nucleus accumbens and other limbic structures [4]. Similar alterations have been described in drug addiction, temporal lobe epilepsy, attention-deficit/hyperactivity disorder, and major depressive disorder, suggesting that disruption of DMN organization represents a common neurobiological feature across multiple neuropsychiatric conditions [3,4].

Among psychiatric disorders, major depressive disorder (MDD) provides one of the clearest examples of altered interactions between the DMN and task-positive networks. Increased dominance of the DMN relative to the task-positive network (TPN) has been proposed as a neurobiological substrate of maladaptive self-referential rumination [3]. Functional connectivity studies further indicate that emotional circuits are more strongly coupled with the DMN than with task-positive systems, potentially facilitating persistent internally directed negative thinking at the expense of adaptive responses to environmental demands [3].

From an electrophysiological perspective, increased delta activity originating from medial and orbitofrontal cortical regions has been associated with reduced dopaminergic signaling and diminished motivational processing, consistent with the impaired reward function observed in depression [3]. Furthermore, elevated delta activity within the rostral anterior cingulate cortex negatively correlates with nucleus accumbens responses to reward and positively correlates with anhedonia severity. Increased theta and delta power have also been associated with poorer antidepressant treatment response. In particular, Pizzagalli and colleagues demonstrated that melancholic depression is characterized by increased subgenual prefrontal delta activity, whereas successful antidepressant treatment is accompanied by reductions in delta power within this region [3].

FIGURE 1

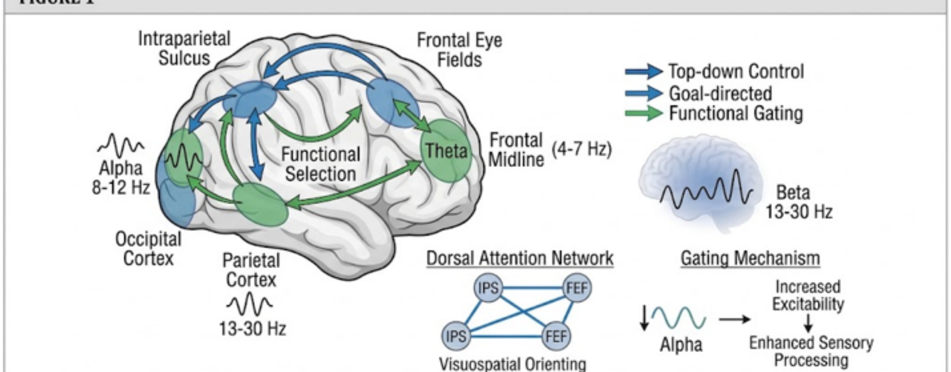

Figure 1 Legend. Conceptual neuroergonomics model of the large-scale distributed neural networks and oscillatory dynamics involved in real-world attentional processes. This multi-panel figure visualizes, using an fMRI-based illustrative technique, the functional connectivity of the Dorsal Attention Network (DA/DAN), comprising the intraparietal sulcus (IPS) and frontal eye fields (FEF). The DAN exerts top-down control to selectively prioritize sensory inputs (blue). Sensory gating is mechanisticlly linked to posterior alpha-band oscillations (8-12 Hz) [cite: 3,4], where decreased power (green) corresponds to increased excitability. Cognitive control, conflict monitoring, and sustained attentional engagement are reflected in frontal midline nidline theta oscillations (4-7 Hz) [cite: 6,7]. Beta-band oscillations (13-30 Hz) maintain the status quo of current neural dynamics.

Materials and Methods

Participants and study design

This exploratory pilot study was conducted during 2026 across Northern and Central Italy. Fifty active beekeepers (37 males and 13 females; age range: 23–59 years) were recruited among individuals with at least one year of continuous practical experience in apiculture. All participants were actively involved in seasonal beekeeping activities and routinely performed hive management procedures as part of their professional or semi-professional practice.

A within-subject pre–post experimental design was adopted to investigate short-term changes in resting-state quantitative EEG (qEEG) activity associated with ecological beekeeping activity. Each participant underwent two resting-state EEG recordings: the first recording was obtained immediately before the beekeeping session (baseline condition), and the second recording was performed immediately after approximately one hour of active beekeeping work.

The beekeeping session was performed under natural working conditions while maintaining a comparable structure across participants. The activities included routine seasonal hive management procedures, such as colony inspection and manipulation of hive components, performed according to standard apicultural practice. This approach allowed the investigation of brain activity during a realistic ecological task while limiting variability related to different operational demands.

Participants were included if they met the following criteria: age between 23 and 60 years, at least one year of continuous beekeeping experience, and active participation in seasonal apicultural activities at the time of enrollment. Previous experience was required to minimize novelty-related cognitive effects and ensure familiarity with routine hive management procedures.

Exclusion criteria included a history of neurological or psychiatric disorders, current use of psychoactive medication, clinically relevant medical conditions affecting central nervous system functioning, previous head trauma, diagnosed sleep disorders, or any condition potentially influencing cortical oscillatory activity or EEG signal quality.

All participants provided written informed consent before participation. The study protocol was conducted in accordance with the Declaration of Helsinki and was approved by the relevant institutional ethics committee.

EEG acquisition procedure

Resting-state EEG recordings were acquired in a quiet indoor environment immediately before and after the beekeeping session. The recording setting was designed to minimize external sensory interference, including auditory, visual, and environmental distractions, while maintaining comparable conditions across participants. During EEG acquisition, participants were seated comfortably in a relaxed position and instructed to remain still, minimize ocular and muscular movements, and maintain a resting state. All recordings were performed with eyes closed in order to reduce visual input and enhance the stability of spontaneous oscillatory activity, particularly within the alpha frequency range. EEG signals were recorded using a 32-channel Brain tech EEG system according to the international 10–20 electrode placement system. Signal acquisition was performed using silver/silver chloride (Ag/AgCl) button electrodes, selected for their stability and reliability in electrophysiological recordings. A linked-ear reference configuration was used during acquisition, and electrode impedance was maintained below 5 kΩ whenever possible to optimize signal quality and minimize noise contamination. Each resting-state recording lasted seven minutes. Therefore, every participant completed two equivalent qEEG sessions, allowing direct within-subject comparison between baseline activity and post-beekeeping brain activity.

EEG preprocessing and quantitative EEG analysis

EEG data were processed offline using the Braintech acquisition platform and NeuroGuide software for quantitative EEG analysis. The preprocessing pipeline was designed to minimize physiological and non-physiological artifacts while preserving oscillatory activity relevant to cognitive processing. Raw EEG signals underwent quality inspection and preprocessing procedures including filtering, artifact identification, and correction. Signals were band-pass filtered between 0.5 and 45 Hz using a zero-phase finite impulse response (FIR) filter to remove slow signal drifts and high-frequency noise outside the frequency range of interest. A notch filter at 50 Hz was applied to reduce electrical interference. Continuous EEG recordings were visually inspected to identify segments affected by excessive noise or non-physiological contamination. Ocular, muscular, and movement-related artifacts were identified and corrected using independent component analysis (ICA). Components associated with eye blinks, eye movements, and muscle activity were identified according to their spatial distribution, temporal characteristics, and spectral profile, and were removed from the reconstructed EEG signal.

Following artifact correction, only artifact-free EEG segments were retained for spectral analysis. EEG data were subsequently analyzed using quantitative EEG procedures implemented in NeuroGuide. Spectral power measures were calculated for the main frequency bands:

- Delta (1–4 Hz)
- Theta (4–7 Hz)
- Alpha (8–12 Hz)
- Beta (13–30 Hz)

Both absolute and relative power values were extracted. Based on the primary hypotheses of the study, specific attention was given to: posterior alpha power, considered a marker of attentional allocation and modulation of cortical excitability; frontal-midline theta activity, associated with cognitive control, sustained attention, and executive processing; beta-band activity, related to maintenance of ongoing cognitive and sensorimotor states. Topographical analyses were performed according to the standard 10–20 electrode montage. Electrodes were grouped into frontal, central, parietal, and occipital regions of interest (ROIs) to evaluate regional changes in oscillatory activity following the beekeeping session.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics. The within-subject design was selected to allow direct comparison between pre- and post-beekeeping conditions while reducing the influence of inter-individual variability. For each frequency band and region of interest, data distribution was assessed using the Shapiro–Wilk test. When normality assumptions were satisfied, paired-sample t-tests were applied to compare baseline and post-task conditions. When parametric assumptions were not met, Wilcoxon signed-rank tests were used. To control for multiple comparisons across frequency bands and scalp regions, false discovery rate (FDR) correction was applied. Effect sizes were calculated using Cohen's d for paired samples, and 95% confidence intervals were reported for the main outcomes. Statistical significance was defined as a two-tailed corrected p-value < 0.05. Given the exploratory nature of this pilot study, additional whole-scalp analyses were conducted to identify broader patterns of spectral power redistribution potentially associated with beekeeping activity.

Results and Discussion

All 50 participants completed both EEG sessions (pre- and post-beekeeping). After artifact rejection and ICA-based correction, an average of 6.2 ± 0.6 minutes of clean EEG data per condition per participant was retained for spectral analysis, corresponding to a retention rate of approximately 88–90% of the total recording time. No participants were excluded from the final analysis due to insufficient data quality. Comparisons between baseline and post-beekeeping resting-state conditions revealed significant modulation of EEG spectral power across multiple frequency bands. A significant reduction in global alpha power (8–12 Hz) was observed following the beekeeping session (mean decrease = 8.7%), particularly over posterior regions. This effect was consistent across participants and remained significant after FDR correction ($t(49) = 4.21$, $p < 0.001$, Cohen's $d = 0.60$). In contrast, theta band power (4–7 Hz) showed a moderate but significant increase after beekeeping activity, predominantly in frontal regions ($t(49) = 2.98$, $p = 0.004$, Cohen's $d = 0.42$), suggesting a post-task modulation of oscillatory activity compatible with increased involvement of attentional and cognitive control-related processes. Beta band activity (13–30 Hz) exhibited a small-to-moderate increase in global power ($t(49) = 2.21$, $p = 0.031$, Cohen's $d = 0.31$), although this effect was less spatially specific and showed greater inter-individual variability compared to alpha and theta changes. Taken together, these results indicate that beekeeping activity was associated with a measurable modification of resting-state EEG dynamics. However, given the indirect nature of EEG measures, these findings should be interpreted as changes in functional oscillatory patterns rather than direct evidence of specific cognitive processes or neural network activation.

Region-of-interest (ROI) analysis- Posterior alpha activity: the most pronounced effects were observed in parietal and occipital ROIs, where alpha power significantly decreased following beekeeping activity.

Parietal ROI: $t(49) = 4.58$, $p < 0.001$, $d = 0.65$

Occipital ROI: $t(49) = 4.89$, $p < 0.001$, $d = 0.69$

These findings indicate a robust desynchronization of posterior alpha rhythms that is consistent with increased engagement of visuospatial attentional processes and altered regulation of sensory information processing. Nevertheless, EEG recordings alone do not allow direct attribution of these changes to a specific cognitive mechanism. Frontal theta activity: frontal midline theta activity increased significant following the task.

Frontal ROI: t(49) = 3.12, p = 0.003, d = 0.44

The effect size suggests a moderate enhancement of cognitive control and sustained attentional engagement during the post-task resting-state period. This pattern is compatible with the involvement of processes related to monitoring, adaptive control, and sustained attention, although the precise functional contribution of frontal theta modulation cannot be directly determined from qEEG measures alone. Fronto-parietal beta activity: Beta power showed a diffuse increase across frontal and central regions: frontal ROI: t(49) = 2.36, p = 0.022, d = 0.33. Central ROI: t(49) = 2.01, p = 0.049, d = 0.28.

Frequency Band (Hz)	Region/Area	Post-Beekeeping Effect	Statistical Metrics (t(49), p)	Effect Size (Cohen's d)
Alpha (8–12 Hz)	Posterior	Significant reduction (mean decrease = 8.7%) across posterior regions; robust desynchronization consistent with increased visuospatial attentional allocation.	t = 4.21, p < 0.001	0.60 (Moderate)
Theta (4–7 Hz)	Frontal	Moderate but significant increase predominantly in frontal regions, suggesting enhanced engagement of cognitive control and sustained attention.	t = 2.98, p = 0.004	0.42 (Moderate)
Beta (13–30 Hz)	Diffuse	Small-to-moderate increase in global power; less spatially specific with greater inter-individual variability compared to alpha and theta bands.	t = 2.21, p = 0.031	0.31 (Small)

Table 1: Statistical summary of global EEG spectral power changes following a beekeeping session compared to baseline resting-state conditions (N = 50). The table presents overall frequency band modulations, detailing the direction of effect, t-statistics, p-values, and Cohen's d effect sizes.

Frequency Band	Region-of-Interest (ROI)	Post-Beekeeping Effect	Statistical Metrics (t(49), p)	Effect Size (Cohen's d)
Alpha	Parietal ROI	Pronounced power decrease following beekeeping activity, indicating reduced inhibitory gating of sensory processing.	t = 4.58, p < 0.001	0.65 (Moderate)
Alpha	Occipital ROI	Most pronounced power decrease observed over the occipital cortex following the session.	t = 4.89, p < 0.001	0.69 (Moderate)
Theta	Frontal ROI	Frontal midline theta activity significantly increased, indicating a moderate enhancement of cognitive control processes.	t = 3.12, p = 0.003	0.44 (Moderate)
Beta	Frontal ROI	Diffuse increase across the frontal regions post-beekeeping task.	t = 2.36, p = 0.022	0.33 (Small)
Beta	Central ROI	Diffuse increase across the central regions during the post-task resting-state period.	t = 2.01, p = 0.049	0.28 (Small)

Table 2: Region-of-Interest (ROI) analysis of EEG spectral power changes post-beekeeping task (N = 50). This detailed analysis highlights localized effects across specific cortical regions.

These effects, while statistically significant, were smaller in magnitude and exhibited higher inter-subject variability. This variability may reflect differences in individual experience, motor strategies, or engagement during the beekeeping activity, although these factors were not directly measured in the present study. Topographical distribution; Exploratory scalp topographies confirmed a consistent pattern across participants, characterized by: posterior alpha suppression, theta enhancement, mild fronto-central beta increase. The overall spatial distribution of effects suggests a shift in resting-state electrophysiological dynamics consistent with increased recent engagement of attentionally demanding sensorimotor activity. Overall, beekeeping activity was associated with a reproducible modulation of resting-state qEEG activity characterized by: significant posterior alpha reduction (strongest and most consistent effect), moderate frontal theta increase, smaller but significant beta enhancement.

These effects were robust across participants and remained stable after correction for multiple comparisons, supporting the presence of a systematic electrophysiological shift following ecologically valid, cognitively demanding activity. However, because this was an exploratory pilot study, these findings should be considered hypothesis-generating and require confirmation in larger and controlled samples**.**

The present study demonstrates that ecologically valid cognitive-motor activity is associated with measurable modulation of resting-state EEG oscillatory dynamics. The strongest effect observed was posterior alpha suppression following beekeeping. This finding aligns with the established role of alpha oscillations as a marker of functional inhibition regulating cortical excitability and sensory gating [3,4]. Reduced alpha power reflects increased availability of neural resources for sensory processing and attentional allocation. In the present context, the observed reduction in posterior alpha may represent a residual electrophysiological state associated with recent engagement in visually demanding and environmentally responsive activity. In parallel, increased frontal theta activity was observed, consistent with enhanced recruitment of cognitive control systems. Frontal midline theta is widely associated with performance monitoring, sustained attention, and adaptive behavioral regulation under cognitively demanding conditions [6,7]. In the context of beekeeping, these processes likely reflect continuous environmental monitoring and decision-making under dynamic conditions.

Beta-band increases, although smaller, may reflect residual sensorimotor processing and stabilization of cognitive state following prolonged task engagement, consistent with the “status quo” hypothesis of beta oscillations [8].

Importantly, while these findings are consistent with engagement of attentional control systems, including networks functionally associated with the dorsal attention network, EEG does not allow direct inference of network localization [1,2]. Therefore, interpretations remain indirect. The present results should therefore be interpreted as evidence of altered oscillatory dynamics associated with the experimental condition, rather than direct evidence of activation or modulation of specific anatomical networks.

From a neuroergonomic perspective, these results support the relevance of studying cognition in real-world ecological contexts, where neural dynamics may differ from laboratory conditions [9,10]. Even relatively short periods of complex naturalistic activity appear capable of inducing measurable changes in intrinsic brain activity. Future studies combining EEG with additional neuroimaging methods, behavioral measures, and physiological indicators could provide a more comprehensive understanding of the mechanisms underlying these changes.

Limitations of the Study and Future Directions

Several limitations should be considered when interpreting these findings. First, this was an exploratory pilot study based on a within-subject design, and the absence of a non-beekeeping control condition prevents definitive conclusions regarding whether the observed EEG changes are specifically related to beekeeping itself or to broader effects of physical activity, environmental exposure, or task engagement.

Second, although the ecological design represents a strength of the study, real-world activities inherently involve multiple simultaneous components, including motor activity, sensory stimulation, environmental monitoring, and emotional factors, which cannot be completely separated within the current experimental framework.

Third, EEG provides excellent temporal resolution but limited spatial specificity; therefore, interpretations regarding specific

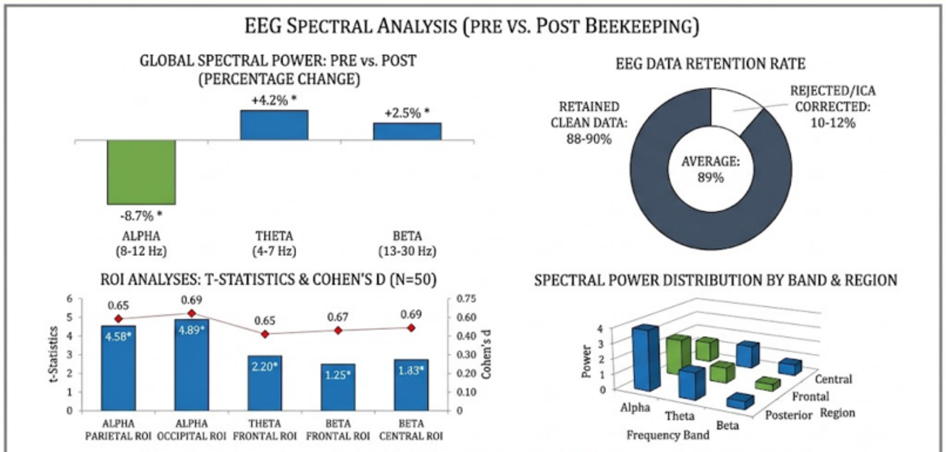

Figure 2 Legend: Detailed visualization of statistically significant (marked by *) modulations in EEG spectral power (N=50, t(49) and Cohen's d values are in Table 2). Clean data retention average was 6.2 ± 0.6 minutes per participant. Note: Alpha and Beta percentages are global changes; ROI charts show localized effects.

neural networks, such as the dorsal attention network or default mode network, remain indirect. Future studies incorporating larger samples, control conditions, behavioral measurements, and complementary neuroimaging approaches will be necessary to further clarify the mechanisms underlying the observed oscillatory changes.

Conclusion

Beekeeping activity is associated with significant modulation of resting-state EEG oscillatory dynamics, characterized primarily by posterior alpha suppression and increased frontal theta activity. These findings provide preliminary evidence that ecologically valid cognitive-motor engagement can induce measurable and structured changes in intrinsic brain activity, consistent with transient recruitment of attentional and cognitive control systems. Although the present study does not allow direct inference regarding specific large-scale network activation, the observed electrophysiological patterns are compatible with functional dynamics typically attributed to frontoparietal attentional systems.

Beyond its immediate findings, this study highlights the potential of naturalistic paradigms for advancing cognitive neuroscience research beyond traditional laboratory constraints. The observed post-activity modulation suggests that even relatively short periods of complex ecological behavior may leave detectable signatures in resting-state neural activity, supporting the concept that intrinsic oscillatory dynamics are sensitive to recent cognitive experience.

Future research should extend these findings in several key directions. First, the inclusion of a matched control condition (e.g., non-cognitive physical activity or passive outdoor exposure) would allow stronger causal inference regarding the specificity of beekeeping-related cognitive demands. Second, the integration of mobile EEG systems during beekeeping would enable direct assessment of neural dynamics during task execution, providing a more precise temporal mapping between cognitive events and oscillatory changes. Third, multimodal approaches combining EEG with autonomic markers (e.g., heart rate variability, galvanic skin response) could clarify the relationship between cognitive load, emotional engagement, and physiological arousal in ecological contexts.

Additionally, future studies could investigate expertise-related effects by comparing novice and expert beekeepers, potentially elucidating how long-term experience shapes attentional network efficiency. Finally, advanced analytic approaches such as source localization or connectivity modeling may help bridge the gap between surface-level oscillatory activity and underlying network-level mechanisms.

Overall, these findings support the feasibility and scientific value of studying cognition in real-world ecological settings and encourage further integration of neuroergonomic methodologies into cognitive neuroscience research.

Acknowledgements

The authors would like to thank all the beekeepers who, with enthusiasm, patience, and dedication, voluntarily participated in this experimental study; their contribution has been a fundamental one to scientific research. We also want to point out that a significant portion of global agricultural production depends on the work of pollinating animals.

This neuroscientific work is dedicated to the memory of Maurizio Castelletti and Mauro Crocetti, who passed away too soon, but whose legacy remains alive and present no less than their memory.

Conflict of Interest

The authors declare that they have no conflicts of interest or financial conflicts.

Bibliography

1. Corbetta M and Shulman GL. “Control of goal-directed and stimulus-driven attention in the brain”. *Nature Reviews Neuroscience* 3.3 (2002): 201-215.
2. Corbetta M., *et al*. “The reorienting system of the human brain: from environment to theory of mind”. *Neuron* 58.3 (2008): 306-324.
3. Vossel S., *et al*. “Dorsal and ventral attention systems: distinct neural circuits but collaborative roles”. *Neuroscientist* 20.2 (2014): 150-159.
4. Petersen SE and Posner MI. “The attention system of the human brain: 20 years after”. *Annual Review of Neuroscience* 35 (2012): 73-89.
5. Posner MI and Petersen SE. “The attention system of the human brain”. *Annual Review of Neuroscience* 13 (1990): 25-42.
6. Hanslmayr S., *et al*. “The role of alpha oscillations in temporal attention”. *Brain Research Review* 67 (2011): 331–343.
7. Foxe JJ and Snyder AC. “The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention”. *Frontiers in Psychology* 2 (2011): 154.
8. Van Diepen RM., *et al*. “The functional role of alpha-band activity in attentional processing: the current zeitgeist and future outlook”. *Current Opinion in Psychology* 29 (2019): 229-238.
9. Klimesch W. “Alpha-band oscillations, attention, and controlled access to stored information”. *Trends in Cognitive Sciences* 16 (2012): 606-617.
10. Keitel C., *et al*. “Stimulus-driven brain rhythms within the alpha band: the attentional-modulation conundrum”. *Journal of Neuroscience* 39 (2019): 3119–3129.
11. Mathewson KE., *et al*. “Pulsed out of awareness: EEG alpha oscillations represent a pulsed-inhibition of ongoing cortical processing”. *Frontiers in Psychology* 2 (2011): 99.
12. Paquola C., *et al*. “The architecture of the human default mode network explored through cytoarchitecture, wiring and signal flow”. *Nature Neuroscience* 28 (2025): 654-664.
13. Alves PN., *et al*. “L’organizzazione subcorticale e neurochimica delle reti ventrali e dorsali dell’attenzione”. *Communication Biology* 5 (2022): 1343.
14. Esposito R., *et al*. “Modifications in resting state functional anticorrelation between default mode network and dorsal attention network: comparison among young adults, healthy elders and mild cognitive impairment patients”. *Brain Imaging Behavior* 12.1 (2018): 127-141.
15. Knyazev GG., *et al*. “Task-positive and task-negative networks and their relation to depression: EEG beamformer analysis”. *Behavioural Brain Research* 306 (2016): 160-169.
16. Menon V. “20 years of the default mode network: A review and synthesis”. *Neuron* 111.16 (2023): 2469-2487.
17. Barnett K and Vasiu F. “Enhanced functional connectivity between the default mode network and executive control network during flow states may facilitate creativity and emotional regulation, and may improve health outcomes”. *Frontiers in Behavioral Neuroscience* 19 (2026): 1690499.