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Immersive Cave Environments in VR: A Tool for Exploring Altered States of Consciousness and Creativity in Archaeology

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Abstract: This study explores the use of immersive Virtual Reality (VR) cave environments to investigate hypotheses concerning altered states of consciousness, creativity, and flexible thinking in archaeological contexts. Building on the premise that ancient humans used caves as sites for rituals involving altered consciousness, we recreated a virtual Cave environment to simulate these experiences and examine their impact on participants' cognitive processes. Participants engaged in pareidolic tasks within both a virtual cave and a virtual open-space environment, allowing for comparative analysis of semantic network organization and subjective experiences. Our findings show that the Cave environment elicited higher emotional arousal and spiritual engagement, as well as an improvement in the aspects of creativity and flexible thinking. These results suggest that VR can serve as a powerful tool in archaeology for reconstructing early humans' experiences and to investigate their psychological and cognitive states, thus providing new insights into their use of caves for mind-altering or ritualistic purposes. This interdisciplinary approach contributes to both cognitive archaeology and the development of immersive VR technologies in scientific research.

Keywords: altered states of consciousness; creativity; flexibility; virtual reality; semantic network analysis; pareidolia; archaeology; cognitive archaeology

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1. Introduction

The role of caves in the cognitive and cultural development of early human societies has long intrigued archaeologists, anthropologists, and cognitive scientists [1]. These isolated natural environments, often navigable only with artificial light, have been proposed as settings where ancient humans engaged in rituals facilitating altered states of consciousness (ASCs). Such states, potentially induced by sensory deprivation or psychoactive substances [2], may have enabled geometric and figurative hallucinations, possibly enhancing symbolic thinking and contributing to the vivid realism and complexity of Paleolithic cave art [3,4].

Darkness is one of the unique sensory conditions of caves. The absence of natural light in these environments has been integral to early human spirituality and cognition, shaping rituals, beliefs, and experiences from prehistoric to modern times due to its symbolic ties to mystery, the supernatural, and death [5]. Additionally, caves possess other unique sensory characteristics, such as reverberating acoustics, known to enhance feelings of mystery, romance, sadness, and fear [6], and flickering torchlight impacting perceptions of time, mood, alertness, and divergent thinking [7]. Together, these sensory attributes could have played a crucial role in altering perception, cognition, and emotional states during rituals.

From a physiological perspective, it has long been known that prolonged darkness, isolation, and sensory deprivation are known to affect circadian rhythms and perceptual states [8]. In the absence of natural light and time cues, individuals experience desynchronization of biological rhythms, distortions in time perception, and alterations in sleep-wake cycles. Additionally, the

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confined and low-oxygen atmosphere in caves has been linked to cardiovascular and metabolic responses, which, when combined with isolation, can heighten stress responses and contribute to perceptual and cognitive shifts, facilitating ASCs during prolonged stays [9]. Those hypoxic conditions in deeper cave environments have been hypothesized to contribute to altered consciousness by inducing hallucinations and heightened emotional arousal [10].

Cognitive archaeologists propose that ASCs experienced in cave environments may have thus enabled early humans to perceive and connect with spiritual or transcendent realms, thereby inspiring the creation of figurative art. This connection could manifest through entoptic phenomena—geometric patterns originating within the visual system during ASCs—as proposed in [11], or through broader consciousness alterations facilitating multidimensional perception, as proposed in [12]. Such altered perceptions may transcend purely neurological explanations, engaging deeper experiential and symbolic layers that have influenced the form and meaning of the art. Specifically, the rhythmic sounds and flickering torchlight, combined with the disorienting nature of caves and psychophysiological restrictions, could have induced trance-like states—a hypothesis resonating with recent findings in VR studies simulating cave environments [13].

Hodgson [14] discusses the psychological and perceptual effects of caves on Upper Paleolithic humans, highlighting them as environments that stimulate intense visual and emotional experiences. He suggests that the darkness, complex rock formations, and unpredictable lighting in caves likely enhanced visual hypothesis-testing, leading early humans to perceive suggestive shapes as animals or other forms. These perceptions, often accompanied by heightened emotions due to the environment's inherent danger, may have appeared magical or otherworldly. The visual system's tendency to fill in gaps under low-light conditions created a rich setting for imaginative interpretations, contributing to the creation and cultural significance of cave art. This interplay of perception, environment, and emotional arousal positioned caves as potent spaces for symbolic and ritualistic activities.

Despite these compelling hypotheses, few empirical studies have tested the relationship between cave environments and the induction of ASCs using controlled experimental designs. The advent of virtual reality (VR) technology offers an innovative approach to addressing this research gap. VR provides an immersive and repeatable platform to simulate the sensory-rich environments of caves, allowing researchers to explore how such conditions might have impacted the cognition and consciousness of early humans. Previous studies have successfully used VR to simulate environmental impacts on cognition, including the emotional benefits of nature in green environments [15,16]. In recent research, the potential of VR to evoke ASC-related changes in cognitive dynamics has been demonstrated; for instance, simulated hallucinatory experiences have been shown to enhance cognitive flexibility and inhibit automatic responses in modern participants [17]. These findings support the use of VR as a valuable tool for examining how sensory alterations in prehistoric cave environments could have shaped human cognition and creativity, fostering states conducive to symbolic and artistic expression.

Recently, Wisher and colleagues [18] have explored with VR how cave settings may have triggered pareidolia—a perceptual phenomenon where people perceive meaningful forms in random patterns—which potentially contributed to early humans' creation of animal depictions on cave walls. In their study, participants in VR were shown 3D models of cave walls with the art removed and were asked to identify shapes; eye-tracking was used to determine visual focus. The findings suggest that modern participants' pareidolic responses corresponded with the locations and forms of animals depicted by Paleolithic artists, thus implying that the immersive and dimly lit cave environment may have facilitated altered perceptual states conducive to art-making.

In another very recent study [13], the authors explored how VR can recreate the sensory and perceptual conditions of Paleolithic cave environments to facilitate archaeological understanding. Through an immersive VR simulation of Atxurra Cave in Northern Spain, the study replicated prehistoric lighting and spatial organization based on archaeological and experimental data. This realistic reconstruction allowed researchers to examine the multisensory challenges and cognitive states that prehistoric humans may have encountered in these settings. By simulating these unique

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conditions, the study underscores VR's potential as a powerful tool for investigating how ancient environments influenced cognition and cultural expression.

Inspired by the promise of VR for archaeological and cognitive research, the study presented in this paper builds on this emerging methodology by investigating the effects of a virtual cave environment on flexible thinking and subjective consciousness. The goal of our study is to explore whether a virtual cave environment can induce alterations in subjective consciousness, creativity, and flexible thinking similar to those hypothesized to have occurred during prehistoric cave activities with the aim to contribute to ongoing debates in cognitive archaeology regarding the cognitive and perceptual underpinnings of Paleolithic cave art.

To assess subjective aspects of consciousness, the participants in our study completed a battery of questionnaires, including a brief version of the Altered States of Consciousness Questionnaire (ASC; [17,19]), the Virtual Reality Neuroscience Questionnaire (VRNQ; [20]), and the Presence and Reality Judgement Questionnaire (PRJQ; [21]). These instruments allow for the subjective assessment of altered states and immersive experiences in different VR environments.

Moreover, individual differences in imagination and personality traits were considered. Using the Big Five Personality Questionnaire [22], the Four-Factor Imagination Scale [23], and the Spirituality Questionnaire [24], we examined whether certain traits, such as a higher propensity for imagination or openness, mediated the experience of altered states in the VR cave environment. Past research has indicated that individual differences can significantly influence the depth and nature of ASC experiences (e.g., in [25]), aligning with theories suggesting that shamans or spiritual leaders in ancient societies may have been more predisposed to entering altered states [26].

We further explored the effect of caves on flexible thinking, defined as an individual's ability to adapt their thinking in response to novel or changing situations, which is a trait often associated with creative problem-solving. Prior research in language has demonstrated that more flexible thinkers tend to exhibit semantic networks with lower modularity and more interconnected associations [27]. By using pareidolia tasks, where participants interpret ambiguous visual patterns in cave-like textures, we aim to measure thinking flexibility and investigate how these tasks might replicate the perceptual and associative processes involved in the creation of cave art [18,28,29].

This study presents a novel interdisciplinary approach that combines VR technology, cognitive psychology, and archaeology to test longstanding hypotheses about ancient human practices. We argue that VR, as an immersive and controllable experimental platform, holds significant promise for advancing our understanding of how ancient environments shaped human cognition and creativity. Furthermore, the integration of VR as a research tool demonstrates its potential not only for archaeological hypothesis testing but also for broader applications in the study of consciousness and cognition.

2. Materials and Methods

2.1. Participants

Thirty-four participants (18 female, 16 male), all native Italian speakers, were recruited from the University of Trento. The participants ranged in age from 21 to 45 years (mean age = 25, SD = 0.9). All participants had normal or corrected-to-normal vision, no history of neurological or psychiatric disorders, and reported no or minimal prior experience with VR. Three participants were excluded from the final dataset due to incomplete tasks (one participant) or technical issues with the audio recordings during data collection (two participants). The final sample included 31 participants (mean age = 24.6, SD = 3.1). All participants provided written informed consent, and the study was approved by the Human Research Ethics Committee of the University of Trento. The experiment was conducted following the principles of the Helsinki Declaration.

2.2. Procedure

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The experiment was conducted in the VR lab at the University of Trento, equipped with Oculus Rift headsets. Participants were instructed to complete the study in two distinct VR environments: a virtual cave and an open-space environment (see Figure 1).

Figure 1. Examples of renderings in the virtual environments. *Top left* – the virtual Cave. *Top right* - The torch used in the virtual Cave. *Bottom left* – the Open Space environment. *Bottom right* – Details of the high-definition rock in the Cave and in the Open Space environments.

Each participant experienced both conditions in a counterbalanced order to control for order effects. The environments were designed to closely simulate natural settings, with the Cave environment characterized by darkness, limited artificial light, enclosed space, and reverberating sounds. Participants navigated the cave using artificial torchlight. The open-space environment was characterized by an expansive, bright, and well-lit natural landscape, serving as a control condition to compare with the sensory-deprived cave setting. Both environments were generated with high-resolution textures, and participants could explore them freely during the task.

The virtual environments were created specifically for this study in Unity, utilizing several advanced tools and plugins to ensure the realistic depiction of both the cave and open environments. The following details describe the technical aspects of both environments:

2.2.1. Cave Environment

- *Design and Structure:* The cave was inspired by the Chauvet Cave in France, known for its prehistoric Paleolithic art. The virtual Cave environment was designed in two conditions: one with complete darkness and another with moderate illumination. Unity's Digger - Terrain Caves & Overhangs tool was used to create the complex cave structures, including overhangs and uneven rocky surfaces. High-resolution rock textures were applied, sourced from Creative Commons high-resolution rock photographs, ensuring the natural appearance of the cave. A series of unique large rocks with stimulating-pattern textures were positioned within the cave to enhance the pareidolic effects.
- *Lighting*: The cave lighting involved two parameters manipulated through Unity's lighting menu: the skybox material and intensity multiplier. In the complete darkness condition, the cave was entirely unlit, relying only on the torch for illumination. In the moderate illumination condition, subtle ambient light was added to simulate low-light environments. A custom flickering effect was implemented for the torch to simulate the movement of fire, dynamically changing the torch's intensity and range. This was achieved using a custom C# script to control the flame's behavior, producing realistic shadows and light diffusion.

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- *Audio*: The virtual Cave environment featured natural sounds including dripping water and wind, enhancing the immersive experience. Initially, Paleolithic-era instruments like the bullroarer, bone flutes, and drums were considered for use as auditory cues. However, due to limitations in recreating a natural soundscape, these abstract sounds were omitted in favor of natural environmental sounds. Footstep sounds synchronized with participant movements and fire sounds from the torch were used to further enhance the sense of immersion.

2.2.2. Open Space Environment

- *Design*: The Open Space environment shared the same planimetric layout as the cave but was visually distinct, featuring grassy terrain and trees. The Open Space environment was fully illuminated with bright, even lighting, providing stark contrast to the dimly lit cave.
- *Immersion Levels:* In the Open Space, participants held a non-functional, unlit torch, which did not interact with the environment. This reduced the interactivity of the experience in a way comparable to the cave, where the torch actively influenced the environment through dynamic shadows and light effects.
- *Audio*: The Open Space environment was enriched with natural sounds, including birdsongs and gentle breezes.

2.2.3. Interaction

- *Torch Mechanics:* In both environments, participants held a torch in their right hand. In the Cave environment, the torch was the primary light source, creating dynamic shadows that moved with the participant's hand movements. This was crucial for studying the pareidolic effects, as the flickering shadows mimicked the visual conditions in prehistoric caves. In the Open Space environment, the torch was unlit, reducing sensory engagement.

2.2.4. Challenges and Solutions

A key challenge in the Cave environment was addressing the unnatural shadow effects caused by Unity's default settings. This was resolved by increasing the shadow rendering distance, allowing for more realistic light behavior around the participant. Another challenge was creating a realistic flickering fire using Unity's particle system and custom shaders, which required iterative testing to achieve natural movement.

2.3. Pareidolic Task

In both VR settings, participants completed a pareidolic task, which involved identifying figures such as faces, animals, or objects in ambiguous visual stimuli (rocks) presented in the environment. Ten different rock stimuli were presented in each environment, with participants viewing each rock from two different positions (for a total of 20 positions per environment). Participants were instructed to report all figures they could identify within a 1-minute period from each viewing position. This task was designed to probe their ability to recognize patterns within random stimuli, a pareidolic phenomenon [28] linked to ASC and creativity [17,29].

A positional cue on the ground of the VR environment indicated where participants should stand while observing the rocks. A bell sound was used to signal the end of each 1-minute viewing period, prompting participants to move to the next positional cue. The pareidolic responses were audio-recorded for subsequent transcription and analysis.

2.4. Questionnaires

After completing the exploration of each environment, participants filled out the following series of questionnaires designed to measure ASC, user experience, and individual differences. The questionnaires were presented in a randomized order across participants.

2.4.1. Altered States of Consciousness (ASC) Questionnaire

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Participants completed a short version of the Altered States of Consciousness Questionnaire (ASC; [17]), which assesses subjective experiences associated with altered states. The questionnaire includes scales measuring dimensions such as emotional arousal, intensity of experience, and spirituality. This tool has been widely used in ASC research [19]. The short form used in this study is particularly well-suited for assessing consciousness changes induced by environmental factors within a brief completion time (e.g., used in [17]).

2.4.2. Virtual Reality Neuroscience Questionnaire (VRNQ)

The Virtual Reality Neuroscience Questionnaire (VRNQ; [20]) was used to assess the participants' user experience in the VR environments, focusing on immersion, quality of graphics and sound, and VR-induced symptoms like nausea and dizziness. Two subscales were selected for this study: the User Experience (UX) scale, which rates the overall quality and immersion of the VR experience, and the VR Induced Symptoms and Effects (VRISE) scale, which measures any adverse effects participants may have experienced, such as disorientation or fatigue.

2.4.3. Presence and Reality Judgement Questionnaire (PRJQ)

To measure participants' sense of presence and the perceived realism of the virtual environments, the Presence and Reality Judgement Questionnaire (PRJQ; [21]) was administered. This questionnaire evaluates how real and immersive participants perceived the VR environments to be, using subscales for reality judgment, emotional involvement, and perceptual congruence.

2.4.4. Personality and Imagination Traits

To investigate individual differences in participants' experiences of ASC, we administered three additional questionnaires:

- The *Big Five Personality Questionnaire* (BFQ), which measures five broad dimensions of personality (openness, conscientiousness, extraversion, agreeableness, and neuroticism) [22].
- The *Four Factor Imagination Scale* (FFIS; [23]), which assesses imagination traits, including frequency, complexity, emotional valence, and directedness of imagination. Previous research has suggested that traits such as openness to experience and imaginative ability may influence susceptibility to ASC.
- The *Spirituality Questionnaire* (SQ; [24]), which assesses core dimensions of spirituality, encompassing belief in God, search for meaning, mindfulness, and a feeling of security.

2.5. Semantic Network Analysis

We analyzed semantic flexibility in the pareidolic data using two complementary network science approaches: examining the semantic network topology [17,27,29] and applying percolation analysis [30]. The semantic networks were constructed at the group level for each condition, with unique responses to the pareidolic task (analyzed stimulus by stimulus) represented as nodes. Links between nodes were weighted based on the frequency of co-occurring responses.

To prepare the data for analysis, pareidolic responses from each participant were transcribed, reduced to single or compound words, and processed for semantic network analysis. A binary matrix was then constructed for each condition, where unique responses (stimulus-wise) formed the columns, and participants formed the rows. Only responses mentioned by at least two participants, and appearing in both the virtual Cave and Open Space conditions, were included in the final dataset. Using this dataset, we calculated cosine similarity between all pairs of unique responses for each condition to create a word-similarity matrix.

The resulting network was filtered using the Triangulated Maximally Filtered Graph (TMFG) method [31], which removes weak associations while retaining the strongest connections between words. This process produced an adjacency matrix where unique responses were represented as both rows and columns.

The semantic network's organization was evaluated using three key topological metrics:

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- *Modularity* (Q): Measures the degree to which the network divides into distinct communities [32].
- *Clustering Coefficient* (CC): Quantifies the tendency of nodes to form tightly connected clusters [33].
- *Average Shortest Path Length* (ASPL): Assesses the efficiency of communication within the network [33].

2.5.1. Percolation Analysis

To assess the robustness and flexibility of the semantic networks, we conducted a network percolation analysis [30]. In percolation analysis, the network is perturbated by removing the links among the nodes below a given increasing threshold through what is called the 'percolation step'. At each percolation step, the size of the Largest Connected Component (LCCS) is calculated, that is the biggest cluster of nodes that are linked only to each other. Once this process is completed, the percolation integral (φ), namely the area under the curve that represents the LCCS across the percolation steps, is computed. In this way, the robustness of the network is assessed. A higher percolation integral indicates a more flexible and resilient semantic network, reflecting greater flexibility in thinking [29,33].

2.5.2. Statistical Analysis of the Semantic Networks

In order to statistically test the validity of our results within the semantic networks topological quantifiers, we used two complementing methods: the leave-one-node-out (LONO) and the leave-one-subject-out (LOSO). On each measure, a two-tailed paired-samples permutation t-test ($\alpha = 0.05$, 10,000 iterations) was performed to compare the conditions in both procedures. Statistical comparisons of the percolation results between the cave and open-space conditions were performed using the LONO and LOSO procedures, as well as link shuffling (LS) and effect of noise (EN) analyses. These methods ensured the robustness of the findings across different statistical approaches. All statistical analyses were conducted using R Studio and Python with the NetworkX and SemNet packages [34]. For comparisons between conditions, we used paired-samples permutation t-tests ($\alpha = 0.05$, 10,000 iterations). Cohen's d was calculated as a measure of effect size, with values of 0.2, 0.5, and 0.8 indicating small, moderate, and large effects, respectively. Multiple comparisons were corrected using the Benjamini-Hochberg procedure.

3. Results

3.1. Fluency in the Pareidolic Task

The number of total responses given in the Open Space condition is 1135 (mean among all the stimuli by subject = 33.38, sd = 18.63), while the number of responses in the virtual Cave condition is 1040 (mean among all the stimuli by subject = 30.59, sd = 16.55). Such difference between fluency in Cave vs Open condition is not significant according to a Welch's t-test ($t=0.66$; $p=0.51$).

3.2. Word Frequency in Pareidolic Task

The analysis of the most frequent words in the pareidolic task across the virtual Cave and the Open Space environments reveals similarities and differences. In both settings, "faccia" ("face" in Italian) emerged as the most common word, indicating a shared human tendency to recognize facial patterns, a fundamental pareidolic response. However, other frequently reported words diverged between the two conditions, reflecting distinct perceptual interpretations tied to each environment. In the cave condition, words such as "uomo" (man), "occhio" (eye), "mano" (hand), and "cuore" (heart) were prominent. Conversely, in the Open Space environment, words like "pesce" (fish), "maschera" (mask), "pipistrello" (bat), and "squalo" (shark) appeared more frequently (See Figure 2).

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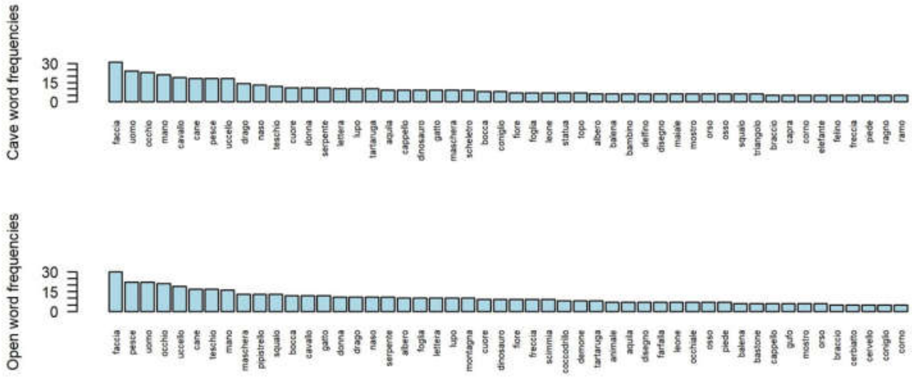

Figure 2. Word frequencies Bar plot of the first 50 most common pareidolic stimuli seen by participants in the two experimental conditions (virtual Cave in the top panel, and Open Space in the bottom panel).

3.3. Unique Responses

The raw responses given by participants in the Pareidolic Task have been transcribed and preprocessed (reduced to a single or compound word, converted from plural to singular) resulting in a dataset composed of the words describing the pareidolic stimuli perceived by participants in Cave and Open Space conditions.

In the virtual Cave condition, participants generated 428 unique responses, 190 of which did not appear in the Open Space condition. In contrast, in the Open Space condition, participants generated 466 unique responses, 228 of which did not appear in the virtual Cave condition.

A McNemar's chi-squared test and the Phi effect size (φ) were used to analyze differences in the proportion of unique responses between conditions. The proportion of unique responses in the Cave condition (65.24%) was not significantly different from that in the Open Space condition (71.04%) ($\chi^2(1) = 3.275$, $p = 0.07$, $\varphi = 0.07$).

3.4. Network Semantic Analysis

We modeled the responses of the pareidolic task for each condition in a group-level semantic network as described before. This resulted in an unweighted, undirected network from which we built the semantic networks (see Figure 3). The organization of the semantic network has been analyzed using three different topological quantifiers: Modularity (Q), Clustering Coefficient (CC) and Average Shortage Path Length (ASPL).

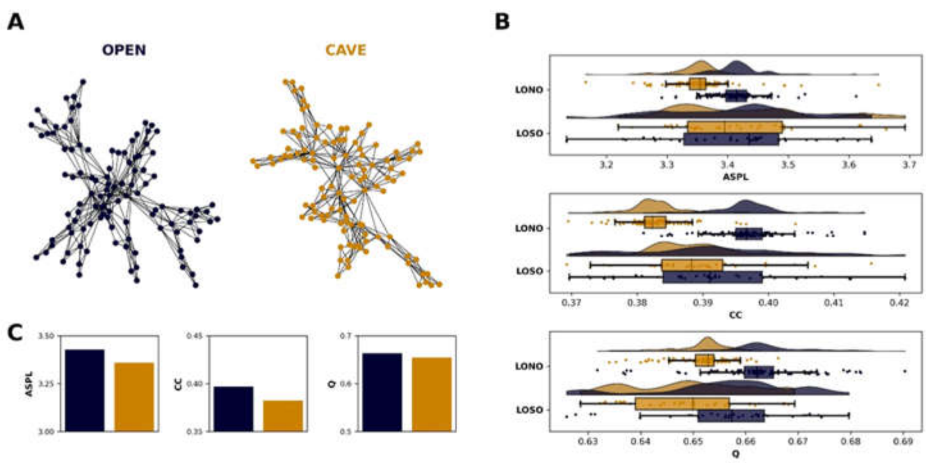

Figure 3. Semantic networks statistical results and topological quantifiers. (A) Spring layout of the semantic networks, undirected and unweighted, of the Open Space and Cave conditions, with nodes

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as pareidolic unique responses and edges as cosine similarity. (B) Raincloud plots of the statistical results of LONO and LOSO procedures on the topological quantifiers. (C) Bar plots representing the topological quantifiers: in blue is represented Open Space, in orange is represented the virtual Cave.

The results show (qualitative and quantitative) differences between the semantic networks obtained by the pareidolic task in the two different conditions (virtual Cave vs Open Space, see Figure 4). Quantitatively, we found significative differences between the aforementioned quantifiers, with a shorter ASPL, a smaller Q and a lower CC in Cave (ASPL= 3.36, Q=0.65, CC=0.38) compared to the Open Space condition (ASPL= 3.43, Q = 0.66, CC = 0.40). The difference was statistically significant in all three topological quantifiers measured using the LONO procedure, while, using the LOSO procedure, the difference in Modularity only reached statistical significance (See Table 1).

Table 1. Results of the permutation t test in Cave and Open Space VR environments. LONO: leave-one-node-out, LOSO: leave-one-subject-out. ASPL: average shortest path length, CC: clustering coefficient, Q: modularity index. P = p-value, d = Cohen's d effect size – 0,2 small; 0,5 moderate; 0.8 large, 1.1 very large.

	LONO				**LOSO**			
Measures	Cave M (SD)	Open M (SD)	P	d	Cave M(SD)	Open M(SD)	P	d
ASPL	3.355	3.414	<.00001	1.25	3.418	3.412	0.82	0.05
CC	0.383	0.397	<.00001	2.80	0.389	0.391	0.36	0.22
Q	0.652	0.663	<.00001	1.43	0.649	0.656	0.03	0.55

3.5. Percolation Analysis

To assess the robustness of the networks, we used a network percolation analysis procedure [30]. We took the weighted adjacency matrix of the previously constructed pareidolic responses and applied these percolation analysis steps to compare the resiliency of the semantic networks of the different conditions (virtual Cave vs Open Space). During this process, network links were progressively removed based on their strength, and the size of the largest connected component (LCCS) was measured at each step. The percolation integral (φ), which represents the area under the curve of the LCCS across percolation steps, was used as an indicator of network robustness. We found a higher percolation integral in the virtual Cave network (φ=53.76) compared to the Open Space network (φ=49.99, see Figure 4).

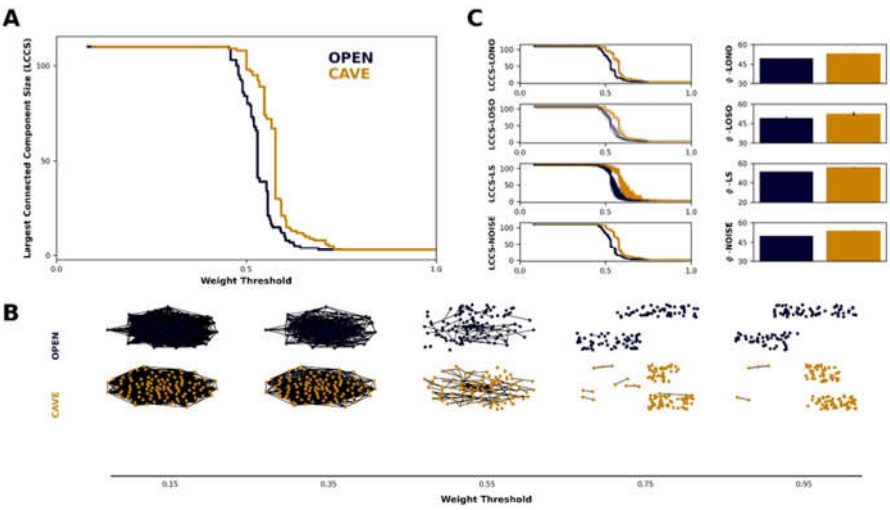

Figure 4. Network Percolation and statistical results. (A) Graphical representation of the line plot of the percolation process of the Open Space (in blue) and Cave (in yellow) networks. On the y axes is represented the number of nodes that survived the percolation process, on the x axes is represented

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the increasing weight threshold of the nodes removed during the percolation steps, from 0.0 to 1.0. (B) Visualization of semantic networks in Open Space and Cave conditions displayed at different weight thresholds along the percolation process. (C) Line plots of the LONO, LOSO, LS, and EN procedures (on the left); bar plots showing the φ between conditions for the four different procedures (on the right).

We used four different statistical approaches to assess the difference of our results: LONO, LOSO, link shuffling analysis (LS), and Effect of Noise (EN). We found the difference statistically significant in all four conditions (see Table 2). These consistent results indicate that the semantic network in virtual Cave condition is more robust and flexible compared to the Open Space semantic network.

Table 2. Results of the comparison between the networks of Cave and Open conditions from the two-tailed paired-sample permutation t-test on percolation integral. Mean and standard deviation in parenthesis. LONO: leave-one-node-out; LOSO: leave-one-subject-out; LS: link shuffling analysis; EN: Effect of Noise analysis. p= p-value, d = Cohen's d effect size – 0,2 small; 0,5 moderate; 0.8 large, 1.1 very large.

Method	**Cave**	**Open**	**p**	**d**
LONO	53.2 (0.18)	49.48 (0.13)	< 0.00001	23.508
LOSO	52.59 (1.19)	49.03 (1.05)	< 0.00001	3.126
LS	56.19 (0.66)	51.6 (0.45)	< 0.00001	8.115
EN	53.85 (0.16)	50.02 (0.16)	< 0.00001	24.181

3.6. Altered States of Consciousness (ASC) Questionnaire

Significant differences were found between the virtual Cave and Open Space conditions on three of the twelve ASC scales investigated (for details on the other non-significant values, see Figure 5)

- *Arousal*: Participants reported significantly higher arousal levels in the virtual Cave condition (mean = 0.53, SD = 0.24) compared to the Open Space condition (mean = 0.40, SD = 0.21), t(33) = 2.939, p = 0.024, d = 0.50.
- *Intensity*: The intensity of the experience was significantly higher in the virtual Cave condition (mean = 0.61, SD = 0.27) compared to the Open Space condition (mean = 0.47, SD = 0.23), t(33) = 3.125, p = 0.024, d = 0.54.
- *Spirituality*: Participants reported significantly higher spirituality in the virtual Cave condition (mean = 0.48, SD = 0.23) compared to the Open Space condition (mean = 0.35, SD = 0.26), t(33) = 2.952, p = 0.006, d = 0.51.

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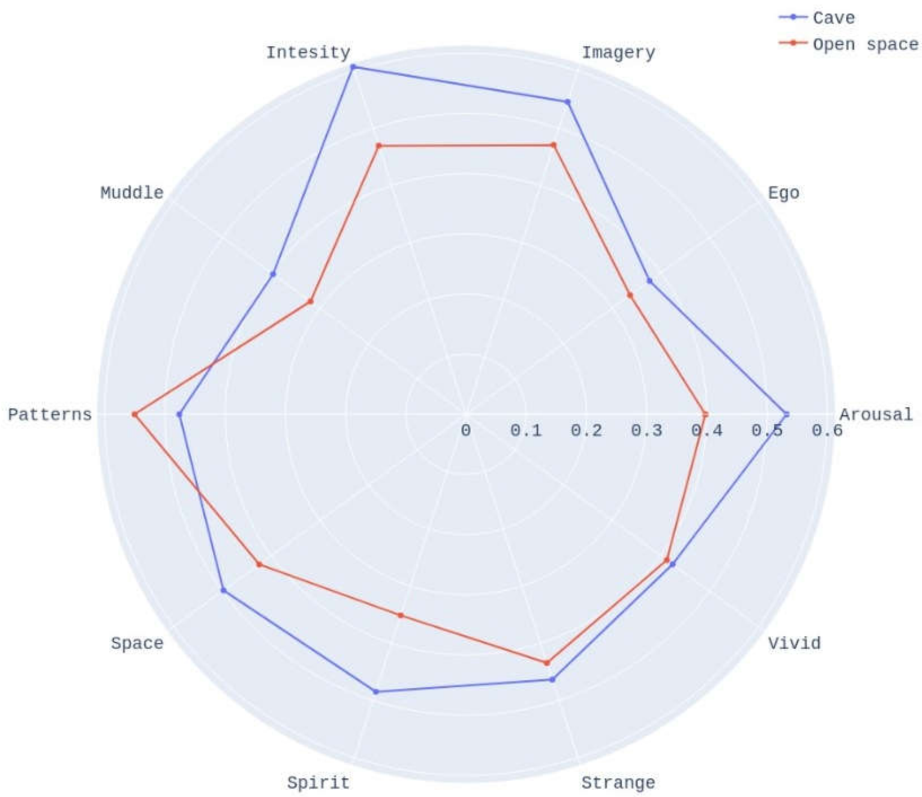

Figure 5. Radar plot of the Altered State of Consciousness questionnaire results. In blue are presented the mean values of the questionnaire filled after the exploration of virtual Cave setting, in red the values after the exploration of the Open Space setting.

3.7. Virtual Reality Neuroscience Questionnaire (VRNQ)

Two scales from the VRNQ were used to compare user experience across conditions:

- User Experience (UX) Scale: Participants reported that the virtual Cave setting was significantly more immersive than the Open Space setting (p = 0.002, d = 0.65). The graphics quality was also rated slightly higher in the cave setting (p = 0.006, d = 0.36), possibly due to the darker, more atmospheric lighting of the Cave environment.
- VR-Induced Symptoms and Effects (VRISE) Scale: No significant differences were found between conditions for symptoms like nausea, dizziness, or disorientation.

3.8. Presence and Reality Judgement Questionnaire (PRJQ)

Significant differences between the virtual Cave and the Open Space conditions were observed in the Reality Judgement and Emotional Engagement scales:

- Reality Judgement Scale:
  - Item 1 ("To what extent was what you saw in the virtual world similar to reality?"): p = 0.024, d = 0.44
  - Item 2 ("To what extent did what you heard influence how real the experience seemed?"): p = 0.0012, d = 0.62
  - Item 7 ("To what extent did the experience seem real to you?"): p = 0.0042, d = 0.25
- Emotional Engagement Scale:
  - Item 5 ("To what extent did things in the virtual world have an impact on you?"): p = 0.046, d = 0.29

3.9. Correlations

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No significant correlations between delta ASC and BFQ, FFIS, or SQ were observed after applying a multiple comparison correction. Uncorrected exploratory analyses, however, revealed additional information. Pearson's correlation analysis showed a significant negative correlation between the Directedness scale of the FFIS and the Spirituality delta of the ASC ($r = -0.423$, $p = 0.013$). This suggests that participants who perceived greater spirituality in the virtual Cave condition tended to score lower on Directedness, possibly indicating less self-centeredness.

Moreover, a positive correlation was found between Emotional Valence of the FFIS and the Intensity delta of the ASC ($r = 0.348$, $p = 0.044$ uncorrected), and between Arousal of the ASC and the Meaning and God subscales of the Spirituality Questionnaire ($r = 0.46$, $p = 0.006$ uncorrected; $r = 0.354$, $p = 0.04$ uncorrected, respectively). A negative correlation was found between Conscientiousness scale of the BFQ and the Space delta and the Spirit delta of ASC ($r = -0.34$, $p = 0.048$ uncorrected; $r = -0.34$, $p = 0.49$ uncorrected, respectively). A negative correlation was also found between Extraversion scale of the BFQ and the Vividness delta of the ASC ($r= -0.368$, $p= 0.03$ uncorrected).

4. Discussion

This study aimed to explore how immersive VR environments, specifically a virtual cave, influence ASC, creativity, and flexible thinking, contributing to cognitive archaeology and anthropology hypotheses. By simulating cave and open-space environments in VR, we examined their impact on perception, cognition, and subjective experiences. Our findings provide preliminary evidence that sensory-deprived, immersive cave environments can foster flexible thought processes and, possibly, enhance creativity, in alignment with previous archaeological theories [1,4]. Additionally, these results contribute to the recently increased use of VR as a tool to test cognitive and cultural hypotheses related to prehistoric human experiences in caves [13,18].

One of the key findings of this study is that the virtual Cave environment elicited significantly higher levels of arousal, intensity, and spirituality compared to the open-space condition. The results from the ASC questionnaire suggest that the sensory-deprived, immersive nature of the virtual Cave environment facilitated a deeper engagement with the experience, akin to the altered states theorized to have occurred in actual prehistoric caves. The heightened emotional responses observed are consistent with previous studies linking ASC to sensory deprivation, rhythmic stimuli, and confined spaces. Similar outcomes have been observed in studies using VR to simulate the sensory characteristics of prehistoric caves, supporting the notion that sensory isolation and environmental stimuli can elicit spiritual experiences and altered states [18]. The significant increase in spirituality reported in the virtual Cave condition may reflect the unique psychological impact of enclosed, dimly lit environments that have been previously associated with trance states and mystical experiences in various cultural contexts [4].

While most findings remained robust under multiple comparison corrections, we reported some uncorrected results to offer exploratory insights into individual differences and mechanisms underlying ASC. For instance, the negative correlation between the Directedness dimension of the Four-Factor Imagination Scale (FFIS) and changes in spirituality suggests that participants with less structured, open-ended imagination may be more responsive to immersive and spiritual experiences in the virtual Cave environment. Although not statistically significant after correction, this aligns with theories linking unstructured cognitive styles to altered states in ritual contexts [1,26]. Similarly, the positive correlation between Emotional Valence and the Intensity delta in the ASC questionnaire suggests a potential link between emotional imagination and deeper engagement with immersive environments. Observed relationships between Conscientiousness and changes in spirituality and spatial perception also hint at personality’s role in shaping responses to altered states.

The semantic network analysis of the pareidolic task supports the idea that the cave environment influenced aspects of creativity and flexible thinking. Participants in the virtual Cave condition exhibited more flexible, less modular semantic networks, evidenced by significantly lower modularity index (Q) and clustering coefficient (CC) compared to the open-space condition. These findings are consistent with research showing that individuals with more creative and flexible thought processes tend to have less modular, more interconnected semantic networks [29].

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The significant reduction in modularity observed in the Cave environment suggests that the ASC experienced in this setting may have allowed participants to access a more fluid and expansive cognitive space. This flexibility in thinking, reflected in the structure of the semantic networks, mirrors processes that may have facilitated the production of cave art during the Paleolithic period. Previous research has posited that ASC, triggered by environmental factors such as flickering light and sensory deprivation, may have played a role in the creation of figurative art by early humans [28]. The ability to perceive meaningful patterns in ambiguous stimuli, as measured by the pareidolic task, provides a modern analog for understanding how prehistoric humans might have interpreted and created images on cave walls.

The percolation analysis further suggests that the semantic network in the virtual Cave condition was more robust and flexible compared to the Open Space condition. A higher percolation integral (φ) in the cave condition indicates that the semantic network resisted percolation attacks for a longer duration before fragmenting, a possible sign of greater cognitive flexibility [30]. The robustness of the cave network across all four statistical approaches—LONO, LOSO, LS, and EN—reinforces the reliability of this finding, showing the flexibility of cognitive associations under the influence of altered states. This increased flexibility is consistent with previous research suggesting that creative cognitive processes are enhanced in immersive environments [17].

The heightened network flexibility observed in our study may have important implications for understanding the cognitive processes that occurred in prehistoric caves. This aligns with previous work suggesting that creativity and flexibility are central to the production of art and symbolic thinking in human evolution. In this context, Carhart-Harris's hypothesis on increased entropy in the brain during ASC [37] offers a valuable parallel. The concept of "pivotal mental states" [38] posits that certain states of heightened neural entropy induced by psychedelic substances can lead to increased thinking flexibility and transformative experiences. While psychedelic substances are known to induce such states, our findings suggest that the sensory and perceptual conditions of Cave environments alone might have been sufficient—or at least supportive—in inducing deep ASCs in the distant past.

The study also aimed at exploring the use of VR as a tool for simulating ancient environments. Our results provide evidence that VR offers, in this respect, several advantages. It allows for controlled, repeatable experiments in which specific environmental factors hypothesized to influence cognition can be manipulated and tested. Unlike physical reconstructions or visits to real caves, VR provides a safe and accessible way to study these phenomena, making it a valuable resource for both archaeologists and cognitive scientists [18]. Moreover, the integration of VR with cognitive measures, such as semantic network analysis and ASC questionnaires, allows researchers to quantify the psychological effects of these environments, providing new insights into the cognitive and emotional experiences of early humans.

While our findings provide valuable insights into the effects of immersive cave environments on cognition and consciousness, there are limitations to consider. First, the sample size (n = 31) was relatively small, potentially limiting the generalizability of the results. Future studies should aim to replicate these findings with larger, more diverse samples to ensure robustness. Second, while our virtual Cave environment was designed to simulate the sensory characteristics of real caves, it cannot fully replicate all aspects of prehistoric cave experiences, such as the effects of hypoxia, temperature, or prolonged isolation. Future research could explore these variables using more sophisticated VR simulations or combining VR with physiological measurements, such as EEG or fMRI, to capture the neural correlates of ASC.

Finally, it would be beneficial to investigate the role of additional factors, such as rhythmic sounds, flickering lights, or even the use of psychoactive substances [2], in enhancing ASC in virtual cave environments. These elements, believed to have been part of prehistoric rituals, could provide a more comprehensive understanding of the mechanisms through which cave environments influenced human cognition and creativity.

In conclusion, this study provides empirical evidence that immersive VR cave environments can induce ASC and enhance aspects of creativity and flexibility, contributing to our understanding of the cognitive processes that may have facilitated the creation of prehistoric cave art. The incorporation of Carhart-Harris's concept of pivotal mental states [38] underscores the potential for such environments to induce transformative experiences by increasing neural entropy and thinking flexibility. The use of VR as a methodological tool in archaeology and anthropology opens new avenues for exploring ancient human cognition and behavior, offering a powerful platform for testing hypotheses about the psychological experiences of early humans. As VR technology continues to advance, its applications in scientific research will likely expand, providing novel insights into both past and present workings of the human mind.

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References

1. Lewis-Williams, D.J. The Mind in the Cave; Thames and Hudson: London, UK, 2002.
2. Winkelman, M. Introduction: Evidence for entheogen use in prehistory and world religions. J. Psychedelic Stud. 2019, 3, 43–62.
3. Froese, T.; Woodward, A.; Ikegami, T. People in the Paleolithic could access the whole spectrum of consciousness: Response to Helvenston. Adapt. Behav. 2014, 22, 282–285.
4. Lewis-Williams, D.J.; Clottes, J. The mind in the cave—the cave in the mind: Altered consciousness in the Upper Paleolithic. Anthropol. Conscious. 1998, 9, 13–21.
5. Dowd, M.; Hensey, R. (Eds.) The Archaeology of Darkness; Oxbow Books: Oxford, UK, 2016.
6. Mo, R.; Wu, B.; Horner, A. The effects of reverberation on the emotional characteristics of musical instruments. J. Audio Eng. Soc. 2015, 63, 966–979.
7. Bartossek, M.T.; Kemmerer, J.; Schmidt, T.T. Altered states phenomena induced by visual flicker light stimulation. PLoS ONE 2021, 16, e0253779.
8. Zubek, J.P. (Ed.) Sensory Deprivation: Fifteen Years of Research; Appleton Century Crofts: New York, NY, USA, 1969.
9. Zuccarelli, L.; Galasso, L.; Turner, R.; Coffey, E.J.; Bessone, L.; Strapazzon, G. Human physiology during exposure to the cave environment: A systematic review with implications for aerospace medicine. Front. Physiol. 2019, 10, 442.
10. Kedar, Y.; Kedar, G.; Barkai, R. Hypoxia in Paleolithic decorated caves: The use of artificial light in deep caves reduces oxygen concentration and induces altered states of consciousness. Time Mind 2021, 14, 181–216.
11. Lewis-Williams, J.D.; Dowson, T.A. The signs of all times: Entoptic phenomena in Upper Palaeolithic art [and comments and reply]. Curr. Anthropol. 1988, 29, 201–245.
12. Luke, D. Rock art or Rorschach: Is there more to entoptics than meets the eye? Time Mind 2010, 3, 9–28.
13. Torres, A.; Medina-Alcaide, M.Á.; Intxaurbe, I.; Rivero, O.; Rios-Garaizar, J.; Arriolabengoa, M.; Garate, D. Scientific Virtual Reality as a research tool in prehistoric archaeology: The case of Atxurra Cave (Northern Spain). Virtual Archaeol. Rev. 2024, 15, 1–15.
14. Hodgson, D. Upper Palaeolithic art as a perceptual search for magical images. Time Mind 2021, 14, 487–499.
15. Bratman, G.N.; Daily, G.C.; Levy, B.J.; Gross, J.J. The benefits of nature experience: Improved affect and cognition. Landsc. Urban Plan. 2015, 138, 41–50.
16. Kjellgren, A.; Buhrkall, H. A comparison of the restorative effect of a natural environment with that of a simulated natural environment. J. Environ. Psychol. 2010, 30, 464–472.

 doi:10.20944/preprints202411.1541.v1

17. Rastelli, C.; Greco, A.; Kenett, Y.N.; Finocchiaro, C.; De Pisapia, N. Simulated visual hallucinations in virtual reality enhance cognitive flexibility. Sci. Rep. 2022, 12, 4027.
18. Wisher, I.; Pettitt, P.; Kentridge, R.W. The deep past in the virtual present: Developing an interdisciplinary approach towards understanding the psychological foundations of palaeolithic cave art. Sci. Rep. 2023, 13, 46320.
19. Dittrich, A. The standardized psychometric assessment of altered states of consciousness (ASCs) in humans. Pharmacopsychiatry 1998, 31 (Suppl. 2), 80–84.
20. Kourtesis, P.; Collina, S.; Doumas, L.A.; MacPherson, S.E. Validation of the Virtual Reality Neuroscience Questionnaire: Maximum duration of immersive virtual reality sessions without the presence of pertinent adverse symptomatology. Front. Hum. Neurosci. 2019, 13, 417.
21. Baños, R.M.; Botella, C.; García-Palacios, A.; Villa, H.; Perpiñá, C.; Alcañiz, M. Presence and reality judgment in virtual environments: A unitary construct? Cyberpsychol. Behav. 2000, 3, 327–335.
22. Caprara, G.V.; Barbaranelli, C.; Borgogni, L.; Perugini, M. The "Big Five Questionnaire": A new questionnaire to assess the five factor model. Pers. Individ. Differ. 1993, 15, 281–288.
23. Zabelina, D.L.; Condon, D.M. The Four-Factor Imagination Scale (FFIS): A measure for assessing frequency, complexity, emotional valence, and directedness of imagination. Psychol. Res. 2020, 84, 2287–2299.
24. Hardt, J.; Schultz, S.; Xander, C.; Becker, G.; Dragan, M. The spirituality questionnaire: Core dimensions of spirituality. **Psychology 2012**, *3*, 116.
25. Tellegen, A.; Atkinson, G. Openness to absorbing and self-altering experiences ("absorption"), a trait related to hypnotic susceptibility. J. Abnorm. Psychol. 1974, 83, 268–277. (Note: This reference was not provided in the list.)
26. Winkelman, M.J. Shamanism: A Biopsychosocial Paradigm of Consciousness and Healing; Bloomsbury Publishing USA: New York, NY, USA, 2010.
27. Kenett, Y.N.; Wechsler-Kashi, D.; Kenett, D.Y.; Schwartz, R.G.; Ben-Jacob, E.; Faust, M. Semantic organization in children with cochlear implants: Computational analysis of verbal fluency. Front. Psychol. 2013, 4, 543.
28. Bednarik, R.G. Rock art and pareidolia. Rock Art Res. 2016, 33, 167–181.
29. Kenett, Y.N.; Anaki, D.; Faust, M. Investigating the structure of semantic networks in low and high creative persons. Front. Hum. Neurosci. 2014, 8, 407.
30. Kenett, Y.N.; Beaty, R.E.; Silvia, P.J.; Faust, M. Flexibility of thought in high creative individuals represented by percolation analysis. Proc. Natl. Acad. Sci. USA 2018, 115, 867–872.
31. Massara, G.P.; Di Matteo, T.; Aste, T. Network filtering for big data: Triangulated maximally filtered graph. J. Complex Netw. 2017, 5, 161–178.
32. Newman, M.E. Modularity and community structure in networks. Proc. Natl. Acad. Sci. USA 2006, 103, 8577–8582.
33. Watts, D.J.; Strogatz, S.H. Collective dynamics of 'small-world' networks. Nature 1998, 393, 440–442.
34. Cosgrove, A.L.; Kenett, Y.N.; Beaty, R.E.; Diaz, M.T. Quantifying flexibility in thought: The resiliency of semantic networks differs across the lifespan. Cognition 2021, 211, 104631.
35. Christensen, A.P.; Kenett, Y.N. Semantic network analysis (SemNA): A tutorial on preprocessing, estimating, and analyzing semantic networks. Psychol. Methods 2022, 27, 765–790.
36. Suzuki, K.; Roseboom, W.; Schwartzman, D.J.; Seth, A.K. A deep-dream virtual reality platform for studying altered perceptual phenomenology. Sci. Rep. 2017, 7, 15982.
37. Carhart-Harris, R.L. The entropic brain—revisited. Neuropharmacology 2018, 142, 167–178.
38. Brouwer, A.; Carhart-Harris, R.L. Pivotal mental states. J. Psychopharmacol. 2021, 35, 319–352.