Degree project

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Lucid Dreaming: Consciousness Through Neuroimaging

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Abstract

The concept of lucid dreaming is truly fascinating as it involves individuals becoming aware of their state of dreaming while still immersed in the dream state. This intriguing phenomenon provides a unique opportunity to explore consciousness. Previous research has indicated that during lucid dreaming, there is heightened activity in the frontal region of the brain as well as an increase in alpha waves. These neural activities mirror those observed during waking consciousness. In this thesis, a comprehensive systematic review is undertaken to examine lucid dreaming from the perspective of neuroimaging techniques. This review challenges the widely held belief that the frontal region is the primary locus of activity during lucid dreaming. Based on results reported, this thesis suggests that the parietal region may also play a significant role in contributing to the experience of lucid dreaming.

Keywords: lucid dreaming, consciousness, neuroimaging techniques

Lucid Dreaming: Consciousness through neuroimaging

Lucid dreaming offers a unique opportunity to explore higher-order consciousness, as dreams are generated through internal imagination and not external stimuli, providing insight into the true nature of consciousness (Revonsuo, 2006). Despite Baird and colleagues (2019) suggesting that lucid dreaming could serve as a cognitive neuroscience methodology for exploring consciousness, little research has been done to establish a connection between these two phenomena. The objective of this systematic review is to investigate the potential insights that can be gained regarding the neural correlates of higher-order consciousness from the phenomenon of lucid dreaming. It will do so by identifying distinct patterns of neural activity and specific brain regions associated with lucid dreaming.

Sleep stage

On average, we spend about a third of our time sleeping. Throughout a typical night, we experience 4-6 sleep cycles, each lasting between 90 to 110 minutes (Memar & Faradji, 2018). Through each sleep cycle, we experience different sleep stages; stage 1 (drowsiness), stage 2 (light sleep), stage 3 (deep sleep), stage 4 (deep sleep/slow wave sleep), and REM sleep (Acharya et al., 2016). The first four stages are classed as NREM (non-rapid eye movement) and described as N1, N2, N3, and N4.

Each sleep stage can be distinguished from the others using electroencephalography (EEG). When we are awake, our brain predominantly operates in the beta (12-30Hz) and alpha (8-12Hz) frequency bands. When we enter stage N1, alpha activity decreases, and theta waves (4-8Hz) increase. In stage N2, alpha activity disappears, leaving only theta frequency activity, occasionally interspersed with sleep spindles (11-15Hz) and K-complexes (a brief negative high-voltage peak). During N3 (deep sleep), slow delta activity (0-4Hz) is predominant, accompanied by sleep spindles (1-3Hz) and K-complexes. In stage N4 (deep sleep/slow wave sleep), brain waves fluctuate between 0.5 and 2 Hz. Upon entering REM sleep, our eyes start to move rapidly, brain-wave frequency significantly increases, and mixed frequencies are present, including sigma waves (12-15Hz), beta waves, and gamma waves (>30Hz).

Lucid dreaming

Lucid dreaming is a fascinating phenomenon in which the dreamer realizes that they are dreaming while still immersed in the dream state. This realization grants the dreamer some degree of control over the dream, enabling them to manipulate the dream's environment, characters, and events to a certain extent.

The term "lucid dreaming" was coined by van Eeden (1913) to describe his personal experience with the phenomenon. However, its status as a legitimate occurrence was limited until Hearne (1978) established an objective method for participants to indicate the onset of lucid dreaming. This was achieved through a pre-arranged eye signaling technique, such as

moving the eyes left-right-left-right, which was recorded through electrooculography and polysomnography during REM sleep. This method has since become the standard way of communicating the onset of lucid dreaming in laboratory settings (Baird et al., 2019).

While participants have reported experiencing lucid dreaming during NREM sleep, as evidenced by their reports upon waking from different sleep stages (LaBerge, 1980a), the eye-signaling technique has shown difficulty verifying lucid onset during NREM sleep. LaBerge and colleagues (1981) were unsuccessful in recording eye signaling during N1 sleep despite the participant reported experiencing a lucid dream upon waking. It was first confirmed when Dane and Van de Castle (1984) successfully recorded left-right-left-right eye movement to signal lucid onset during N1 sleep. It has since been verified during N2 sleep (Mota-Rolim et al., 2015), but never observed in N3 sleep (Baird et al., 2019). A study found that lucid dreaming is more prevalent during REM sleep (LaBerge et al., 1986) and far more difficult to achieve during NREM sleep (Stumbrys & Erlacher, 2012).

Levels of lucidity

Kellogg (1992) kept a dream diary and recorded all his dreams. After several years he had recorded over 7,000 dreams, of which around 500 were lucid dreams that varied in degree of lucidity and control. He sorted each dream into one of seven classifications based on the level of lucidity and control he was able to exercise: pre-lucid, sub-lucid, lucid, fully lucid, fully lucid but powerless, and super lucid.

When a dreamer becomes consciously aware of something unusual in a dream but fails to realize that they are dreaming, they are having a pre-lucid dream; while in a sub-lucid dream, the dreamer has a vague awareness that they are dreaming but does not act on this knowledge and simply goes along with the dream as it unfolds.

In a lucid dream, one is fully aware of the dream state. The dreamer can actively choose whether to go along with the dream or make choices and try out different experiences.

If one can remember previous lucid dreams and has enough control to perform tasks with ease that one has failed during previous dreams, one experiences a fully lucid dream.

In a fully lucid but powerless dream, one has knowledge of prior lucid dreams but no power to change the dream scenario. This is a frustrating experience for the dreamer, as they are aware of their lack of control and inability to change the dream.

Finally, in a super lucid state, one experiences a high level of awareness and has complete comprehension of the lucid dream potential. The dreamer is in complete control of their dream state and can manipulate it to their liking. They have a heightened sense of self-awareness and can perform complex tasks that they may not be able to do in waking life.

Induction technique

Lucid dreaming can be induced through different techniques. One group of techniques is cognitive/behavioral. A systematic review (Stumbrys et al., 2012) identified

four techniques that proved most efficient. The mnemonic induction technique created by LaBerge (1980b) involves being awakened during sleep and asked to recall various dream elements. The sleeper is asked to remember these elements when going back to sleep. The idea is to realize that one is dreaming when one experiences these elements again in a dream. The reality test (Taitz, 2011) involves frequently asking oneself "am I dreaming?" and observing one's surroundings while awake. When the same question is asked in a dream and inconsistencies are noticed in the environment, one becomes aware that one is dreaming. The wake-back-to-bed technique (VanDeKeere, 2007) involves setting an alarm to wake after a few hours of sleep, staying up for 30 minutes to an hour, then going back to sleep with the intention of having a lucid dream. Tholey's (1983) combined technique involves a combination of reality testing, dream recall, and mnemonic induction. Paulsson and Parker (2006) report that Tholey's combined technique is more effective than any individual technique. Kumar et al. (2018) found that 83% of participants who practiced Tholey's technique for three months experienced lucid dreams during this period.

The second category of techniques makes use of stimuli, including sensory, auditory, visual, and tactile cues, or transcranial current stimulation, to stimulate different areas of the brain. Typically, individuals are exposed to cues upon waking and directed to identify them in their dreams. Carr et al. (2023) found that combining a series of 500-700-900Hz beeps during 200ms on/off periods as well as a red LED light flashing three times during 500ms on/off periods before participants slept significantly increased eye-signaling verified lucid dreams when the auditory and visual cues were introduced again during REM sleep. Leslie and Ogilvie (1996) observed that stimulating the vestibular system in the morning by gently rocking a hammock increased the occurrence of lucid dreaming. Voss et al. (2014) discovered that applying gamma-frequency transcranial direct current stimulation (tDCS) to the frontal region induced lucid dreaming during REM sleep in 77.5% of participants.

The final category of techniques involves substance intervention in controlled laboratory conditions. Galamantine (Sparrow et al., 2016) has been shown to increase the vividness of lucid dreaming, and magnesium (Peuhkuri et al., 2012) its frequency.

Prevalence

Snyder and Gackenbach (1988) report that 58% of the population has experienced at least one lucid dream, while 21% experience one monthly. However, the reported prevalence varies considerably. Stepansky et al. (1998) found a prevalence of 26% based on a survey of 1,000 Austrians aged 14-69. Yu (2008) found a prevalence of 61% based on a questionnaire given to 348 Chinese university students, while Erlacher et al. (2008) found a prevalence of 47% based on a questionnaire given to 153 Japanese university students. A meta-analysis (Saunders et al., 2016) reported a mean score of 63% across studies. These findings suggest that the prevalence of lucid dreaming may vary significantly across populations and cultures.

Alternatively, the varying prevalence rates might be attributable to methodological differences. Ribeiro et al. (2016) discovered that, when a definition of lucid dreaming was provided, the prevalence rate was 81% among 315 students; while, without a definition, the rate dropped to 73% when asking about dream awareness or 50% when asking about dream control. Schredl and Erlacher (2004) observed that lucid dreaming is more prevalent in children and that prevalence decreases with age, while women experience more episodes than men.

Aim

This review aims to identify consistent patterns of neural activity and brain regions associated with lucid dreaming across a wide range of studies using various neuroimaging tools. The objective is to interpret these findings in relation to higher-order processes such as conscious awareness and self-reflection.

In line with the research aim, two research questions were formulated:

1. Which brain region(s) are responsible for lucid dreaming?
2. Which higher-order processes are implicated in lucid dreaming?

Methods

Search strategy

On May 10, 2024, a search was conducted using the search string (lucid dream* OR dream lucidity) AND (neuroimaging OR EEG OR electroencephalogram OR electroencephalography OR fMRI OR functional magnetic resonance imaging OR TMC OR transcranial magnetic stimulation OR tDCS OR transcranial direct-current stimulation OR PET OR position emission tomography OR CT OR computerized tomography OR MEG OR magnetoencephalography). Results were limited to English articles with no restrictions on publication dates, resulting in a wide range of studies identified from as early as 1982 to as recent as 2022 published in peer-reviewed journals searching on titles, abstracts, and keywords. Web of Science resulted in 20 articles, Scopus 34, and PubMed one.

Fifty-five articles were identified of which 18 were duplicates. The remaining 37 articles were screened by title and abstract, with eight deemed not relevant. After reading the full text of the remaining 29 articles, 17 that did not meet the inclusion criteria were eliminated. One article did not provide original data, one provided data that was contaminated by movement artifacts, six did not provide neuroimaging data, three did not provide data based on lucid dreaming, three were reviews, and three were theoretical papers. Finally, 12 articles were included in the analysis.

In addition, one article (Holzinger et al., 2006) was included via the reference list from Baird et al. (2019), bringing the total number of articles to 13. See Figure 1.

Inclusion/exclusion criteria

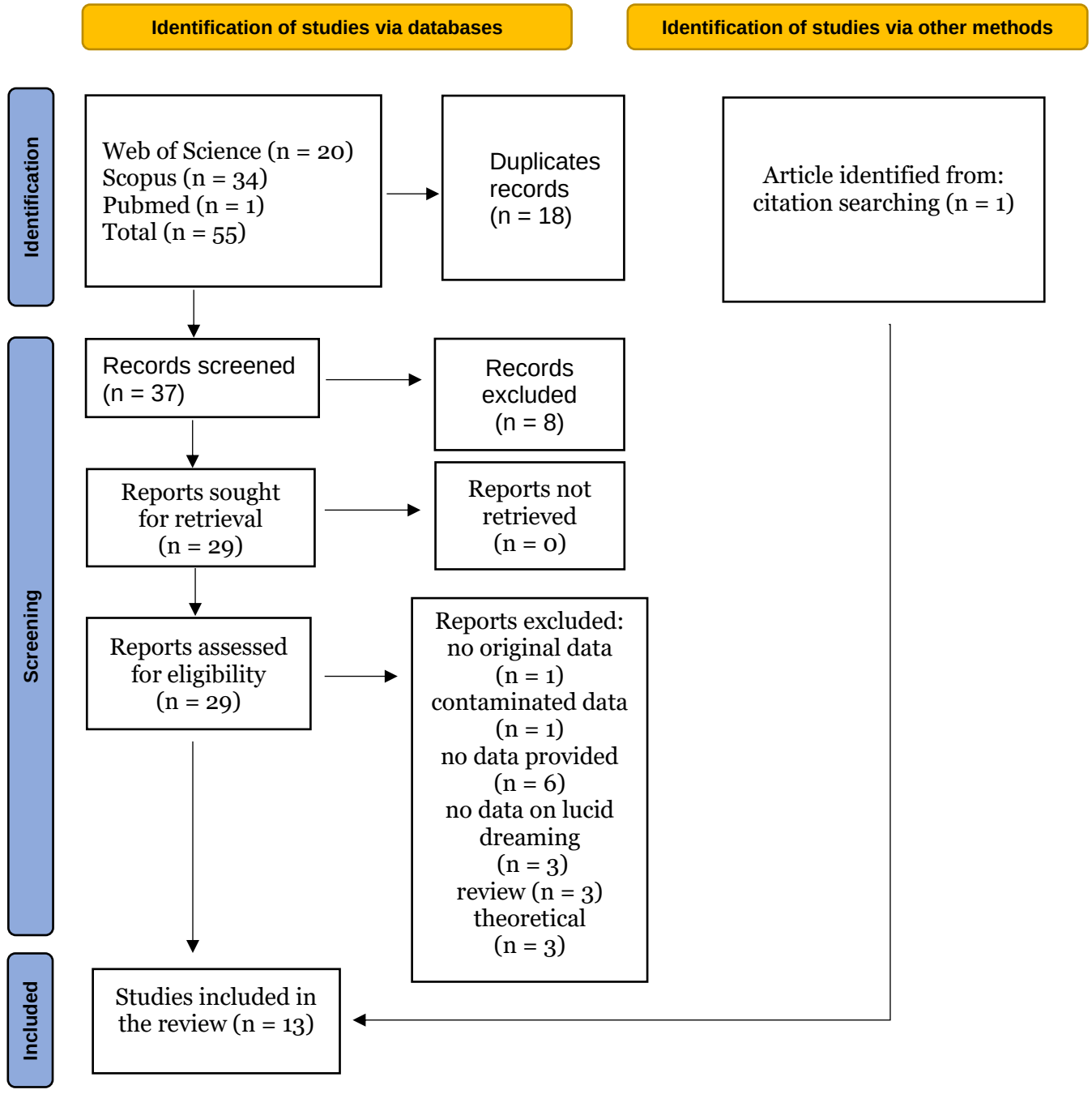
To be included, studies needed to provide neuroimaging data or data based on transcranial current stimulation. Second, they were required to demonstrate the effect of lucid dreaming on the human brain.

Data extraction

Data collection focused on obtaining detailed information about the study participants. This included gender, previous experiences of lucid dreaming, dream recall ability, age, and health status, including any pre-existing medical conditions. The sample size and instrument used to collect the data (brain-imagining method or transcranial current stimulation) were noted. If any induction technique was used, it was documented, along with the comparison condition, brain areas activated during lucid dreaming, and final results.

Figure 1

PRISMA Flow diagram



Page et al. (2021).

Results

Of the 13 articles, three used functional magnetic resonant imaging (fMRI) and ten used EEG. Of the latter, two used electrical stimulation at the scalp to induce lucid dreaming: one used transcranial alternating current stimulation (tACS) and the other used tDCS. See Table 1.

Lucid dreaming was verified either through predetermined eye movement as evaluated by a researcher external to the project or through subjective accounts collected via mentation reports or questionnaires such as the 28-question lucidity and consciousness in dreams scale "LuCiD", which identifies levels of consciousness in dreams (Voss et al., 2013), or the dream lucidity questionnaire "(DLQ)", which evaluates awareness, control, and remembrance in dreams (Stumbrys et al., 2013).

Brain areas identified through fMRI

Baird et al. (2018) compared a control group matched on age, gender, and dream-recall frequency with 14 individuals who had frequent lucid dreams. During MRI scan, subjects were directed to remain awake, still, and relaxed with eyes open. Voxel-based morphometry revealed no difference in gray-matter structure between the frequent lucid dreamers and control group. Investigating resting-state functional connectivity, it was found that the frequent lucid-dreaming group showed increased functional connectivity between the left anterior prefrontal cortex and brain regions including the inferior parietal lobule, middle temporal gyrus, and inferior frontal gyrus, in comparison to the control group. The frequent-lucid-dreaming group demonstrated decreased functional connectivity between the left anterior prefrontal cortex and bilateral insula.

Filevich and colleagues (2015) divided 62 individuals into frequent and non-frequent lucid dreamers based on responses to the LuCiD scale. Participants were instructed to keep their eyes closed during structural data collection. After controlling for age, gender, dream-recall frequency, and intracranial volume, voxel-based morphometry analysis revealed that the high lucidity group exhibited greater gray matter volume in Brodmann areas 9 and 10 (BA9/10) along with the hippocampus, anterior cingulate cortex (ACC), and supplementary motor area. Studies suggest that larger gray-matter volume in BA10 may indicate improved metacognitive ability (Fleming et al., 2010; McCurdy et al., 2013) or monitoring activity (De Martino et al., 2013; Fleming et al., 2012), with shared mechanisms across tasks. Filevich and colleagues conducted an additional experiment to examine the involvement of the same brain areas in thought monitoring. Employing region of interest (ROI)-based analysis, the researchers examined the role of BA9/10 in thought monitoring, with the ACC serving as a control region. The study revealed increased involvement of BA9/10 but not the right ACC during the monitoring task compared to no monitoring task.

Table 1

Summary of results

Article	Participants	Measurement	Comparing	Induction Technique	Result	Brain areas identified
Baird et al. (2018)	N=28 F=18 (age 18-34) novice and frequent lucid dreamers[1]	fMRI	novice and frequent lucid dreamers	none	Frequent lucid dreamers exhibit higher levels of resting-state functional connectivity between key regions of the brain.	prefrontal cortex, bilateral angular gyrus, bilateral middle temporal gyrus, and right inferior frontal gyrus; decreased functional connectivity between the anterior prefrontal cortex and insula
Brylowski et al. (1989)	N=1 F=0 (age 25) frequent lucid dreamer	EEG/LuCiD scale	regular REM sleep and lucid REM sleep in the same subject	none	During lucid REM sleep, there was increased H-reflex suppression compared to regular REM sleep.	no specific brain regions identified
Ogilvie et al. (1982)	N=10 F=5 (age 19-31) persons reporting good dream recall	EEG/ questionnaire	alpha feedback/no alpha feedback, high/low alpha activity in REM sleep, first/second arousal	alpha feedback training	The study shows a correlation between the level of alpha-waves present during REM sleep and the frequency of lucid dreaming reports.	central and anterior regions
Dodet et al. (2015)	narcolepsy N=12 F=7 and cataplexy N=8 F=*not indicated* (age 16 to 40) control N=5 F=3 (age 25 to 40)	EEG	regular REM sleep and lucid REM sleep	none	The study found that, during lucid dream episodes, there is a decrease in brain activity in the delta frequency bands.	frontal and central regions

[1] Frequent lucid dreamers were identified as those having one or more lucid dreams per month (Snyder & Gackenbach, 1988)

Baird et al. (2022)	N=6 F=2 (age not indicated) persons reporting good dream recall	EEG	regular REM sleep and lucid REM sleep	none	Lucid dream episodes were associated with a significant decrease in the activity of low-frequency bands, specifically in the delta and beta waves.	no specific regions identified; decreased activity in the low-frequency brains was found across the entire brain
Filevich et al. (2015)	N=62 F=*not indicated* (age not indicated) novice and frequent lucid dreamers	fMRI/LuCiD scale	novice and frequent lucid dreamers	none	The study indicates that frequent lucid dreamers have a larger gray matter volume in certain areas of the brain.	Brodmann areas 9 and 10, hippocampus, anterior cingulate cortex, and supplementary motor area
Tyson et al. (1984)	N=10 F=5 (age 19-31) persons reporting good dream recall	EEG/questionnaire	lucid dreams, prelucid and non-lucid dreams	five participants were given alpha feedback training	Variance in alpha oscillation power was discovered between pre-lucid dreaming, lucid dreaming, and regular REM sleep.	no brain regions identified
Dresler et al. (2012)	N=4 F=0 (age 27-32) frequent lucid dreamers	fMRI/EEG/ questionnaire	regular REM sleep and lucid REM sleep	none	There was increased activation in brain regions during lucid dreaming.	bilateral precuneus, bilateral inferior and superior parietal lobules, bilateral basal occipitotemporal cortex, left frontopolar cortex, right frontopolar/dorsolateral prefrontal cortex, right cuneus, bilateral lingual gyrus
Stumbrys et al. (2013)	N=19 F=13 (age 21-33) frequent lucid dreamers	EEG/DLQ	control nights and nights when tDCS was used	tDCS	The study found that tDCS stimulation increases the frequency of lucid dream episodes experienced.	dorsolateral prefrontal cortex

Blanchette-Carrière et al. (2020)	N=33 F=22 (age >18) novice and frequent lucid dreamers	EEG/LuCiD scale	control nights and nights when tACS was used	tACS	The effects of 40Hz tACS did not increase the frequency of lucid episodes.	frontal lobe
Leslie and Ogilvie (1996)	N=8 F=4 (age *not indicated*) university students	EEG	stationary and rocking condition	a hammock used to stimulate the vestibular nuclei	When the participants experienced the rocking condition, it resulted in a noticeable increase in alpha-wave activity linked to increased lucidity and self-reflectiveness.	vestibular system
Holzinger et al. (2006)	N=11 F=4 (age 21-37) frequent lucid dreamers	EEG	regular REM sleep and lucid REM sleep	light stimulus (flashing LED)	Lucid episodes were associated with an increase in low beta-wave oscillation.	parietal lobe
Voss et al. (2009)	N=6 F=>1 (age not indicated) undergraduate students	EEG	regular REM sleep and lucid REM sleep	lucidity training	During lucid REM sleep, there was an increase in the power of 40Hz brain waves.	frontolateral and frontal regions

Dresler et al. (2012) carried out a study in which four individuals spent up to six nights in an MRI machine. Although all four were skilled lucid dreamers, only one of them achieved lucid dreaming during the experiment, with two lucid dreams on separate nights verified by predefined eye movements. An fMRI analysis comparing these two lucid dream episodes to non-lucid REM sleep revealed that the lucid dreams led to significant activation in cortical areas including the bilateral precuneus, bilateral inferior and superior parietal lobules, bilateral basal occipitotemporal cortex, left frontopolar cortex, right frontopolar/dorsolateral prefrontal cortex, right cuneus, left frontal eye field, and bilateral lingual gyrus.

Brain activity identified through EEG

Brylowski et al. (1989) studied a single participant who was a proficient lucid dreamer familiar with using eye movement to signal the onset of a lucid dream. This participant spent four nights in a laboratory wearing EEG electrodes. Following each instance of awakening, the participant provided written reports detailing his mental activity. Verification of a lucid dream was based on presence of an eye-movement signal in line with the participant's written report. Eight of the 18 recorded REM sleep periods were identified as lucid REM sleep periods. In the analysis of H-reflexes (a response to low-level electrical stimulation of the afferent nerve fibres in the spinal cord), the polygraph record was divided into five-second epochs to distinguish between regular sleep and lucid REM sleep. Of 2,470 REM epochs (206 min) collected, 150 (12.5 min) were identified as lucid REM. The study found that the mean H-reflex amplitude during lucid REM periods was consistently lower than that during regular REM sleep.

Voss et al. (2009) studied six participants who underwent weekly lucidity training and reported experiencing three or more lucid dreams per week. The participants spent up to five nights in a laboratory where data was collected from 19 electrodes positioned according to the 10/20 system. The results revealed that both lucid and regular REM sleep exhibited heightened activity in delta (1-4Hz) and theta (4-8Hz) frequency bands compared to waking. However, lucid dreams showed additional activation in the 40Hz range, particularly in frontal and frontolateral regions. Lucid dreams displayed increased coherence in the 1-8Hz range, particularly in the frontal and frontolateral regions, resembling patterns observed during waking states. All participants exhibited greater coherence in the frontolateral region during lucid dreaming compared to waking, and higher coherence in the frontal region compared to regular sleep. REM sleep coherences were notably reduced across all frequencies, indicating widespread desynchronization.

Ogilvie et al. (1982) studied ten individuals with strong dream-recall, all of whom reported experiencing several lucid dreams per year. These participants spent up to three nights in the lab with 17 EEG electrons measuring brain activity. Five of the participants were

randomly assigned to the experimental group, which received alpha feedback training (learning to regulate neural activity through deep relaxation, visualization, and breathing techniques). During the study, when alpha-wave activity was at its highest or lowest, measured from central and anterior electrodes C4 and A2, the participants were awakened and asked to describe their dreams. The study revealed that both subject-rated lucid and pre-lucid sleep were associated with higher alpha-wave power and increased synchronization of alpha waves.

Dodet et al. (2015) studied 53 narcolepsy patients and 53 controls matched on age and gender instructed to initiate eye movements during periods of lucid dreaming while monitored with six EEG electrodes. Of 35 REM periods recorded, 14 were lucid REM sleep. The results indicate decreased coherence in the gamma frequency bands during lucid REM compared to regular REM sleep across all electrode sites. Coherence was also lower in the delta band, with reduced coherence in the theta and beta bands between specific electrodes. Further analysis showed an overall decrease in signal strength at frontal and central elections sites: delta band at F7, F8, C3, and C4, alpha at C4, and theta at F8 and C4. Meanwhile, analysis showed decreased power during both lucid and non-lucid REM sleep compared to waking across alpha, beta, and gamma bands.

Baird et al. (2022) analysed data from 28 EEG electrons across six participants with good dream-recall. Of 28 REM sleep periods recorded, 14 included signal-verified lucid dreams. H-reflex was recorded from one subject, with no observed difference between lucid and regular REM sleep. The initial observation of spectral power (breakdown of EEG signals into frequency bands) revealed a significant increase in group average across frontal gamma bands in lucid dreams compared to regular REM sleep, primarily at F7 and F8. However, when segments contaminated with potential saccadic spike artifacts (small bursts of EEG activity not produced by brain activity but resulting from constant minor eye movement) were removed, a decrease in frontal 40Hz frequency was observed in both lucid and REM sleep, with no significant difference between conditions. Analysis across all scalp regions showed a significant decrease in delta and beta frequency bands in lucid vs. regular REM sleep. However, when the number of phasic and tonic segments (EEG segments with and without occurrence of eye movement respectively) during lucid dreaming was matched with baseline REM, only a significant decrease in the delta band was found between conditions. The experiment also found that long-range coherence (interaction between distal cortical areas) was reduced in the delta band during lucid dream episodes compared to regular REM sleep.

Holzinger et al. (2006) monitored 11 experienced lucid dreamers for two nights using four electrodes placed at frontal and parietal regions: F3, F4, P4, and P3. They compared 42 non-lucid REM epochs to 36 lucid REM epochs confirmed by eye signaling and waking

reports. The findings indicate that lucid dreaming led to increased interaction between frontal and parietal regions. The ratio of frontal to parietal beta-1 activity was approximately 1/1.16 during non-lucid dreaming and 1/1.77 during lucid dreaming. Results showed that beta-1 activity (12-16Hz decreased in the frontal region and increased in the parietal region during lucid dreaming. Hemispheric differences between conditions were observed, with the greatest increase occurring in the left parietal lobe while lucid dreaming, although it did not reach statistical significance.

Tyson et al. (1984) analyzed 38 dreams recorded from ten good dream recallers, some being experienced lucid dreamers. Five participants received alpha feedback training. Participants were equipped with EEG electrons and were awakened during REM sleep when their alpha activity was either low or high to give an account of their dreams. The results indicate a distinct pattern of REM alpha activity between dreams enabling researchers to correctly identify 71% of dreams within subjects as prelucid, lucid, or nonlucid. Dreams categorized as non-lucid were found to have relatively low levels of alpha activity at the end and beginning of the REM period, while dreams classified as pre-lucid displayed higher alpha levels at these times. Lucid dreams characterized by moderately low levels of alpha activity at the beginning and end proved to be the most challenging to distinguish.

Leslie and Ogilvie (1996) studied seven individuals with strong dream recall abilities who spent two nights sleeping in a laboratory hammock. One night served as a control condition, while the experiment night involved the hammock being rocked at a frequency of 1Hz. EEG electrodes were used to record activity from the C3 and C4 sites while participants were in REM sleep. They were awakened during REM sleep and asked to report their dream experiences. A total of 45 valid reports were analyzed based on vestibular imagery (sense of body orientation in space), bizarreness, and degree of lucidity. The results reveal a significant difference in degree of lucidity between the stationary and rocking conditions during the early REM periods, but this difference diminished in the late REM periods. This suggests that rocking during the early REM periods led to increased subject-rated lucidity. The rocking condition was associated with heightened vestibular imagery and more bizarre dream reports. While not statistically significant, there was a tendency towards higher alpha and delta activity in the rocking condition.

Transcranial direct and alternating current stimulation

Both studies using electrical stimulation used a sham trial as a control condition. During sham night, experimenters sat up the equipment as on experiment night but without activating the current stimulation.

Blanchette-Carrière et al. (2020) conducted a study with 40 participants, 20 of whom were experienced lucid dreamers. Participants took two 90-minute morning naps while subjected to tACS or no stimulation in a counterbalanced order. The tACS stimulating

electrons (anodes; positively charged electrodes) were placed in the frontal region at F3 and F4, while EEG electrodes were placed in the frontal, central, and occipital regions at Fz, C4, C3, O1, and O2. In the experimental condition, tACS was directed at 40Hz with an intensity of 250 μA five times during 30-second-on, 30-second-off stimulation. Naps were collected from all participants (50 in total): 27 during tACS stimulation, 23 from the control condition. The study found that objectively verified lucid dreams using eye signaling occurred in five out of 27 cases (18.5%) for tACS trials and in four out of 23 cases (17.4%) for sham trials. Experienced lucid dreamers become lucid in three out of 14 cases (21.4%) for tACS trials and four out of 15 cases (26.7%) for sham trials. Subjectively defined lucid dreams, as measured by the LuCiD scale, occurred in 13 out of 27 (48.2%) tACS trials and nine out of 23 (39.1%) sham trials. Among frequent lucid dreamers, the occurrence was six out of 14 times (42.9%) during experimental trials and six out of 15 times (40.0%) during the control condition. The results do not support the hypothesis that frontal 40Hz tACS enhances self-awareness in dreams. Specifically, administration of 40Hz tACS during REM sleep does not lead to an increase in objectively or subjectively defined lucid dreaming.

Stumbrys et al. (2013) studied 19 participants, eleven of whom were frequent lucid dreamers. tDCS was administered at 1mA for 10 minutes to activate the dorsolateral prefrontal cortex during REM sleep. The tDCS stimulating electrodes (anodes) were placed at F3 and F4, with inhibitory electrodes (cathodes) applied to the supraclavicular area. Ten EEG electrodes were placed at frontal, anterior, central, and occipital positions FZ-A1, C3-A2, C4-A1, O2-A1, O1-A2. Participants provided self-ratings based on the DLQ. The study found that dream reports were longer on tDCS nights compared to sham nights. Participants rated their dreams as more lucid on tDCS nights. On tDCS nights, four out of 40 (10%) dream reports were scored as lucid, compared to 3/55 (5.5%) on sham nights. The increase in lucid dreams during tDCS was reported by frequent lucid dreamers only, based on participants' self-ratings.

Discussion

Identifying brain areas associated with lucid dreaming through fMRI, Baird et al. (2018) found increased functional connectivity between the left anterior prefrontal cortex and various brain regions in frequent lucid dreamers, while Filevich et al. (2015) observed greater gray matter volume in such brain regions as BA9/10, the hippocampus, and the ACC in individuals with high trait-lucidity scores. Dresler et al. (2012) identified significant activation in cortical areas during lucid dreams, including the bilateral precuneus and superior parietal lobules.

Through experiments using EEG, Brylowski et al. (1989), studying the correlation between H-reflex amplitude and lucid dreaming, discovered that the average H-reflex amplitude during lucid REM was consistently lower than during regular REM sleep. Voss et

al. (2009) found unique patterns of brain activity during lucid dreams compared to regular REM sleep, particularly heightened activation of the 40Hz frequency band in frontal and frontolateral regions, as well as increased coherence resembling waking states. Ogilvie et al. (1982) stressed the connection between alpha-wave power and synchronization with both lucid and pre-lucid sleep. Dodet et al. (2015) found reduced coherence in gamma frequency bands during lucid REM sleep compared to regular REM sleep across all electrode sites, as well as diminished power in various frequency bands between electrode sites. Baird et al. (2022) found alterations in EEG spectral power across frequency bands during lucid dreams compared to regular REM sleep, but when segments contaminated with artifacts were removed, they observed little difference.

Holzinger et al. (2006) observed increased interaction between frontal and parietal regions during lucid dreaming, with changes in particular beta-1 activity. Tyson et al. (1984) found that patterns of alpha activity were different in pre-lucid, lucid, and non-lucid dreams. Leslie and Ogilvie (1996) showed that stimulating the vestibular system during REM sleep had an impact on the content and degree of dream lucidity based on bizarreness reported by participants.

Research using transcranial alternating and direct current stimulation by Blanchette-Carrière et al. (2020) and Stumbrys et al. (2013) explored the impact of stimulation on inducing lucid dreams. While Blanchetta-Carrière did not find that frontal 40Hz tACS enhanced self-awareness in dreams, Stumbrys reported longer dreams and increased lucidity ratings when stimulating the dorsolateral prefrontal cortex with tDCS during REM sleep.

The findings suggest that, while there is considerable variability in the brain regions associated with lucid dreaming across studies, the frontal region plays a key role. Multiple studies, including those conducted by Baird et al. (2018), Filevich et al. (2015), and Dresler et al. (2012), report increased functional connectivity, increased gray matter, and increased activity in multiple frontal areas during lucid dreaming. Voss et al. (2009) found increased activity and coherence in frontal regions compared to regular REM sleep and waking.

Several studies noted increased alpha activity, particularly in the frontal region, during lucid dreaming. Ogilvie et al. (1982) and Tyson et al. (1984) both observed heightened alpha-wave activity in the frontal regions, with Tyson suggesting a link between alpha-wave activity and degree of lucidity. Leslie and Ogilvie (1996) found that stimulating the vestibular nuclei led to increased lucid dream reports and increased alpha-wave activity. The difference in alpha-wave activity between lucid dreaming and pre-lucid dreaming observed by both teams raises questions about the role of alpha-wave activity in achieving and maintaining lucidity.

The activation of the frontal lobe during lucid dreaming is not surprising, given that alpha-wave activity is the hallmark of the unconscious or pre-conscious mind, with

increasing prominence of beta activity marking the fully awake and reflectively conscious mind, even as the unconscious mind continues working away in the background. This highlights the strong relationship between consciousness and lucid dreaming.

Three of four studies that measured activity in the parietal region found a link to lucid dreaming. Dresler et al. (2012) and Holzinger et al. (2006) observed increased activity in the parietal region during lucid dreaming. Baird et al. (2018) and Holzinger observed increased interaction between frontal and parietal regions during lucid dreaming.

Limitations

Analysis of the 13 studies presents challenges to providing a cohesive account of brain regions and neural activity during lucid dreaming. These challenges emerge from variations in methodology, such as comparing lucid dreams with regular REM sleep between subjects, within subjects, or among groups of frequent and non-frequent lucid dreamers. Discrepancies in the number of EEG electrodes used, from four to 28, and the lack of information regarding electrode placement further complicates analysis.

Only some of the EEG studies (Blanchette-Carrière et al., 2020; Dodet et al., 2015; Holzinger et al., 2006; Stumbrys et al., 2013; Voss et al., 2009) collected data from EEG electrodes placed according to the standard, internationally recognized 10/20 system. This suggests cautions interpretation of the data provided by the remaining studies (Baird et al., 2022; Brylowski et al., 1989; Leslie & Ogilvie, 1996; Ogilvie et al., 1982; Tyson et al., 1984).

There were also differences in data analysis. Baird et al. (2022) was the only EEG study that removed potential saccadic spike artifacts and adjusted the number of tonic and phasic segments of lucid dreams to match baseline REM sleep.

Future research

Further research is necessary to establish the connection between lucid dreaming and higher-order processes such as conscious awareness and self-reflection. Simply comparing lucid dreaming to a control condition is not sufficient to the task. Future researchers are advised to frame their inquiries around specific higher-order processes linked to distinct brain regions.

A significant and unexpected finding was the potential link between frontal and parietal regions during lucid dreaming. This is noteworthy because the frontal region has been consistently associated with conscious processes and identified in multiple studies as involved in lucid dreaming. This raises the importance of exploring the role of the parietal region in lucid dreaming and in relation to conscious processes.

Lucid dreaming is more prevalent in children and diminishes with age. The frontal region is not fully developed until adulthood, challenging the constant emphasis on the frontal region to lucid dreaming. This makes it all the more crucial to understand the role of the parietal lobe.

Although this thesis made a search across three databases with a comprehensive search query, only a small fraction of the studies using neuroimaging to investigate the neural correlates of lucid dreaming were obtained. Future systematic reviews should include a larger number of databases.

Ethical issues

A number of the studies (Brylowski et al., 1989; Holzinger et al., 2006; Ogilvie et al., 1982; Tyson et al., 1984) did not report obtaining informed consent from participants or ethical approval from a review board or ethics committee. Baird et al. (2018) and Baird et al. (2022) secured written informed consent from each participant and ethical approval from the University of Wisconsin–Madison Institutional Review Board and Stanford University Institutional Review Board respectively. They report conducting their studies in compliance with the Declaration of Helsinki. Dodet et al. (2015) and Filevich et al. (2015) report receiving informed consent from all participants and approval from an ethics committee. Voss et al. (2009), Dresler et al. (2012), and Leslie and Ogilvie (1996) only report obtaining informed consent.

Both Blanchette-Carrière et al. (2020) and Stumbrys et al. (2013) used transcranial electrical stimulation aimed at temporarily altering brain waves. Studies were approved by an ethics committee, and informed consent was obtained from each participant. However, raising the question of whether tDCS/tACS stimulation might, perhaps only in rare circumstances, lead to lasting changes even though these technologies are considered perfectly safe.

Conclusion

This thesis aimed to identify the brain regions and patterns of neural activity responsible for lucid dreaming, and how they relate to higher-order processes (which brain regions(s) are responsible for lucid dreaming?, p. 7). The majority of studies found increased activation in frontal regions. Several found a link between the parietal region and lucid dreaming. This thesis has effectively addressed the brain regions(s) associated with lucid dreaming. Further research is needed to establish the nature of the link between lucid dreaming and specific conscious processes (which higher-order processes are implicated in lucid dreaming?, P. 7).

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