Behavioral/Cognitive

Metacognitive Mechanisms Underlying Lucid Dreaming

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Lucid dreaming is a state of awareness that one is dreaming, without leaving the sleep state. Dream reports show that self-reflection and volitional control are more pronounced in lucid compared with nonlucid dreams. Mostly on these grounds, lucid dreaming has been associated with metacognition. However, the link to lucid dreaming at the neural level has not yet been explored. We sought for relationships between the neural correlates of lucid dreaming and thought monitoring.

Human participants completed a questionnaire assessing lucid dreaming ability, and underwent structural and functional MRI. We split participants based on their reported dream lucidity. Participants in the high-lucidity group showed greater gray matter volume in the frontopolar cortex (BA9/10) compared with those in the low-lucidity group. Further, differences in brain structure were mirrored by differences in brain function. The BA9/10 regions identified through structural analyses showed increases in blood oxygen level-dependent signal during thought monitoring in both groups, and more strongly in the high-lucidity group.

Our results reveal shared neural systems between lucid dreaming and metacognitive function, in particular in the domain of thought monitoring. This finding contributes to our understanding of the mechanisms enabling higher-order consciousness in dreams.

Key words: BA10; brain structure; introspection; lucid dreaming; metacognition

Introduction

Metacognition is the ability to reflect on and report one's own mental states (Schooler, 2002). Unlike diverse cognitive processes during wakefulness, dreaming is not generally accessible to metacognitive monitoring (Windt and Metzinger, 2007). Rapid eye movement (REM) sleep is the sleep stage most strongly associated with dream mentation. During REM sleep, deactivations of the dorsolateral prefrontal and frontopolar cortices have been suggested to underlie decreases in metacognitive monitoring, such as restricted volitional capabilities, impaired critical thinking, and a complete lack of insight into the true state of mind (Hobson and Pace-Schott, 2002). In contrast to REM sleep, the rare condition called lucid dreaming allows some dreamers to regain their reflective capabilities and become metacognitively aware of their current state of consciousness.

Although standard polysomnographic criteria of REM sleep are maintained and REM sleep muscle atonia prevents overt motor behavior, lucid dreamers are able to communicate their state by predefined volitional eye movements, clearly discernable in the electrooculogram (Hearne, 1978; La Berge et al., 1981). Two studies characterized brain activity during lucid dreaming episodes, using this approach to identify their onset. Voss et al. (2009) found that the frequency spectrum of electroencephalographic activity in the frontal areas during lucid dreaming presents "hybrid" features of both REM sleep and wakefulness. Also, Dresler et al. (2012) showed greater blood oxygen level-dependent (BOLD) activity in right dorsolateral prefrontal cortex, and bilateral frontopolar areas, in lucid dreams as compared with REM sleep. Hence, metacognitive insight into the dreaming state was consistently characterized by increased activation in prefrontal cortical regions, which show activation decreases during normal REM sleep (Maquet et al., 1996).

During wakefulness, prefrontal areas have been linked to metacognitive evaluation. For example, visual metacognitive ability has been associated with gray matter (GM) measures in Brodman Area (BA) 10 of the frontopolar cortex (Fleming et al., 2010; McCurdy et al., 2013). Importantly, as Noreika et al. (2010) have noted, a direct relationship between the neural bases of lucid dreaming and metacognition is often assumed, but has never been explicitly tested. In particular, it is currently unknown whether interindividual variability in frontopolar cortex neuroanatomy, which underlies metacognitive variability during wakefulness, is also connected to metacognitive processes during sleep, namely lucid dreaming.

Frequent lucid dreamers are rare (Schredl and Erlacher, 2011), which makes it difficult to find participants that will be able to gain and signal lucidity in the laboratory. However, lucid dreaming can be studied even during wakefulness, if some of its enabling mechanisms are stable and trait-like. In fact, associations between dream lucidity and personality traits (Blagrove and Hartnell, 2000; Patrick and Durndell, 2004; Schredl and Erlacher, 2004) or behavioral performance (Blagrove et al., 2010) have

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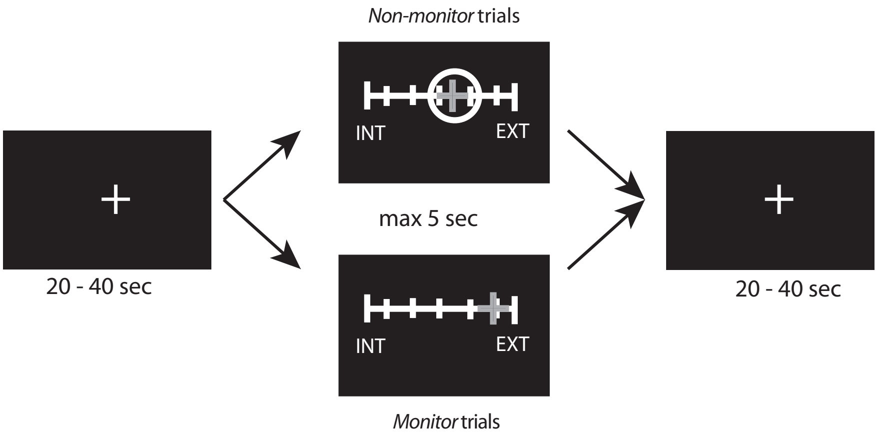

Figure 1. fMRI thought-monitoring task. In the nonmonitor condition participants slid a cursor sideways along a scale to match a target circle. In the monitor condition, participants slid the cursor along the scale to indicate how internally oriented or externally oriented their thoughts were (see Materials and Methods). The two conditions were matched for visual and motor features, but differed in the thought-monitoring component.

been reported. Here we characterized interindividual differences across groups of study participants with different levels of lucid dreaming ability. We hypothesized that prefrontal GM volume is positively associated with experienced dream lucidity, and that brain areas associated with high lucidity show increased BOLD activity during metacognitive monitoring.

Materials and Methods

Participants

We recruited participants from a participant database by telephone contact. The experiment was framed as "The neural bases of metacognition," and we did not mention our interest in lucid dreaming at the time of recruitment. Sixty-nine healthy participants took part in the experiment (18–37 years of age, 34 female) after giving informed consent. Five participants did not complete the lucid dreaming questionnaire and one further participant did not respond to any of the trials in the thought-monitoring task, resulting in 63 participants included in the final analyses. All participants were right handed and had no history of psychiatric disease in the past year. The ethics committee of the German Society of Psychology (Ethikkommission der Deutschen Gesellschaft für Psychologie) approved all procedures.

Procedure

MRI scanning: thought-monitoring task

Following acquisition of T1-weighted structural images, participants completed two 11 min runs of a thought-monitoring task (adapted from Smallwood et al., 2008; Christoff et al., 2009). Each of the runs was divided into two conditions: "nonmonitor" and "monitor." The nonmonitor condition appeared first and acted as a control for visual and motor components of the monitor condition. Because we were only interested in investigating interindividual differences, the order of the conditions was the same for all participants. There were in total 20 trials per condition.

A sign at the start of the block indicated the onset of each condition. A white fixation cross then appeared over a black background (Fig. 1). After an interval of 20–40 s (uniformly distributed), a visual analog scale appeared on the screen. The extremes of the scale were labeled "INT" and "EXT," for "internally oriented thoughts" and "externally oriented thoughts" respectively. To prevent anticipation, the location (right/left) of the INT and EXT signs varied randomly across trials. As soon as the scale appeared, subjects pressed either one of the two right-hand buttons to move a red cursor rightward or leftward. They then used their left hand on a button box to submit their response. In the nonmonitor condition, participants moved the cursor to match a target position marked by a white circle, ignoring the INT and EXT signs. To prevent anticipation, the target and starting positions of the cursor were fully randomized. In the monitor condition, no circle appeared. Instead, participants moved the cursor along the scale to indicate how externally oriented or internally oriented their thoughts were, immediately before the appearance of the scale. We defined externally oriented thoughts as those related to the immediate external environment, such as the scanner noise, the visual aspects of the stimuli, etc. In contrast, we defined internally oriented thoughts as those that were not immediately related to the external environment, such as planning for the day ahead, or remembering past events. We encouraged participants to thoroughly evaluate their own thoughts, to provide continuous judgments along the internal–external dimension, as opposed to giving binary responses. The scale remained on the screen until participants submitted their response, or for a maximum response time of 5 s. Participants practiced the task outside the scanner and were given time to ask questions, until they felt comfortable with it.

Questionnaires

After the scanning session, we briefed participants on lucid dreams. We explained that lucid dreaming means to become aware that one is dreaming, within a dream. We informed participants that although not everybody is able to experience lucid dreams, it is not a rare phenomenon. We then gave each participant a link to an online survey.

The survey included a question related to the general (nonlucid) dream recall frequency. Possible answers were "almost every morning," "more than once a week," "2–3 times per month," "about once a month," "less than once a month," or "never". The survey also included two different lucidity scales. First, a single question inquired about the frequency of lucid dreams (Schredl and Erlacher, 2004). Possible answers were "More than once a week," "about once a week," "2–3 times per month," "about once a month," "about 2–4 times per year," "about once a year," "less than once a year" or "never," Second, the survey included a questionnaire on lucid dreaming, the LuCiD scale (Voss et al., 2013), which addresses dimensions of insight, control, through, memory, dissociation, positive emotion, negative emotion, and realism in dreams. We asked participants to complete the LuCiD scale, referring to their "most recent, most lucid dream," We computed the LuCiD score as the simple sum of all items. From this score we excluded those items related to negative emotion and realism, because they are not unique to lucid dreams, but common to both lucid and nonlucid dreams (Voss et al., 2013). Although the LuCiD scale measures the key aspects of dream lucidity in detail, it lacks a measure of how frequent these dreams are. To measure these two aspects together, we asked participants to complete the LuCiD scale every morning for 1 week, and to complete it each day referring exclusively to their dream of the preceding night, if they could recall it. We aimed at obtaining a measure of lucidity that was specific to the week immediately after scanning. The actual number of times that participants completed the survey was very heterogeneous, ranging from a single completed survey, to a maximum of 18 times. The survey began with a question asking whether participants recalled their dreams of the preceding night. Only in case that they did, the LuCiD scale was delivered. The heterogeneity in the number of response instances suggests that these data may be confounded with both dream recall frequency and, more importantly, with attitudes toward dream lucidity. Consequently, we did not base our analyses on these measures, but on a combination of the LuCiD score and lucid dreaming frequency scores: we computed a standardized sum score of the LuCid and frequency scores. As this composite score assesses both quality and quantity of lucid dreaming capability, we call this measure "trait-lucidity."

The survey additionally included a rumination and self-reflection questionnaire (Trapnell and Campbell, 1999), two questionnaires on public and private self-consciousness (Fenigstein et al., 1975; Grant et al., 2002), and a visual imagery scale (Marks, 1973). Public self-consciousness included items such as, "I am concerned about what other people think of me." Private self-consciousness included items such as "I reflect about myself a lot," and the self-reflection questionnaire included "I love analyzing why I do things." Participants responded to all items on a six-point scale, ranging from 1 (strongly disagree) to 6 (strongly agree).

MRI data acquisition parameters

We acquired images on a 3 T Magnetom Trio MRI scanner system (Siemens Medical Systems) using a 12-channel radiofrequency head coil and structural images using a three-dimensional T1-weighted magnetization prepared gradient-echo sequence based on the ADNI protocol [www.adni-info.org; repetition time (TR) = 2500 ms; echo time (TE) = 4.77 ms; TI = 1100 ms, acquisition matrix = 256 × 256 × 176, flip angle = 7°; 1 × 1 × 1 mm voxel size]. We asked participants to keep their eyes closed during the structural data collection.

We collected functional images using a T2*-weighted echo planar imaging (EPI) sequence sensitive to BOLD contrast (TR = 2000 ms, TE = 30 ms, image matrix = 64 × 64, FOV = 216 mm, flip angle = 80°, voxel size 3 × 3×3 mm^3, 36 axial slices). We presented visual stimuli in the scanner through Visuastim digital video goggles (Resonance Technology). We collected responses using a four-button bimanual response box (Current Designs).

MRI data processing and analysis

Voxel based morphometry. We processed anatomical images with VBM8 (http://dbm.neuro.uni-jena.de/vbm), incorporated into the SPM8 toolbox (http://www.fil.ion.ucl.ac.uk/spm). We respected the default parameters for image preprocessing. The VBM8 toolbox involves bias correction, tissue classification, and affine registration. We used the affine registered GM and white matter (WM) segments to build a customized DARTEL (diffeomorphic anatomical registration through exponentiated lie algebra) (Ashburner, 2007) template. We then created warped GM and WM segments. We applied modulation to preserve the local amount of a particular tissue during geometrical transformation by dividing voxel values in the segmented images by the Jacobian determinants derived from the spatial normalization step. In effect, the analysis of modulated data tests for regional differences in the absolute amount (volume) of GM. Finally, we smoothed images with a kernel of 8 mm full-width at half-maximum (FWHM). For statistical analysis, we ran whole brain paired *t* tests comparing GM volume between lucidity groups. We thresholded the resulting maps with $p < 0.001$ and the statistical cluster extent threshold was corrected for multiple comparisons combined with a nonstationary smoothness correction (Hayasaka et al., 2004).

fMRI data processing and analyses. We excluded the first four volumes of all EPI series from the analysis to allow the magnetization to approach a dynamic equilibrium. We applied slice-time correction and realignment to all EPI sets. A mean image for all EPI volumes was created, to which we spatially realigned individual volumes by means of rigid body transformations. We coregistered the structural image with the mean image of the EPI series. We normalized the structural T1 image to the Montreal Neurological Institute (MNI) template, applied the normalization parameters to the EPI images to ensure an anatomically informed normalization. Finally, we smoothed images with a kernel of 8 mm FWHM.

We defined reaction times (RTs) as the earliest movement of the cursor, and movement times (MTs) as the time of the button press to submit the response. In trials in which no cursor movement was present (presumably because the starting position of the cursor was exactly the target position); the MT was taken as the RT. We ran statistical analyses at the subject level using a general linear model (GLM). We modeled each appearance of the visual scale (each trial) as a discrete event, with a duration given by the total MT. The resulting vectors were convolved with a canonical hemodynamic response function and its temporal derivatives to form the regressors in a design matrix. We used a high-pass filter of 128 s to remove low-frequency drifts in the time series data. We also included in the GLM realignment parameters in all six dimensions to account for variance associated with head motion. Statistical parameter estimates were computed separately for each voxel for all columns in the design matrix, and contrasted to test for main effects, at the within-participant level. The resulting contrast images were then entered as input images at the second (between-participant) level, to test for main effects of condition.

We used the Marsbar toolbox (v0.43, http://marsbar.sourceforge.net) to build regions-of-interest (ROIs) and extract BOLD signal estimates. We used MRIcron (http://www.mccauslandcenter.sc.edu/mricro/mricron) to report and display fMRI results.

Stimuli and statistical testing

Stimuli and tasks were presented with MATLAB version r2012a (MathWorks) using the Psychophysics Toolbox version 3.0 (Brainard, 1997; Kleiner et al., 2007) and the COGENT 2000 toolbox (http://www.vislab.ucl.ac.uk/cogent.php). We computed statistical analyses with SPSS 20, (IBM) and R, version 3.0.3 (R Core Team, 2013).

Results

VBM results: lucid dreaming

To identify the neural bases of lucid dreaming, we median split participants into two groups according to their trait-lucidity score (high- and low-lucidity, $n = 31$ in each group). We excluded one participant from the analyses because their score matched the median trait-lucidity score. We confirmed that the results remained largely unchanged when we included this participant randomly in either lucidity group. We then compared the brain structure of the two lucidity groups using voxel-based morphometry (VBM). Using age, gender, general (nonlucid) dream recall frequency, and total intracranial volume as covariates of no interest, we found that the high lucidity group presented greater GM volume in two separate clusters within BA9/10 [peak MNI: (4, 57, 31), uncorrected cluster extent (k) = 87 and (−30, 51, 6), $k = 314$]. We also found GM volume in hippocampus bilaterally (peak MNI: (−21, −31, −3), $k = 430$ and (21, −31, −3), $k = 280$], and two additional clusters, one in right anterior cingulate cortex [ACC; peak MNI:(10 48 9), $k = 192$] and in left supplementary motor area [SMA, peak MNI: (−15 14 67), $k = 302$]. All clusters were corrected for nonstationary smoothness (Hayasaka et al., 2004) and minimum expected cluster extent ($k = 83$). Greater GM volume in BA10 has been associated with greater metacognitive ability in the visual domain (Fleming et al., 2010; McCurdy et al., 2013). In addition, this area has been related to monitoring activity (Fleming et al., 2012; De Martino et al., 2013). This raises the intriguing possibility that lucid dreaming might in fact rely on some core metacognitive mechanisms shared across different metacognitive tasks. To test this hypothesis, we evaluated whether the areas in BA9/10 that we identified are involved in thought monitoring processes (Fig. 2).

Monitoring task: behavioral results

To rule out any behavioral differences between the two lucidity groups, we examined the distribution and speed of responses in the monitor and nonmonitor conditions, for each group. We first examined the distribution of responses along the internal-external axis in the monitor condition (Fig. 3*A*). Aggregated responses for participants in each group were uniformly distributed along the internal-external continuum, with a small dip in the middle values, suggesting that participants tended to consider their thoughts as "mostly internal" or "mostly external." Importantly, there were no overt differences between the two lucidity groups.

We then calculated mean RTs (first time of movement) and MTs (time to click) for each condition, separately for the high

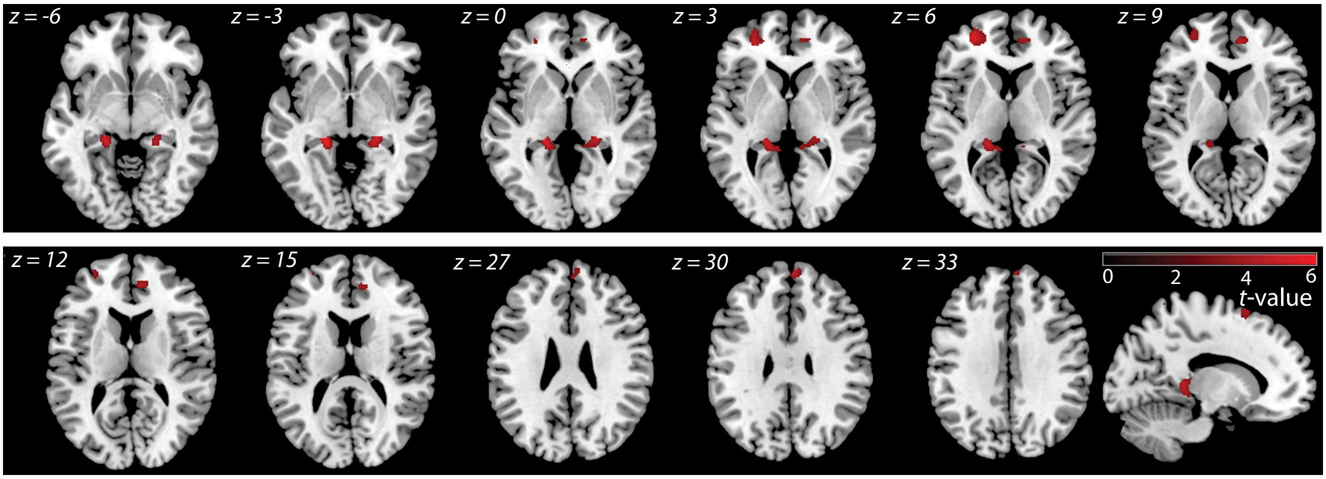

Figure 2. VBM differences between the two lucidity groups. The high-lucidity group showed greater GM volume in two separate clusters within BA9/10, in right ACC, left SMA and hippocampus bilaterally. Results are corrected for minimum cluster extent and nonstationary smoothness (Hayasaka et al., 2004).

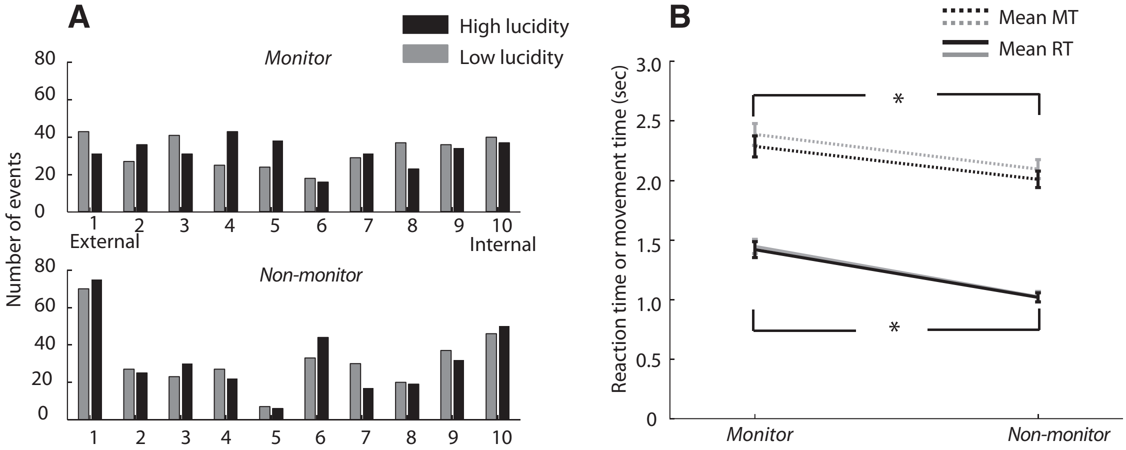

Figure 3. Behavioral results in the thought-monitoring task ***A***, Distribution of responses for the thought-monitoring task on the continuous internal– external scale for each of the lucidity groups. ***B***, Mean RTs (solid lines) and MTs (dashed lines) for the monitor and nonmonitor conditions. Error bars represent SEM, and asterisks indicate significant differences ($p < 0.05$).

lucidity and low lucidity group (Fig. 3*B*). We analyzed RTs and MTs separately. As expected, a two-way mixed effects ANOVA on the RTs with the factors of condition (monitor/nonmonitor) and lucidity (high/low) revealed a significant effect of condition ($F_{(1,60)} = 103.043$, $p < 0.001$) with longer RTs in the monitor condition as compared with the nonmonitor condition. This difference might represent the RT cost of thought monitoring. Importantly, there was no significant effect of lucidity ($F_{(1,60)} = 0.021$, $p = 0.884$) or condition *x* lucidity interaction ($F_{(1,60)} = 0.038$, $p = 0.846$).

The same was true for a two-way mixed ANOVA on the MTs, where monitor MTs were significantly longer than nonmonitor MTs ($F_{(1,60)} = 19.436$, $p < 0.001$), but there were no significant differences between lucidity groups ($F_{(1,60)} = 0.753$, $p = 0.389$) or a condition *x* lucidity interaction ($F_{(1,60)} = 0.001$, $p = 0.976$).

Because we found no significant RT or MT differences between lucidity groups, we sought for differences in the pattern of BOLD activity between the groups, which cannot simply be explained by behavioral differences.

Monitoring-related BOLD activity

We conducted a ROI-based analysis to test whether the areas within BA9/10 identified in the VBM analysis are involved in thought monitoring processes. As a control region, we included the ACC cluster identified in the VBM analysis, as it lies within an anatomically distinct region on the frontal cortex for which no prominent role in metacognition has been reported. We first built three spherical, 5 mm ROIs, centered on the peak voxel of each of the three prefrontal clusters identified by VBM. We then extracted percentage signal change in BOLD activity (relative to the implicit baseline) for each condition separately, and for each ROI (Fig. 4). To identify which of these areas show a significant effect of condition in BOLD activity, we three independent mixed effects 2 × 2 ANOVAs, one in each of the individual ROIs, with the factors of condition and lucidity. As expected, we found significant effects of condition in the two ROIs located within BA9/10 [peak MNI: (−30 51 6): $F_{(1,60)} = 9.490$, $p = 0.003$ and peak MNI: (4, 57, 31), $F_{(1,60)} = 5.995$, $p = 0.017$]; but not in the ROI included in right ACC [peak MNI: (10 48 9), $F_{(1,60)} = 4.442$, $p = 0.235$]. Together, these results show that the BA9/10 ROIs that showed greater GM volume for the high-lucidity group as compared with the low-lucidity group are also differentially involved in thought monitoring activity. Importantly, this is not a general effect, but is specific to BA9/10.

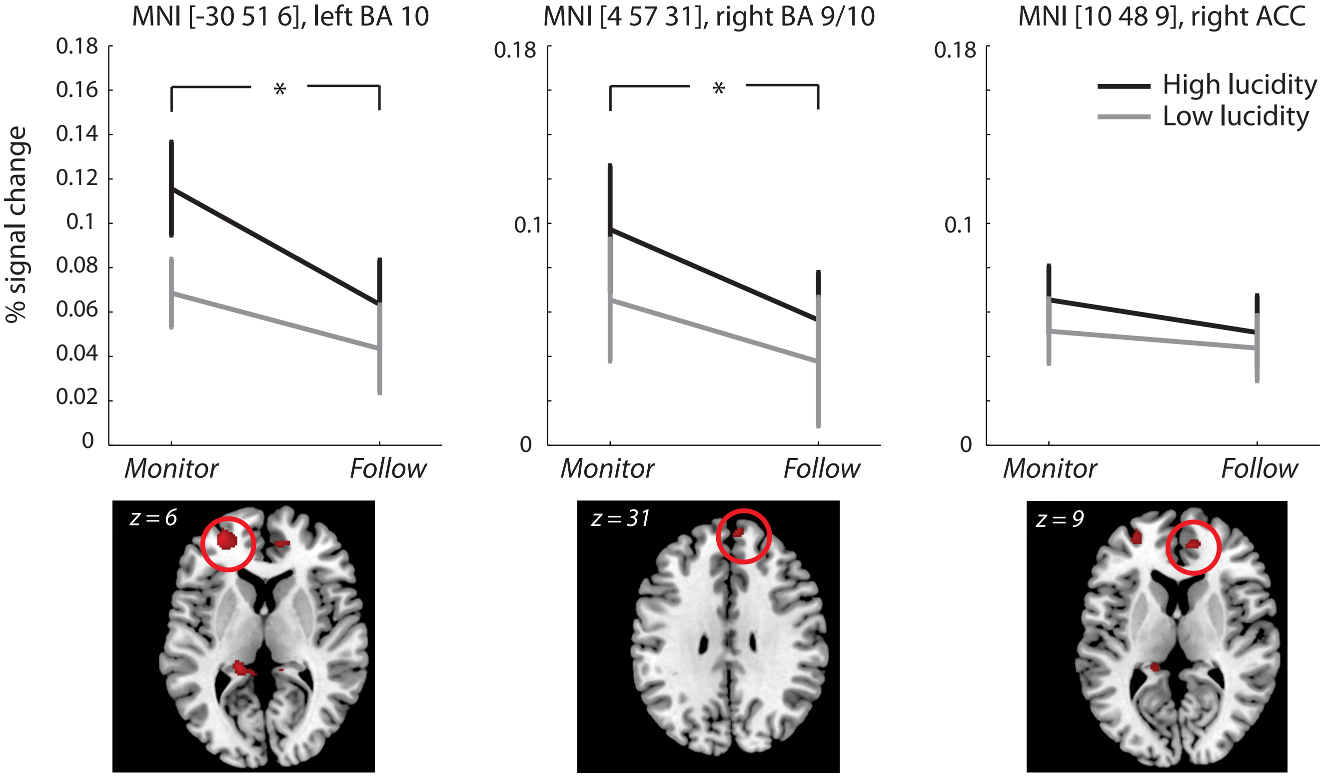

Figure 4. fMRI results in the thought-monitoring task. Extracted percentage signal change from a spherical 5 mm ROI around the peak voxel of each of the three clusters within frontal cortex (bottom displays the cluster from which the spherical ROIs was built). Error bars represent SEM, and asterisks indicate significant differences ($p < 0.05$).

Discussion

Lucid dreaming has often been related to metacognition (Kaiian, 1994; Kahan, 2001; Hobson and Voss, 2011). To our best knowledge, however, no previous study has tested a link between lucidity and metacognitive ability at the neural level. Here, we compared two groups of participants, split according to their score in a validated lucid dreaming questionnaire (Voss et al., 2013). First, we found that participants in the high-lucidity group had greater GM volume in BA9/10 compared with those in the low-lucidity group. Moreover, a ROI defined a priori around the peak GM difference voxel showed greater BOLD signal during a thought-content monitoring condition as compared with a control condition that required no thought monitoring, but controlled for low-level visual input and motor output. This suggests that the areas in BA9/10 identified by structural analyses play a role in second order monitoring activity. In addition, the high lucidity group showed a trend toward stronger difference between the monitor and nonmonitor conditions compared with the low-lucidity group. This suggests that the corresponding patterns of brain activity might be more distinct between conditions for participants in the high-lucidity group than in those participants in the low-lucidity group. Together, these results support our main hypothesis and show, for the first time, a neural link between dream lucidity and metacognitive function.

Role of BA9/10 in metacognition

Ample evidence supports a metacognitive role for the frontal pole. First, it has been associated with multiple, abstract high-order functions, ranging for example from organization of working memory contents (Bor et al., 2003) to multitasking and theory of mind (Roca et al., 2011). In one influential view, BA10 is at the highest point of a gradient, and processes information that is both more abstract (Badre and D'Esposito, 2009) and higher in an action-planning hierarchy (Koechlin et al., 2003). BA9/10 have been shown to subserve self-reflection (Johnson et al., 2002) and BA10 has been proposed to allow for the conscious switching between internally and externally directed cognition (Burgess et al., 2007). Two studies (Fleming et al., 2012; McCurdy et al., 2013) linked GM volume in BA10 with performance in visual metacognition tasks. In line with the suggestion that metacognitive ability is a uniquely human trait (Frith, 2012), the frontopolar cortex is significantly larger in humans than in other primate species (Semendeferi et al., 2001) and has even been suggested to be a distinctively human brain structure. Of note, striking similarities between brain areas activated during lucid dreaming and those anatomically most pronounced in humans have been highlighted before (Dresler et al., 2014a). In particular, electrical brain stimulation data demonstrated that the induction of frontal activity facilitates lucid dreaming using 40 Hz tACS (Voss et al., 2014; see also Stumbrys et al., 2013); and fMRI data demonstrated increased BA9/10 activity to be related to dream lucidity (Dresler et al., 2012). Clinically, metacognitive insight during dreaming and during pathological conditions, such as psychosis shows remarkable anatomical overlap (Dresler et al., 2014b). In sum, our results are consistent with the literature, and suggest BA10 as a candidate mediator of metacognition, operationalized here as thought monitoring in general, and lucid dreaming ability in particular.

Because of the specific nature of the thought-monitoring task, it is important to be cautious in interpreting the generality of the metacognitive process. Specific task demands might have been particularly similar to the process of gaining dream lucidity, and might mislead us to suggest a broad metacognitive mechanism.

Role of hippocampus in metacognition

In addition to the BA9/10 area, we found that high lucidity was associated with greater GM volume in left hippocampus. Although interesting, our result is preliminary, and only allows us to speculate on the possible involvement of hippocampus in lucid dreaming. In contrast to the diversity of metacognitive domains that have been associated with structure or function in frontal pole areas, hippocampal involvement in metacognitive monitoring is typically restricted to metamemory tasks. Greater BOLD signal levels in hippocampus have been found in comparisons of feeling-of-knowing versus confidence and familiarity judgments (Chua et al., 2009) and high confidence compared with low-confidence judgments (Yonelinas et al., 2005; Chua et al., 2006; Kuchinke et al., 2013). In addition, volume in both left hippocampus and amygdala has been found to correlate with total word count of dream reports, and dream bizarreness and vividness (De Gennaro et al., 2011). Thus, the joint involvement of hippocampus in both high confidence situations and dream recall makes it a plausible player in dream lucidity. We speculate that greater hippocampal GM allows for a better discrimination between high and low-confidence states and helps to provide certainty about the fact that one is dreaming. This certainty allows the dreamer to both sustain the reflective state, and gain volitional control.

Importantly, this interesting finding also highlights the notion that metacognitive monitoring does not depend exclusively on a single prefrontal-dependent mechanism but likely relies on a combination of factors.

Trait stability of dream lucidity

Here we based our analyses on the unbiased combination of two different measures of dream lucidity. On the one hand, the LuCiD questionnaire measured detailed qualitative aspects of the "most recent, most lucid" dream, with higher scores corresponding to dreams that more strongly incorporated characteristic aspects of dream lucidity, such as for example memory of waking life, insight into the dream state and control of dream events. On the other hand, lucid dream frequency measured exclusively how frequently dreamers gained "some" degree of lucidity, independently of the specific dream contents. We assumed that these measures represented stable characteristics of each individual. In what follows, we ask whether it is valid to assume that lucidity is a stable trait, and if this assumption might have led to an overestimation of the effects.

Research on personality and individual differences has described associations between frequency of lucid dreams and personality traits. Schredl and Erlacher (2004) have shown that although lucid dreaming frequency does not appear to correlate with any of the "big five" personality dimensions, it is associated with subdimensions of the openness to experience personality factor, namely absorption and imagination. Also interestingly, associations between lucid dream frequency and internality in locus of control scales have been reliably found (Blagrove and Tucker, 1994; Blagrove and Hartnell, 2000; Patrick and Durndell, 2004). Additionally, the comparison between participants with high and low dream recall frequency (not necessarily lucid) has revealed differences in brain function. Eichenlaub et al., (2014a) have shown larger brain reactivity to one's own name in fronto-central areas, (Ruby et al., 2013) and stronger resting state activity in temporoparietal junction and medial prefrontal cortex, areas thought to be involved in dream encoding and retrieval (Eichenlaub et al., 2014b).

Together, these results suggest that dream characteristics such as general recall frequency and lucidity can be studied as stable personality traits. At the same time, they raise a voice of caution: although in our analyses we controlled for dream recall frequency, some aspects of the results presented here might have to do with individual differences in dreaming "styles" that correlate with dream lucidity or personality traits. Structural analyses alone cannot disentangle these effects. To the extent that the pattern of BOLD activity provides meaningful information on the function of each area, our results point to the fact that the clusters we identified within BA9/10 are in fact related to monitoring and lucid dreaming. Other clusters, such as the one we found in ACC, do not show this pattern of activity, and therefore might be related to other personality traits that covary with lucidity.

Finally, if lucidity as measured by the LuCiD questionnaire is not stable, then the different periods of time elapsed between the reported dream and the time of scanning should have introduced more measurement noise. In consequence, we should have seen an underestimation, and not an overestimation, of the effects. We therefore argue that measuring trait-lucidity can be considered a conservative approach.

Conclusion

By definition, lucid dreaming denotes the successful reflection on the current state of mind, i.e., an act of metacognition. Our data indicate that lucid dreaming may be a specific form of metacognition, relying on neural mechanisms akin to thought monitoring. Although this result has been previously suggested based on dream reports and theoretical arguments, these results provide the first confirmation of this link from a neuroscientific perspective.

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