Cognitive control and semantic thought variability across sleep and wakefulness

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Abstract

The flow of thought is persistent, and at times merciless. Mental content is generated throughout the day and into the night, moving forward predictably at times but surprisingly at others. Understanding what influences the trajectory of thought – how thoughts continuously unfold over time – has important implications for the diagnosis and treatment of spontaneous thought disorders like schizophrenia and recurrent nightmares. Here, we examine whether cognitive control (i.e., deliberate constraints) restrict moment-to-moment topical content shifts across sleep and wakefulness, thus acting as a fundamental constraint on thought variability. Thought variability was measured as the semantic distance between sequential thought phrases and was applied to reports from a variety of dreaming and waking experiences. Our results show that within both waking thought and dreams, conditions typically marked by higher levels of cognitive control are associated with decreased thought variability. During wakefulness, on-task conditions were associated with reduced levels of semantic thought variability compared to off-task conditions and semantic thought variability was greater when thoughts wandered around more freely. During sleep, lucid dreams marked by higher levels of metacognition were associated with reduced levels of semantic thought variability compared to non-lucid dreams. These results suggest that cognitive control may limit thought variability across the 24-hour cycle of thought generation. Such results are notably consistent with the Dynamic Framework of Thought, where mental states are expected to vary on continuum of deliberate constraints, with lower cognitive control leading to a categorical cluster of spontaneous thought processes that includes both mind-wandering during wakefulness and non-lucid dreams during sleep.

Keywords: spontaneous thought, dreaming, mind-wandering, lucidity, nlp

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Introduction

There are clear limitations on our ability to control our own thoughts. It is very challenging to focus perpetually on a particular thought [1], to avoid a particular thought [2], and to stop thought altogether [3]. Control over moment-to-moment mental content is highly variable within and across individuals [4]. People might spend up to a third of their day off-task, thinking of topics they had no intention of thinking about [5], and even more under times of stress [6]. Furthermore, the structure of our thought stream appears altered in many clinical populations, including ADHD [7, 8] and frequent nightmare sufferers [9]. Despite large fluctuations in thought trajectory and the clinical relevance of such fluctuations, neurocognitive features that influence thought trajectory are still largely unknown [10].

The difficulty of quantifying thought trajectory poses difficulties for making progress in this research area. Self-report approaches include asking participants to push a button during thought transitions [11] or to respond to a simple query about whether the mind was moving [7, 12–16]. The latter method has been used to dissociate thought trajectory from the broader concept of task-unrelated thought [12, 15]. More recently, another fine-grained approach is to have external raters evaluate a thought report for the number of hard transitions or jumps between thoughts [11, 17, 18]. This process, though cumbersome, has led to the validation of powerful automated tools that quantify thought movement at larger scales and with more objectivity [11, 18]. Such automated approaches leverage latent semantic analysis – a popular natural language processing tool that represent words or sentences as vectors – to extract the semantic embedding of individual thought segments and quantify the mathematical distance between consecutive thoughts in semantic space [11, 17–19]. Another approach is to identify the amount of episodic detail within each thought [20] and quantify these shifts [21].

Another notable limitation in understanding the principles of thought movement is that most prior work exclusively concerns waking thought. Yet, thought continues during most stages of sleep [22, 23], varying from a near-total absence of thought [24, 25] to fully immersive narratives [26]. Prior studies of both waking and dreaming thought have primarily focused on categorical rather than dynamic content differences [27, 28]. However, a recent experience-sampling study comparing the dynamics of waking and dreaming thought observed similar levels of self-reported thought movement within waking and dreaming [13]. Incorporating dreaming thought into theoretical and empirical models of thought movement might lead to principles of thought movement that apply to the full 24-hour cycle [29, 30].

Theoretically speaking, the Dynamic Framework of Thought is one such framework that has attempted to describe the nature of thought across the sleep-wake cycle [31]. In this framework, various mental states are arranged in a two-dimensional space where constraints from various sources play a large role in their level of spontaneity. Cognitive control is one of the two main sources of such constraints according to the Dynamic Framework (the second source is automatic constraint processes such as affective and sensory salience that occur outside cognitive control). Lower cognitive control leads to more spontaneous thoughts in waking (i.e., mind-wandering) and sleep (i.e., dreaming). Within this framework, thoughts that are more "goal-directed" (and therefore associated with greater cognitive control) are predicted to have a more narrow focus (and thus less semantic variability) compared to thoughts that are less deliberately constrained, which may represent times when the mind is wandering from one thing to the next.

Despite this clear theoretical prediction, it has not been widely empirically tested to date – particularly within the context of two mental states that purportedly have higher variability in thought: mind-wandering and dreaming (see Figure 2 of [31]). Furthermore, prior work investigating cognitive control's relationship with thought treated waking and dreaming as uniform/categorical states. Thus, whether cognitive control has a similar influence on thought variability in both dreams and wake of a healthy population is still unknown. Studies are needed to address this question in order to test the Dynamic Framework and to situate spontaneous thoughts across the sleep-wake cycle within a clearer and more continuous dimensional space.

In the current study, we hypothesized that conditions typically associated with relatively increased cognitive control in waking and dreaming would be associated with narrowed thought trajectories (i.e., reduced semantic thought variability), as predicted by the Dynamic Framework of Thought. We quantified thought movement in waking and dreaming thoughts that varied in their amount of self-reported cognitive control. Waking thoughts were reported throughout the day along with two distinct self-reported measures of mind-wandering: task-unrelatedness and the amount of thought movement [15, 16]. Dreaming thoughts were reported in an online dream journal along with self-reported levels of lucidity [32]. In both these datasets, thought variability was measured objectively as the semantic distance between moment-to-moment thoughts as they unfolded over time [33–35]. Based on the Dynamic Framework of Thought [31] and the Default Variability Hypothesis [36], we expected that cognitive control would constrain thought variability, lowering thought movement when cognitive control increased.

Results and Methods

Our approach was to aggregate subjective reports describing a variety of mental states [31], quantify thought movement using semantic incoherence [33, 35], and then test the relationship between thought variability [36] and cognitive control. Datasets were selected from existing sources [16, 32] based on their wide coverage of different mental states.

Semantic incoherence as a measure of thought variability. To quantify the amount of thought variability within a given text report, we calculated the amount of semantic incoherence of each text [33–35, 37] (Figure 1A). In brief, 1) each text report was

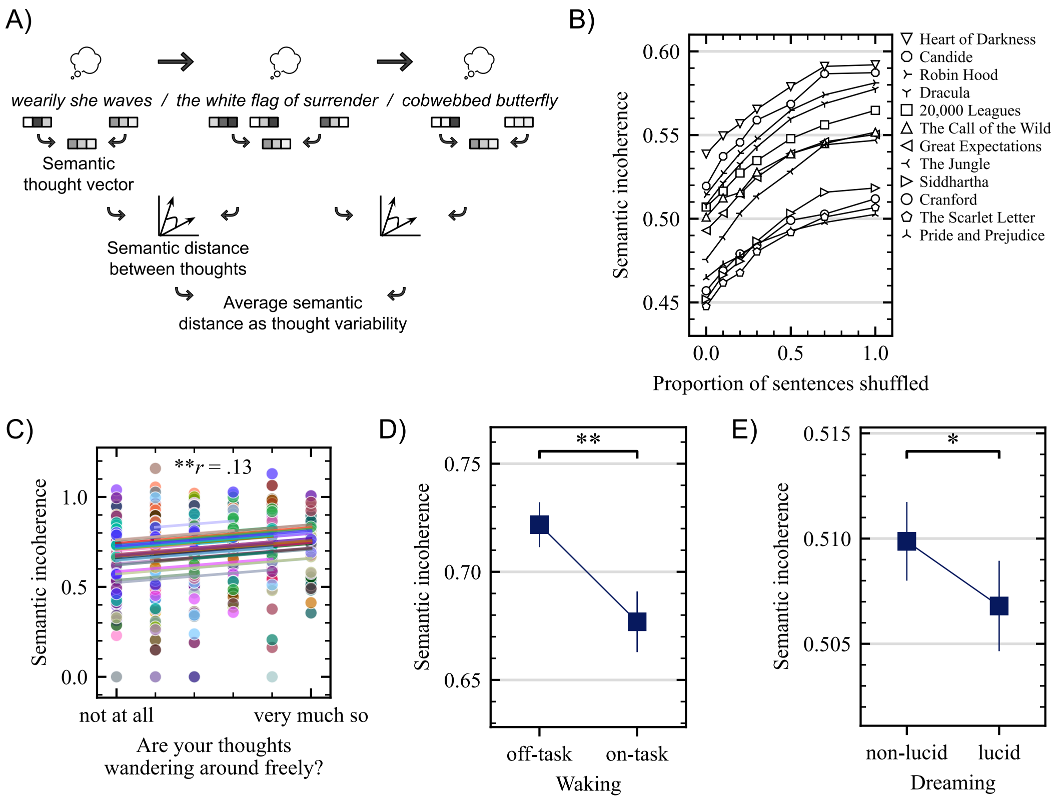

Figure 1. Figure 1. Semantic incoherence as a measure of thought variability is reduced under cognitive control in wake and sleep. (A) Thought variability is measured by generating a single semantic representation of each thought, finding the semantic distance between each consecutive thought pairs, and averaging those distances together. Example text is a haiku written by Tracy Davidson. (B) This measure shows a consistent increase when shuffling increasingly large portions of classic literature. (C) Over multiple days of experience sampling, increased thought variability was associated with decreased thought movement. (D) Over multiple days of experience sampling, being focused on a task was associated with decreased thought variability. (E) In public dream journals, metacognitive lucid dreams were associated with reduced thought variability. $*p < .05$, $**p < .01$

segmented into individual phrases, 2) 300-dimensional semantic embeddings were extracted for each noun, verb, and adjective with four or more letters 3) each phrase was summarized as the average semantic embedding of words within each phrase, 4) the cosine distance between each pair of consecutive phrases was calculated, and 5) the average of all cosine distances was the final measure of thought variability. Text reports were segmented in sentences, except for mind-wandering reports which were segmented into noun chunks (i.e., a noun and its surrounding context) due to their lack of sentence structure or punctuation. Text preprocessing, part-of-speech tagging, and semantic embedding extraction were performed using the `spaCy` Python package [38], where the language embedding space was trained on a large variety of English language sources including Wikipedia, news articles, and movie subtitles (`spaCy` *en_core_web_lg* model `v3.4.1`). Semantic incoherence scores were averaged within each participant and condition for all pairwise comparisons. All statistical analyses were run using the `Pingouin` Python package [39]. To demonstrate the efficacy of semantic incoherence as a measure of topic variability in text, classic literature from the Standardized Project Gutenberg Corpus [40] was used to calculate semantic incoherence across different degrees of random sentence shuffling (Figure 1B).

Thought variability is greater during off-task thought and when thoughts wander around freely. To track levels of thought movement under variable cognitive demands in daily life, we used experience samples from an ecological momentary assessment study (see [16] for methodological details). Here, participants reported their thoughts throughout the day (up to 6 times a day for a week) in response to text message prompts. They 1) provided a written description of their ongoing thoughts; and 2) answered two questions that assessed their self-reported levels of freely moving thought (1-6 Likert scale) and whether their thoughts were on-task or off-task (implemented as a dichotomous measure). Both of these measures have been used to assess mind wandering in previous studies [15] and are tied to constructs of constraints and executive control. In We observed a positive repeated-measures correlation [41] between thought movement and semantic incoherence ($N = 46$, $r_{rm}(604) = 0.13$, 95% $CI = [0.05, 0.20]$, $p = .002$), suggesting a negative linear relationship between cognitive constraints and thought variability (Figure 1C). We also observed higher (Wilcoxon signed-rank test; $N = 44$, $W = 267$, $p = .007$) levels of semantic incoherence in off-task ($M \pm SD = 0.722 \pm 0.069$) than on-task thoughts ($M = 0.678 \pm 0.093$), suggesting that thoughts had less variability during on-task thoughts (Figure 1D).

Metacognition constrains dreaming thought variability. Though dreams tend to entail low levels of cognitive control and metacognition, lucid dreams – defined as having recognition of the dream state – are a notable exception [42, 43]. To investigate how lucidity during dreams influences thought variability, we used lucid and nonlucid dream reports from a collection of dream reports from a public online dream journal [32]. As predicted, we observed higher semantic incoherence scores (Wilcoxon signed-rank test; $N = 1199$, $W = 335118$, $p = .040$) in nonlucid ($M = 0.510 \pm 0.064$) than lucid dream reports ($M = 0.507 \pm 0.074$), suggesting that thoughts move more freely during nonlucid dreams (Figure 1E).

Discussion

In the current investigation, we found that conditions typically associated with higher cognitive control were also associated with reduced semantic distance between moment-to-moment thoughts (i.e., thought variability). Reduced waking thought variability was associated with increased on-task thought and decreased levels of freely moving thought. Reduced sleep thought variability was associated with metacognition while dreaming. By showing that conditions of increased cognitive control were associated with reduced thought variability in both sleep and wake, these results support the notion that cognitive control places a fundamental constraint on thought movement.

The continuous thought dynamics influenced by cognitive control within waking and dreaming are consistent with Dynamic Framework of Thought [31]. This model places all thought on a continuum of deliberate cognitive constraints, which our data supports. Notably, prior work often references mind-wandering and dreaming as categorical blocks along the continuum of constraint. The current study provides quantitative support for sub-state degrees of deliberate constraints that operate even with "spontaneous thought" states like mind-wandering and dreaming, which highlights how even within these states there might be a wide variability of subjective experience [43]. A wide range of thought variability within and across both waking and dreaming might be driven by contextual demands and better serve a proposed function of spontaneous thought, such as memory consolidation [10, 36].

Our results are also consistent with neural predictions of the Dynamic Framework of Thought, whereby deliberate thought constraint is implemented through top-down neural signaling from frontoparietal control networks down to the salience and default mode networks. The default mode network has been implicated in the generation of spontaneous thought across both waking and dreaming [44], and in particular has been proposed as a mechanistic origin of non-lucid dream-content generation [45]. Though neuroimaging data regarding lucid dreaming is historically scant, some evidence suggest that lucidity is associated with a general increase in prefrontal cortex involvement relative to non-lucid moments of dreaming [42, 46, 47]. In keeping with these ideas, we propose that the lower thought variability observed in lucid dreams compared to nonlucid dreams arises due to a top-down frontoparietal control signal during lucid dreaming that modulates activity in the default mode network. Additionally, frequent lucid dreamers show increased coactivation across subregions of the frontoparietal control network during rest [48].

Recent theoretical accounts place dreaming within a broad category of spontaneous thought [10, 31]. While this might be true for most dreams, our results show that lucid dreams might be considered a unique case of relatively nonspontaneous thought during sleep. Similar to the reduction in thought variability during on-task thought while awake, lucid dreams showed reduced thought variability during dreaming. The wake-like levels of metacognition during lucid dreams might offer enough cognitive control while dreaming to allow the dreamer to engage in full goal-directed and intentional thought processes, essentially non-spontaneous thought. However, our analyses did not distinguish between lucid dreams with dream control and those without. Lucid dreams are often associated with having a degree of control over the dream narrative, but sometimes negligible control [43, 49], so perhaps only lucid dreams with volitionally altered dream content result in nonspontaneous thought processes.

Aside from the theoretical contributions to spontaneous thought, our results also speak to the utility of using participants' language patterns as an assessment of their thought dynamics. The use of language patterns has been gaining popularity in other fields, but has rarely been applied to understand how thoughts arise and unfold over time (though see [17, 18] for notable exceptions using the think-aloud paradigm). Here we show that language patterns, assessed as either retrospective recall or during ecological momentary experience sampling, can be a marker of variability in our thought stream. Of particular note, such variability was sensitive to different levels of constraints and cognitive control, highlighting its usefulness in distinguishing disparate states. At the same time, this measure provides additional validity for the freely moving thought question presented in the wakeful mind wandering dataset. This self-report question was intended to capture the level of constraints placed on thought [16], and should theoretically be associated with higher levels of thought variability (i.e., increased semantic incoherence) as thoughts are more free to move from one to the next, or wander from topic to topic. Our results provide support for this prediction of more movement in thought, which has previously only been validated using other self-report measures [16] or measures derived from neural activity [14]. The use of semantic incoherence as an objective and automated measure of thought variability in self-reports offers a tool for future related work.

One limitation of the current study is that the analyses did not account for demographic variability, psychiatric diagnoses, or affective state, all factors that are known to influence mind-wandering and other thought processes. Second, waking and dreaming thought are highly complex states, and it is likely that constructs other than cognitive control make unique contributions to the amount of thought variability. For example, the increased agency in lucid dreams might have reduced thought variability independently of insight. Similarly, other non-deliberate constraints (i.e., automatic constraints) might have contributed to thought variability [31]. Third, semantic incoherence is one of many approaches to measuring language. Alternative measures might provide additional insights in the future.

We did not compare thought variability directly between waking and dreaming. The Dynamic Framework of Thought and other accounts make specific predictions about the relationship between waking and dreaming thought dynamics, but the large discrepancy between how our datasets were collected precluded deriving conclusive results from such an analysis. Dream reports in the current study were not collected immediately during or after they occurred, whereas waking reports were collected in real-time using experience sampling [50]. Though dream reports are considered reliable accounts of experience [51], they are susceptible to memory fallacies [52] Dream reports collected directly from REM awakenings differ substantially from morning reports, including a higher level of bizarreness [53]. Prior work using self-report measures of thought variability suggest that dreaming thought consists of similar levels of variability as task-independent waking thoughts, both of which show higher variability than task-dependent waking thoughts [13]. Future work comparing waking and dreaming thoughts within-individuals using a serial awakening paradigm [54] and language measures would provide valuable additional insights into the mechanisms of thought generation.

The flow of thought is persistent. Mental contents are generated during almost all waking hours and reappear during sleep, but only a subset of these thoughts arise predictably and with conscious intent. Here, we show that thoughts are more predictable, at least content-wise, when supported by cognitive control, and that this principle is present during both waking and dreaming thought. Impairments in the ability to constrain thought variability and thought's moment-to-moment movement may be one of the major factors that underlie clinically significant alterations in spontaneous thought. Furthermore, understanding the processes by which cognitive control reduces the unpredictability of thought might offer insights to support the development of future therapies.

Declarations

Resource availability. All datasets come from prior publications and information on their availability can be found in the original references. All analysis code is available in a public GitHub repository (https://github.com/remrama/thococo).

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Competing Interests. The authors declare no potential competing interests.

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