Spontaneous Thought as an Unconstrained Memory Process

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The stream of thought can flow freely, without much guidance from attention or cognitive control. What determines what we think about from one moment to the next? Spontaneous thought shares many commonalities with memory processes. We use insights from computational models of memory to explain how the stream of thought flows through the landscape of memory. In this framework of spontaneous thought, semantic memory scaffolds episodic memory to form the content of thought, and drifting context modulated by one’s current state – both internal and external – constrains the area of memory to explore. This conceptualization of spontaneous thought can help to answer outstanding questions such as: what is the function of spontaneous thought, and how does the mind select what to think about?

Spontaneous Thought as an Unconstrained Memory Process

In our minds, thoughts unfold continuously and freely. We can go from focusing on the world around us to noticing an emotion to thinking about something that happened in the past to imagining something that can never be, all in a moment’s time. We spend almost half of our mental lives this way, drifting from unbidden imagery to future plans [1]. William James first described this ceaseless ‘stream of thought’ over a century ago [2], and researchers today are still unraveling the mysteries of how this stream flows through the landscape of thought [3–7]. Scientists now use the term spontaneous thought (see Glossary) to describe this type of thinking, and they define it by its relatively unconstrained nature: spontaneous thought is all thought that unfolds unrestrainedly; it follows our mental whimsy whenever we are not fully focusing on explicit goals, external tasks, or salient stimuli (Box 1). The landscape of spontaneous thought includes mind wandering, daydreaming, creative thought, and even dreaming (Box 2). How can researchers map out this vast territory? What determines what we think about from one moment to the next?

To answer these questions, we draw on insights from research on memory. We suggest that spontaneous thought can be seen as an unconstrained memory process [7–12]. Spontaneous thought draws on content from memory stores, and arises from largely the same neural systems as memory search processes. Bridging the domains of spontaneous thought and memory, we propose a framework of spontaneous thought as a dynamic, associative, and state-dependent process built on semantic and episodic memory, and guided by a drifting mental associative context and current state. In outlining this framework, we draw on existing computational models of memory search processes to identify how memory processes can give rise to spontaneous thought. This framework can provide new insights into the stream of thought and the landscape through which it flows.

Spontaneous Thought as Spontaneous Memory Replay

Episodic memory comprises much of the content of our spontaneous thought. During periods of quiet rest, people spontaneously revisit recent experiences, a process known as offline memory replay [13–16]. Researchers estimate that ~60% of mind-wandering episodes are episodic in nature [17].

However, although offline memory replay is a form of spontaneous thought, spontaneous thoughts are not merely direct recapitulations of past experiences. Instead, spontaneous thoughts often comprise counterfactual variations on past experience and drive forward in time to visions of the future and imagined scenarios [7,18]. At least 50% of spontaneous thoughts are about the future and the past [7,19]. Both types of thought – retrospective and prospective – draw upon episodic and semantic memory. According to the constructive episodic simulation hypothesis, people
Box 1. Defining Spontaneous Thought through What It Is Not

Because spontaneous thought is defined by its unconstrained nature, one can also define it by contrasting it to thoughts that are highly constrained, either deliberately or automatically. For example, spontaneous thought is not goal-directed or governed by cognitive control, unlike the thought processes that are necessary to read this paper or design the perfect date. Spontaneous thought is also not fully determined by salient stimuli, such as the annoying fly buzzing in your room, the throbbing pain in your stubbed toe, or the worry that you are unable to ignore [22]. Researchers have often focused their investigations on the thoughts determined by these types of strong deliberate and automatic constraints, implemented by mechanisms such as cognitive control and attention [3,121,122]. Spontaneous thought is everything that these highly constrained thoughts are not.

The neural dynamics of spontaneous thought support the distinction between deliberate and automatic constraints. The core subsystem of the default network is a key hub in generating the stream of thought. It can flexibly couple with other networks in the brain, including the frontoparietal control network, the dorsal attention network, and salience networks [22]. The frontoparietal control network couples with the core subsystem to apply deliberate constraints, and the salience networks and the dorsal attention network couple with the core subsystem to apply automatic constraints. The interactions between these networks give rise to the ever-changing constraints on thought.

Deliberate and automatic constraints are not categorically on or off. Instead, thoughts lie along a continuum from completely unconstrained (e.g., dreaming) to completely constrained by deliberate and/or automatic constraints [22]. Thought can be subject to these constraints to varying degrees. Creative thinking, for example, often entails free-flowing ideation within a problem space, as well as the goal of selecting only the most useful ideas [120,123,124]. Therefore, although spontaneous thought is relatively free from constraints, it is only rarely completely impervious to them (Box 2). For example, ongoing goals and emotions affect spontaneous thought processes such as mind wandering [79]. In other words, weak deliberate and automatic constraints can still affect spontaneous thought. For instance, your stubbed toe may seed a subsequent stream of thought that contains other instances of pain. In sum, spontaneous thought is not so much a category as a portion of a large continuum of thought that includes mind wandering, daydreaming, creative thought, and dreaming.

How do our memory systems support this type of unconstrained imagination? A key neural hub in memory processes is the medial temporal lobe (MTL) subsystem of the default network, which includes the hippocampal formation, the parahippocampal cortex, and their cortical projections, including the retrosplenial cortex, ventral medial prefrontal cortex, and angular gyrus [25]. The MTL, and the hippocampus in particular, is well known for its role in semantic, declarative, episodic, and associative memory [27–31]. It allows us to remember what we experienced and where we experienced it [32–35] by linking experiences to their temporal and spatial contexts [36,37]. Regions such as the angular gyrus [38] and parahippocampal cortex [39] offer the structure that is necessary to construct mental simulations [25,40] by integrating experiences into more abstract, conceptual knowledge [38] and tracking contextual information during episodic simulation [41].

The hippocampus is also the neurobiological source of spontaneous, ‘offline’ memory replay. Rodent studies tell us that, during periods of rest after a task, the hippocampus replays its recent real-life experiences. For instance, after a rodent runs down a track or explores a maze, neurons in the hippocampus that encode spatial locations will spontaneously reactivate during rest, essentially replaying the rodent’s experience of the newly learned trajectory [42]. Humans likewise spontaneously replay recent experiences at rest [15,43–45]. In humans, this replay has its origins, similarly to other memory processes, in MTL activity [26,44–47]. However, spontaneous hippocampal replay does more than recapitulate ‘online’ hippocampal activity from the original, real-life episode. Instead of merely simulate future events or imaginative scenarios by flexibly recombing episodic details of past experiences [20]. Semantic memory contributes structure and meaning to these simulations [21]. This means that episodic simulation is the fodder for spontaneous thought: people recombine details of past episodes, scaffolded by semantic representations, to create novel episodic simulations of past or future scenarios [22–26].
replaying the trajectories of recent experiences, the hippocampus generates novel reconfigurations of these experiences in the same environment [48]. In fact, hippocampal replayed trajectories in rodents can follow a seemingly random pattern through the explored environment, and often do not correspond to the prior actual movement pattern of the animal [49].

During periods of rest, when people are most likely to experience spontaneous thought, the brain seems to trace a random trajectory through its recent experiences. This random trajectory arises from an episodic memory retrieval mechanism known as pattern completion [50]: partial activation of one memory representation triggers activation of the entire pattern. For example, seeing someone eat ice cream might activate a memory of going out for ice cream on a hot summer’s day; summer might trigger a memory of swimming; the color blue might remind you of the cover of a book you read recently, and so on. A series of cascading pattern completions can activate one memory after another, creating both novel patterns in the hippocampus and novel patterns of distributed neocortical activity [8]. The result is a type of ‘wandering’ neural activity that can help explain the ‘wandering’ nature of much spontaneous thought.

Spontaneous activity in the MTL network generates these variable neural patterns. In turn, interaction between regions in the brain’s default network [11,12,22,25,51–59] integrates these patterns into spontaneous thought: the MTL couples with the core subsystem of the default network, which consists of the medial prefrontal cortex and posterior cingulate cortex, to inject its highly variable content into the stream of thought [8,22]. This means that the MTL is involved in the associative, imaginative, and creative thinking that occurs during spontaneous thought [40,60–63], in part because this type of thinking, like memory replay, draws on past episodic experiences. These periods of spontaneous thought during unoccupied wake time, like periods of dreaming, support optimal learning and memory consolidation [16,64,65], which together make it possible for people to strategically review their experiences and generalize from them (Box 3).

Features of Spontaneous Thought

We aim to leverage parallels between memory and spontaneous thought to build a framework for spontaneous thought. Such a framework needs to account for three key features of spontaneous thought: its dynamism, its associativeness, and its state-dependence.
Dynamic

Spontaneous thought is highly dynamic: thoughts move from one topic to the next continuously [22], at an estimated rate of about 4.3 thought transitions per minute [66]. The speed of this movement varies [67], but, irrespective of whether it unfolds slowly or quickly, thought is always in motion. William James [2] described this dynamism: ‘Like a bird’s life, [the stream of thought] seems to be made of an alternation of flights and perchings’ (p. 243). The ‘perchings’ represent substantive, concrete content that can be held in mind for a longer period of time. The locations where the mind may perch cover a huge area within the landscape of thought [68]. Perches can also vary widely in modality: they can be images, words, auditory experiences, emotions, or physical sensations [23,24,40,63,69–74]. The ‘flights’ are dynamic transitions between these states; they are rapid and transitory, and each flight may cover a long distance within the mental landscape.

Associative

Flights from one thought to the next may be highly variable, but they are not random. Instead, thoughts are highly associative [75]: they are linked by pre-existing associations between topics. This associative feature of thought is a staple of many classic philosophical accounts of thought and reasoning [9], as well as of explanations for creative thought [76].

State-Dependent

The flights and perches of thought are also affected by features or cues provided by one’s current state. Although spontaneous thought is free from strong constraints by definition (Box 1), it can still

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**Box 3. The Function of Spontaneous Thought**

Spontaneous thought makes up ~30–50% of our waking thoughts [1,17,134,135], on top of the time we spend dreaming. Why do we devote so many hours and cognitive resources to spontaneous thought?

One possibility comes from research on offline memory replay. Memory replay is crucial for consolidating new experiences [15,45,136–138], but not all experiences are called upon equally during memory replay [139]. Memory replay during waking and sleep often features content that is emotional [140], rewarded [141], or that is known to be important for the future [142,143]. People leave waking rest and sleep with particularly enhanced memory for these replayed experiences.

Spontaneous thought may likewise function to consolidate memory [15,47,144]. In fact, the neural dynamics of spontaneous thought seem to be tailored to enhance both episodic and semantic memory [8]. Within the MTL, each episodic event is encoded in a particular activation pattern. To avoid competition between related memories during retrieval, these patterns need to be sufficiently unique [145]. During spontaneous thought, these activation patterns are reactivated in novel sequences. The randomness of these sequences is essential for enhancing episodic memory storage: novel sequences help to decorrelate the neural representations. For instance, episodic memories of events that took place close together in time are recalled out of their temporal order, which allows the formation of associations that are unrelated to the temporal order. Recalling these overlapping memory traces separately can strengthen the neural representation of each memory’s essential features to improve episodic memory efficiency [8].

Repeated reactivation of memories in novel combinations can also help to generalize information from episodic experiences to semantic memory [8]. After the hippocampus helps to accurately store experiences in real time, higher-level learning systems in the neocortex use these stored experiences to generalize, explain, and interpret. These neocortical learning systems depend on repeated examples to correctly distill the commonalities across episodes. The learning process works best if the examples are presented in an interleaved and somewhat random order to avoid interference from irrelevant shared features [146]. Spontaneous thought, with its constantly moving and highly variable content, provides optimal conditions for this high-level learning.

In other words, the dynamics of spontaneous thought may constitute an optimized sequence of memory replay that helps us to retain the most important pieces of information, forget irrelevant information, and learn to extract larger patterns from our experiences. This optimization of memory may help us not only to make sense of the past but also prepare us for the future by enabling us to maintain a sense of self, come up with creative ideas, and handle what comes next [6,105].
be subject to weak constraints. For instance, thought can be shaped by external factors, such as one’s location and the stimuli in it, as well as by internal factors, such as one’s mood or ongoing goals. Even in the absence of strong attentional coupling to the immediate environment, internal and external stimuli can still serve as starting points for thought, and the brain can integrate these stimuli into spontaneous thoughts as they form [77]. Internal states (e.g., negative affect) can modulate the direction in which thoughts proceed (e.g., toward events in the past [78]), and personal goals or motivations, known as current concerns, can modulate the likelihood that thoughts circle back to a particular topic [79]. In other words, thoughts are shaped not only by preceding thoughts but also by the current state of the person doing the thinking and the world around them.

**Parallel Dynamics in Memory and Spontaneous Thought**

In sum, spontaneous thought is dynamic, associative, and state-dependent. Memory search and recall processes share these same three features. For instance, successful retrieval of a relevant memory relies on a highly dynamic memory search process that moves quickly through candidate memories [80–82]. This memory search process is also highly associative: existing associations between different memories determine what is recalled next [83–86]. Further, like spontaneous thought, episodic memory retrieval is sensitive to the current state: mood, culture, and local external cues all affect recall [87–89]. These shared features offer further evidence for a considerable overlap between spontaneous thought and the more constrained forms of thought involved in memory search.

**A Framework for Spontaneous Thought**

Memory and spontaneous thought comprise similar content and arise from similar neural substrates [8,10,22,26,58,90,91]. We suggest that researchers can advance our understanding of spontaneous thought by attending to the features it shares with memory. Memory researchers have an established practice of developing formal models to explain the dynamics of memory search processes [92]. Computer scientists have successfully used episodic and semantic memory to develop artificial intelligence that mimics the dynamics of daydreaming [93] and creative ideation [94]. To the extent that spontaneous thought can be understood in the same way as episodic and semantic memory processes, we should be able to apply models from the cognitive psychology of memory to better understand how spontaneous thought unfolds: to the extent that models of memory fail to capture spontaneous thought, we can adapt the model and, in doing so, hone our understanding of spontaneous thought. We offer here a generative framework for understanding the flights and perches of spontaneous thought (Figure 1).

**Modeling the Trajectory of Thoughts through Episodic and Semantic Memory**

At the base of this framework lies the content that spontaneous thoughts and simulations draw on: episodic memory [8,22]. These episodic seeds, generated by the MTL, provide the characteristic highly variable content of spontaneous thought. Semantic memory scaffolds the construction of novel episodic simulations [21,95,96]. Semantic memory stores our abstract knowledge about the world [97] and our past [98], which is necessary to support abstract reasoning, counterfactual thought, and imagination [99]. During spontaneous thought, semantic memory provides a structure for episodic memory to fill in the experiential details [21]. Indeed, several clinical disorders of spontaneous thought can be traced to deficits in episodic memory and/or its semantic scaffolding (Box 4). Although typically considered to be distinct types of memory, semantic and episodic memory are tightly linked and are sometimes hard to distinguish [98]. Our framework attempts to capture their continuous dynamic interplay.

**Foraging and Random Walk Models of a Semantic Search**

How can a stream of thought arise from the structure of these two types of memory content? To answer this question, we turn to computational memory models. A common task used to study the dynamics of memory search is the semantic fluency task, where participants name as many items as they can from a target category (e.g., animals). The pattern of responses of the participants in the task provides a window into the organization of semantic memory content and the process the
mind uses to explore that content. For instance, in a semantic fluency task with the category ‘animals’, people may first name pets (e.g., cat, dog, fish), then aquatic animals (e.g., shark, whale, dolphin), then farm animals (e.g., cow, sheep, pig), and so on. This process shares the dynamics and associativeness of spontaneous thought. Therefore, models of semantic fluency can illuminate the path of spontaneous thought through the landscape of memory.

Models of spatial foraging have been highly successful at explaining participant responses during semantic fluency tasks. These models can explain why participants retrieve semantically related items in clusters, as well as how and when people switch from one cluster to another [100]. In spatial foraging, people search for resources that occur in patches (e.g., berries on bushes) within an environment that has many such patches (e.g., distributed bushes). People continue to search in a local patch until it becomes too difficult to find what they are looking for there. At that point, they leave the current patch to find a new, unpicked one. The optimal time to switch to a new patch is the moment when the rate of collecting new items in the current patch decreases to the same rate as the long-term average intake over all patches. This spatial foraging model can be applied to semantic space instead of physical space to model semantic fluency tasks: in the same way as berries are stored on bushes, we store conceptually related items in semantic clusters. Participants who perform better at the semantic fluency task tend to switch to a new ‘patch’ closer to the computationally derived optimal time.

Researchers have also used a random walk model to understand semantic fluency [101]. In this model, people search through a semantic network generated from free association data; the network is made up of paths between associated items. When many paths connect different concepts, those concepts form ‘patches’ in a spatial representation of semantic space. A random walk traverses this semantic network by randomly moving along existing paths, and one is therefore more likely to follow a path between items in the same semantic cluster than to follow a path between clusters, mimicking results obtained with the foraging model.

Ultimately, both models explain semantic search in a way that resembles the ‘flights and perches’ of spontaneous thought. Perches are the items within the clusters or patches distributed in semantic space, and flights are the processes the mind uses to traverse this space. The foraging and random
walk models provide distinct mechanisms for explaining the features of spontaneous thought. In the foraging model, the search algorithm alone accounts for the dynamism of spontaneous thought, and the spatial model of semantic space represents the associative structure. The random walk model has the virtue of being simple, but it achieves this simplicity in part by not distinguishing between the associative structure and the process used to query it [102]. Instead, it relies on its flexible representation of semantic space to account for both the dynamism and associativeness of thought. Despite their different mechanisms, however, both models capture many of the key features of spontaneous thought.

Practical Applications

We can borrow from the foraging and random walk models to describe how people traverse memory stores to generate dynamic, associative spontaneous thoughts. The primary difference between a
model of memory search and a model of spontaneous thought is that the former operates over an explicit goal, and the latter does not. That is, these memory models describe a process that is designed to forage as many resources from semantic memory as possible. Resources are sources of 'value' that motivate the memory search to unfold as it does. What are the resources that guide the spontaneous thought stream? We suggest that, in applying the principles of goal-directed memory search to goal-free mental wanderings, we can begin to answer an outstanding question about spontaneous thought: what goal is spontaneous thought optimized to achieve?

First, we can test the hypothesis that spontaneous thought does operate over goals, albeit less explicitly than deliberative thought. Indeed, much of the thematic content of spontaneous thought comprises ongoing goal pursuits or current concerns [79,103]. Thoughts that address a current concern may be more 'valuable' than wholly undirected thoughts [103,104]. Under this hypothesis, spontaneous thought may be a useful tool to ensure that the mind is primed and prepared to act in accordance with current concerns when the opportunity arises [105–107]. If spontaneous thought is driven to process current concerns, we would predict that topic switches will occur when thoughts stray too far from current concerns.

Alternatively, spontaneous thought may be optimized to improve memory efficiency (Box 3). Activating memory traces out of their original order can help to optimize episodic memory storage by decorrelating individual memories that occurred close together in time. In addition, reinstating episodic memories multiple times in different contexts helps to optimize semantic memory: identifying the regularities among otherwise fragmented episodic experiences facilitates learning of abstract semantic information (Box 3). Indeed, much of the content of spontaneous thought consists of exactly this type of varied episodic simulations [8], or random replays and recombinations of recent experiences. To model this phenomenon, we would need to combine the foraging and random walk models. Within a patch, the search can be described with a random walk, while the boundaries of the current patch are dynamically constrained based on one's current location in the space [108]. If the trajectory of spontaneous thought is designed to optimize memory storage and facilitate learning, we would predict that topic switches will occur when the rate at which episodic details are produced decreases below a set threshold. That is, memory-optimizing spontaneous thought would prioritize detailed and vivid simulations. Because proximal events are easier to vividly recall than distal ones [109–111], this might explain why much of spontaneous thought gravitates toward psychologically proximal content, such as recent or near-future experiences [18,112–114].

In addition to these testable predictions about the function of spontaneous thought, applying the foraging model allows us to quantify parameters that describe the dynamics of thought. In foraging, the optimal time to switch to a new patch is the threshold at which the rate of intake in the current patch slows to the overall experienced rate of intake. In spontaneous thought, different thresholds will give rise to different thought patterns. For instance, if the threshold is set too low, thoughts will jump from patch to patch too quickly, making thought rapid and disjointed. Conversely, if the threshold is set too high, thoughts will jump from patch to patch infrequently, leading to repetitive, ruminative thought. There are likely individual differences in the threshold value people use, as well as differences within individuals over time. These differences may help to explain individual differences in creative thought [76,115,116], or changes in thought patterns in various mental disorders (Box 4). By exposing this patch-switching threshold parameter, the foraging model provides an effective way to quantify an otherwise elusive aspect of spontaneous thought.

A hybrid of the foraging and random walk models applied to semantic and episodic memory can explain much of the dynamics and associativeness of spontaneous thought. The random walk over episodic memory gives rise to the vivid episodic simulation that is prevalent in spontaneous thought, and the foraging model adds a way to transition to a different topic, mimicking the flights and perches of spontaneous thought. As such, these models provide a window into the low-level dynamics of spontaneous thought. However, they do not explain how people select which region of semantic and episodic space to search, within the vast scope of possible spontaneous thoughts. That is, there
are more constraints on thought paths than merely the semantic structure over which foraging and random walk models are optimized to search. Therefore, we next add two layers to our framework to further explain the trajectory of thought through semantic space.

Selecting the Content of Spontaneous Thought

In addition to the layers that represent the episodic and semantic content of spontaneous thought, our framework incorporates two superordinate layers: drifting mental context and the current state. Both layers help to determine what portion of semantic space to explore by shaping the strength of the association between thoughts. During spontaneous thought, our minds can traverse all associations acquired over a lifetime. The semantic search models above approximate such an associative structure based on the static properties of natural language use. However, spontaneous thought can explore such a vast semantic space that this approximation is insufficient to fully determine the path of thought. Our framework incorporates a layer that accounts for multiple types of associations between concepts, including not only semantics but also time, space, social structure, emotions, etc. Importantly, this context layer dynamically updates based on the content of the current thought. In addition, we know that spontaneous thought is shaped by one’s current state, as described above. Our framework incorporates these factors as a fourth layer to account for the state-dependence of the content-selection process.

Context Maintenance and Retrieval Model of Free Recall

How can we characterize the drifting contexts and states that select which portion of memory space to explore? To answer this question, we once again turn to computational memory models. Memory search during free recall is an apt process to focus on. During free recall tasks, participants study a list of words and then recall them later on. Retrieval in this task is unstructured, but there are consistent patterns in the order in which participants retrieve items. For instance, responses often reflect the order in which the items were presented during the learning phase. Like spontaneous thought, free recall involves traversing concepts based on the associations between them.

The context maintenance and retrieval (CMR) model is particularly successful at capturing participant responses during free recall tasks [117]. In this model, three factors determine the recall of each subsequent item: semantic associations, temporal context, and source context. First, semantic associations lead people to recall words in clusters that mirror their co-occurrence in natural language. Second, as words are presented in the learning phase, they become associated with the words presented immediately before and after during learning. This temporal information influences the order in which words are later recalled: words that were presented together tend to be recalled together. Finally, words learned in the same task context also tend to be recalled together. For example, items presented in the same modality (e.g., aurally) or in the same location (e.g., room A), will share a source context, and this will be different from the source context shared by words presented in a different manner (e.g., visually; room B). Each of these factors shapes the associations people form between items as they learn them.

In the CMR model, each recalled item has its own source associations, temporal associations, and semantic associations, which together define the drifting mental context at that moment in recall. To account for people’s experiences before the learning phase, the associative matrix for temporal context is initialized based on semantic associations. Temporal information during the learning phase then updates this structure. During recall, the temporal and source context are combined into the internally maintained representation of context. Each context takes the form of a spotlight that can illuminate a subset of items [117]. Each spotlight is trained on the currently recalled item, and in the process it also illuminates nearby, associated items. For instance, the spotlight of temporal associations will illuminate items learned immediately before and after the current item; the closer in time an item was learned, the brighter it will be illuminated. Similarly, the spotlight of source associations will illuminate items learned under the same task conditions. The brightness of the spotlight represents the strength of the association, its light becoming more and more diffuse with distance. The item that is illuminated most strongly by the combination of all spotlights will be recalled next.
The spotslights then move to that item, which determines the selection of the next item, and the process repeats. Thus, throughout recall, the spotslights of context update the associations for each subsequent item.

**Practical Applications**

The CMR model explains how a drifting mental context determines the order of freely recalled items. We can test the role of each hypothesized constraint using CMR. For instance, temporal associations are very informative in a free recall task, but we suspect that they may be less important in spontaneous thought. For instance, offline memory replay often does not follow the temporal order of actual experience [48,49]. Indeed, this deactivation of temporal associations can benefit memory optimization (Box 3). Thus, spontaneous thought may be driven by a drifting context that is not as strongly constrained by temporal associations as free recall is. If this is true, we would expect that a CMR model that heavily weights temporal associations would perform worse in modeling spontaneous thought than a version that weights temporal associations more lightly. By adaptively adjusting the weight on temporal associations, we can quantify the extent to which this contextual factor constrains spontaneous thought. In addition, spontaneous thought is modulated by many more types of context associations than are free-recall tasks, and we can use CMR to also test the roles of other types of associations.

Varying the weights on different types of context associations also provides a powerful way to incorporate the influence of one’s current state on spontaneous thought. The current state encompasses both the external environment, including local stimuli, and the internal mental state, including affect and current concerns. As such, current state incorporates all sources of weak constraints on thought (Box 1). In our model, the current state serves as a superordinate layer that modulates the weights assigned to different context associations. For example, in a highly social environment, social associations might become more important [118]. The content of thought itself can also feed backward to modulate the current state. For instance, stumbling on a highly emotional or traumatic episode can change the state of one’s mood, shifting the weights on affective context and triggering more negatively valenced associations. In this way, state variables can shape thought by adjusting the intensity of each spotlight of context. This process also constrains the number of concurrently active types of associations, relieving us from needing to compute a combination of all possible context associations acquired over a lifetime; we can instead model only those that are most relevant to the current state. To test this component of the framework, we can manipulate state before and during a thought sample to affect the currently salient contextual associations that determine the next topic of thought.

**Summary**

When these elements are combined, they yield a framework with four components: episodic memory, semantic memory, drifting context associations, and current state (Figure 1). The dynamics of thought are generated by a random walk over episodic memories scaffolded by semantic space. A foraging mechanism determines when to move on to a new portion of semantic space. At that time, a CMR-like drifting mental context determines which area to search and where thought goes next. The different types of associations that make up this mental context are not weighted equally: instead, the weights can shift based on current state.

Together, these four components provide a framework for spontaneous thought. This framework leverages the understanding of memory provided by cognitive psychology to account for the key features of spontaneous thought: its dynamism, its associativeness, and its state-dependence.

**Outstanding Questions**

How does spontaneous thought arise from episodic and semantic memory? Moreover, how does the mind select the content of thought? The proposed framework models the progression of the stream of thought as a foraging-like search process through semantic and episodic memory, guided by state-dependent context associations. Can a formal model based on this framework accurately capture the neural and cognitive dynamics of spontaneous thought?

Spontaneous thought arises largely from a dynamic interplay between the core and MTL subsystems of the default network. How do these brain regions implement each facet of this spontaneous thought process? Can computational models of constrained memory processes successfully scale up to the unconstrained process of spontaneous thought? Can these models (or models of more complex, naturalistic memory recall) be successfully adapted to accurately predict the trajectory of spontaneous thought? What is the purpose of spontaneous thought? Is it optimized to resolve current concerns and/or to improve memory efficiency?

Memory search during free recall is shaped by temporal and task associations between studied items. During spontaneous thought, temporal context may become less important, and other factors may become more important. Which context associations shape spontaneous thought, and to what extent? The trajectory of our thoughts can be influenced by our internal mental states and the world around us. Which environmental factors are most influential in shaping our thoughts? How do these factors shape drifting context associations during spontaneous thought?

Spontaneous thought has several proposed benefits, such as memory consolidation, maintaining a sense of self, and planning for the future. There are prominent examples of spontaneous thought gone
Concluding Remarks
Spontaneous thought unites several different psychological constructs, including mind wandering [7], daydreaming, creative thought [119,120], and dreaming. Although these classes of thought may appear to be heterogeneous, they are all characterized by their relatively unconstrained nature (Box 1). We propose here that we can capture the cognitive dynamics of spontaneous thought by leveraging models that capture memory-related processes such as free recall and semantic fluency [100,101,117].

We have synthesized contributions from these models to devise a framework of spontaneous thought in which a CMR-like memory search process shaped by drifting context associations and modulated by current state draws upon topics in semantic space. This semantic space scaffolds episodic simulations, which form the main content of spontaneous thought. The episodic simulations unfold much like a random walk until the current memory patch becomes depleted, at which point we draw on the drifting context to find a new patch to explore. The current state modulates the relevance of each context factor.

Examining processes that memory and spontaneous thought have in common can lead to valuable insights into two crucial questions about spontaneous thought (see Outstanding Questions): how does spontaneous thought arise from episodic and semantic memory stores? Furthermore, how does the mind select the content of thought? The framework presented here leverages the cognitive psychology of memory to further the emerging field of spontaneous thought. This framework serves as a first step toward a more formal model of the cognitive dynamics of spontaneous thought, and provides a new conceptualization of the stream of thought as an unconstrained, memory-based process.

Acknowledgments
The authors thank Abla Alaoui Soce, Kelly Besecke, Ken Norman, Hanna Pickard, and Mark Thornton for their feedback on earlier versions of this manuscript, and members of the Princeton Social Neuroscience Laboratory for helpful discussions.

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