REVIEWS

Mind-wandering as spontaneous thought: a dynamic framework

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Abstract | Most research on mind-wandering has characterized it as a mental state with contents that are task unrelated or stimulus independent. However, the dynamics of mind-wandering — how mental states change over time — have remained largely neglected. Here, we introduce a dynamic framework for understanding mind-wandering and its relationship to the recruitment of large-scale brain networks. We propose that mind-wandering is best understood as a member of a family of spontaneous-thought phenomena that also includes creative thought and dreaming. This dynamic framework can shed new light on mental disorders that are marked by alterations in spontaneous thought, including depression, anxiety and attention deficit hyperactivity disorder.

As we take … a general view of the wonderful stream of our consciousness, what strikes us first is this different pace of its parts. Like a bird's life, it seems to be made of an alternation of flights and perchings … The resting-places … can be held before the mind for an indefinite time … The places of flight … obtain between the matters contemplated in the periods of comparative rest. William James, *Principles of Psychology*, 1890.

The 'flights' and 'perchings' of our thought, so poetically described by William James[1], are as mysterious to us as they are intimately familiar. To James, a perching represented a mental state including contents such as imaginings, worries and inner speech, whereas a flight represented the 'movement' from one mental state to another. Although the forefather of psychology emphasized the spontaneous and dynamic nature of thoughts, research in the century that followed left these topics largely unexplored.

In the past 15 years, mind-wandering and spontaneous thought have become prominent topics in cognitive psychology and neuroscience[2]. However, most theories of mind-wandering still overlook the dynamic nature of thought that James viewed as central. By focusing on these dynamics, in this Review, we formulate a novel framework for understanding spontaneous thought and mind-wandering. By introducing this framework, we bring together a diverse range of relevant findings from psychology, neuroscience and the clinical area.

Mind-wandering: the forgotten dynamics

Until the mid-1990s, cognitive psychology and the emerging field of cognitive neuroscience were dominated by a task-centric view of mental processes.

Experimental designs were carefully constructed to minimize the effects of task-unrelated thoughts that were generally viewed as experimental 'noise'. Indeed, cognitive neuroscientists commonly used 'rest' (that is, a period during which participants did not perform any experimental tasks) as a baseline condition. This practice was predicated on the assumption that any mental processes that occur during periods of rest would essentially constitute such noise. This assumption, however, was called into question by observations that periods of rest consistently recruit brain regions involved in memory[3–5] and complex reasoning[6], and by an influential meta-analysis by Shulman and colleagues[7] showing that a specific set of brain regions — that later became known as the default network (DN)[8] — are consistently more active during baseline conditions than during experimental tasks.

Although topics such as daydreaming, mind-wandering, stimulus-independent thought and task-unrelated thought had been studied for decades[9–19], they had been relegated to the backwaters of psychological research[2]. The advent of the DN created a major shift in scientific attention: mind-wandering research came into prominence within both mainstream psychology[20,21] and cognitive neuroscience[22,23]. However, this new research inherited a historical legacy[24] from previous task-centric views: mind-wandering became predominantly defined as the opposite of task-related and/or stimulus-related thought. For example, a recent theoretical review[25] defines mind-wandering as "a shift in the contents of thought away from an ongoing task and/or from events in the external environment". This prominent definition regards mind-wandering as a type of thought characterized by its contents (or, in William James's terms, the bird's perchings rather than its flights).

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This definition has been implicitly or explicitly endorsed by most of the empirical investigations on mind-wandering so far[26]. Although it has generated a wealth of empirical findings about task-unrelated and stimulus-independent thought, this content-based definition fails to capture what is arguably the key feature of mind-wandering[27,28], reflected in the term itself: to wander means to "move hither and thither without fixed course or certain aim" (REF. 29).

To say that one's mental states are task unrelated or stimulus independent tells us nothing about how such states arise or change over time[27]. Only once we consider the dynamics of thought are we able to make crucial distinctions between different types of thought. One such distinction is between rumination and mind-wandering. Rumination is sometimes viewed as negatively valenced mind-wandering[20] (or mind-wandering gone awry). In one way, this makes sense: both mind-wandering and rumination tend to be stimulus independent and unrelated to the current task (that is, what the subject is currently doing)[21,30]. However, when we consider the dynamics of thought, mind-wandering and rumination seem antithetical: although thoughts during mind-wandering are free to 'move hither and thither', thoughts during rumination tend to remain fixed on a single theme or topic[27]. Furthermore, the content-based view of mind-wandering relies on a relatively narrow definition of the term 'task' as being confined to the goals of the current experiment. However, if we define the term task more broadly to also include one's personal concerns (for example, completing an essay by the end of the week), then mind-wandering is often task related because spontaneously occurring thoughts often reflect personal goals and concerns[19,27,31,32].

Spontaneous thought: a definition

Here, we define spontaneous thought as a mental state, or a sequence of mental states, that arises relatively freely due to an absence of strong constraints on the contents of each state and on the transitions from one mental state to another. We propose that there are two general ways in which the content of mental states, and the transitions between them, can be constrained (FIG. 1). One type of constraint is flexible and deliberate[26], and implemented through cognitive control[33,34]. For example, we can deliberately maintain our attention on a dry and boring lecture, bringing our thoughts back to the lecture whenever they begin to stray. Another type of constraint is automatic in nature. Automatic constraints can be thought of as a family of mechanisms that operate outside of cognitive control to hold attention on a restricted set of information[27]. Affective salience[35–37] and sensory salience[38] can both act as sources of automatic constraints. Despite our efforts, for example, we may find ourselves unable to disengage our attention from a fly buzzing in a quiet library or from a preoccupying emotional concern.

Within our framework, mind-wandering can be defined as a special case of spontaneous thought that tends to be more-deliberately constrained than dreaming, but less-deliberately constrained than creative thinking and goal-directed thought[39] (BOX 1; FIG. 1). In addition, mind-wandering can be clearly distinguished from rumination and other types of thought that are marked by a high degree of automatic constraints, such as obsessive thought.

Recent advances have begun to reveal the neural underpinnings of spontaneous thought and mind-wandering. We review these advances through the lens of our framework, which explains the contrast between spontaneous and constrained thought in terms of the dynamic interactions between large-scale brain networks. Using this framework, we also discuss a number of clinical conditions that are marked by excessive variability or excessive stability of thought and the way mental states change over time.

Brain networks and their interactions

Among brain networks that are currently recognized in cognitive neuroscience, the DN (FIG. 2a) is most frequently brought up in relation to mind-wandering and spontaneous thought. The DN was originally identified[7,8] as a set of regions that are consistently deactivated across a range of externally oriented experimental tasks. This network has been linked to spontaneously occurring, internally oriented mental processes[22,23,40]. However, DN recruitment is not specific to spontaneous cognition: it is also consistently observed during internally oriented, but deliberate, goal-directed tasks, including episodic memory retrieval, autobiographical future thinking and mentalizing[41–44].

The DN is composed of several functionally distinct subsystems[45] (FIG. 2a). The core DN subsystem (DN_{CORE}) is characterized by its hub-like properties and its contributions to internally oriented cognition[45]. The second DN subsystem is centred around the medial temporal lobe (MTL) and is known for its roles in memory and
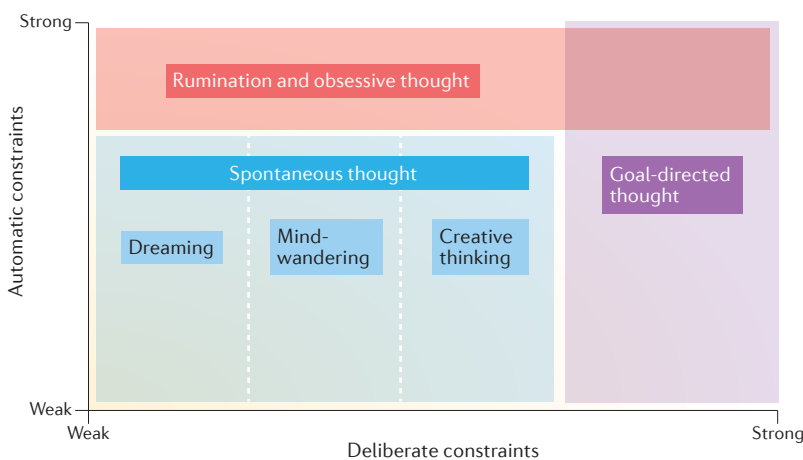

Figure 1 | **Conceptual space relating different types of thought.** Deliberate and automatic constraints serve to limit the contents of thought and how these contents change over time. Deliberate constraints are implemented through cognitive control, whereas automatic constraints can be considered as a family of mechanisms that operate outside of cognitive control, including sensory or affective salience. Generally speaking, deliberate constraints are minimal during dreaming, tend to increase somewhat during mind-wandering, increase further during creative thinking and are strongest during goal-directed thought[39]. There is a range of low-to-medium level of automatic constraints that can occur during dreaming, mind-wandering and creative thinking, but thought ceases to be spontaneous at the strongest levels of automatic constraint, such as during rumination or obsessive thought.

Stimulus-independent thought
A thought with contents that are unrelated to the current external perceptual environment.

Cognitive control
A deliberate guidance of current thoughts, perceptions or actions, which is imposed in a goal-directed manner by currently active top-down executive processes.

constructive mental simulations[43,44,46,47]. Here, we refer to this subsystem as DN_{MTL}. The third DN subsystem seems to be linked to a wide range of functions, including mentalizing, conceptual processing and emotional processing[47]. We refer to this subsystem using the generic designation 'DN_{SUB3}' because its precise role in the DN has yet to be clarified. The DN_{MTL} and DN_{SUB3} are both closely connected to the DN_{CORE}, which serves as a major conduit for information flow through the overall DN system[45].

In contrast to the DN, which seems to be primarily involved in internally oriented mental processes, the dorsal attention network (DAN) (FIG. 2b) becomes preferentially recruited when we turn our attention towards the external world[48]. The DAN is thought to support selective attention to sensory features of the environment and link this sensory information to motor responses[48]. We hypothesize that the DAN increases the stability of attention over time by constraining the spontaneous movement of attention.

Attention and the focus of thoughts frequently shift back and forth between the internal and external environment[49,50], and there seem to be corresponding reciprocal shifts between DN and DAN recruitment: when regions of the DAN are active, there is often a simultaneous deactivation of the DN in many different task paradigms[7,51]. This antagonism has been observed in intrinsic fluctuations in the functional MRI (fMRI) brain signal during rest[52] and in neuronal populations recorded using electrocorticography in people with epilepsy[53], although the stability of this antagonism across different conditions has not yet been systematically investigated.

One way in which thoughts can be triggered to shift between an internal and an external focus is when something salient captures attention in an automatic or 'bottom-up' manner. A right-lateralized ventral attention network (VAN) (FIG. 2c) may function to automatically direct (or re-orient) attention towards salient perceptual stimuli[48]. A more general salience network[54] (FIG. 2c) has been

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Box 1 | Dreams and creativity as spontaneous thought

The similarities between waking spontaneous thought and dreaming while asleep have been noted for decades[183]. Both waking thought and dreams are instantiated mainly in the audiovisual modalities, centre on one's current goals and concerns, draw heavily on semantic and episodic memory in constructing simulations and future plans, and are laden with a wide range of affect[184]. Within our framework, dreaming is a type of spontaneous thought that is highly unconstrained, hyperassociative and highly immersive, and therefore it is predicted to be associated with very low or absent deliberate constraints (although lucid dreaming is an important exception). Dreaming should also be associated with a strong influence from internal sources of variability, combined with low to medium influence from automatic constraints. At the neural level, dreaming should be accompanied by a strong recruitment of default network (DN) medial temporal lobe (MTL)-centred subsystem (DN_{MTL}) regions, relatively weak to medium recruitment in regions of the core DN subsystem (DN_{CORE}) and strong deactivations in frontoparietal control network (FPCN) regions. A recent meta-analysis[184] of studies of rapid-eye-movement (REM) sleep, the sleep stage associated with, by far, the highest rate of dreaming, reveals a pattern of activation that is consistent with these predictions (see the figure, part **a**). Whereas regions of the FPCN, including the rostrolateral prefrontal cortex (rlPFC)–dorsolateral PFC (dlPFC), show deactivation during REM sleep relative to waking rest (areas in blue), regions within the DN_{MTL}, including the hippocampal formation (HF) and parahippocampal cortex (PHC), show greater recruitment in REM sleep versus rest (areas in red). By contrast, the DN_{CORE} seems to be recruited to a comparable degree by REM sleep and waking rest. Creativity can also be seen as a form of spontaneous thought. Creative thinking may be unique among other spontaneous-thought processes because it may involve dynamic shifts between the two ends of the spectrum of constraints. The creative process tends to alternate between the generation of new ideas, which would be highly spontaneous, and the critical evaluation of these ideas, which could be as constrained as goal-directed thought in terms of deliberate constraints and is likely to be associated with a higher degree of automatic constraints than goal-directed thought because creative individuals frequently use their emotional and visceral reactions (colloquially often referred to as 'gut' reactions)

while evaluating their own creative ideas[185]. Consistent with our framework, studies demonstrate[186,187] that the DN_{MTL}, including the HF and PHC, is more active during creative-idea generation than during the evaluation of these ideas (see the figure, part **b**; areas in red). By contrast, regions within the FPCN and the DN_{CORE} are more active during the evaluation of creative ideas than during their generation (see the figure, part **b**; areas in blue). The study from which the findings in part **b** come from used functional MRI (fMRI) to examine brain activation in artists while they were drawing visual art in the scanner using an fMRI-compatible drawing tablet[186].

AI, anterior insula; dACC, dorsal anterior cingulate cortex; FEF, frontal eye field; IFG, inferior frontal gyrus; IPS, intraparietal sulcus; LingG, lingual gyrus; LTC, lateral temporal cortex; MOG, medial occipital gyrus; MT+, middle temporal motion complex; OFC, orbitofrontal cortex; PCC, posterior cingulate cortex; pIPL, posterior inferior parietal lobule; Prec, precuneus; rACC, rostral ACC; rmPFC, rostromedial PFC; SPL, superior parietal lobule; TPC, temporopolar cortex. Part **b** is adapted with permission from REF. 186, Elsevier.
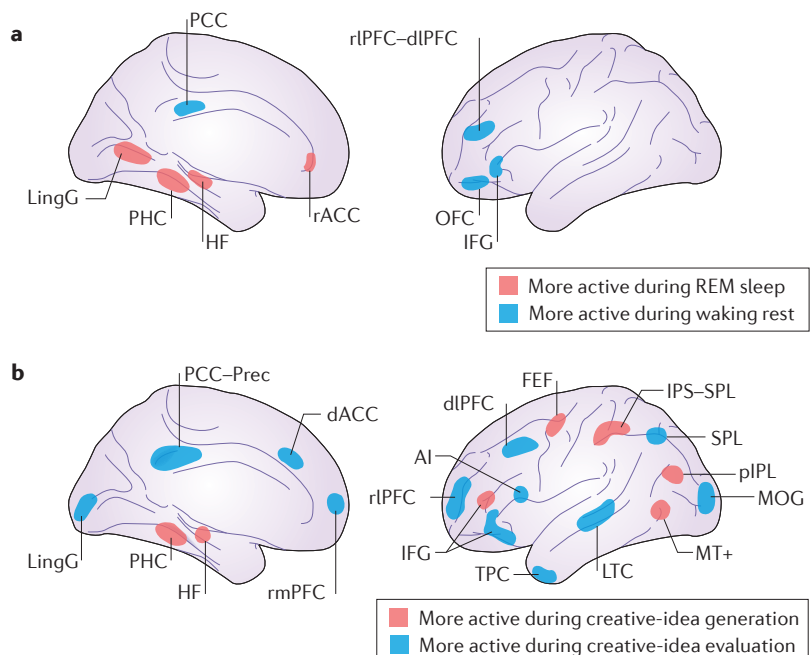
proposed to detect both external and internal salient events. Both the VAN and the general salience network are involved in automatic bottom-up salience detection, and there is substantial anatomical overlap between them, especially within areas around the anterior insula. This has led some scientists to view the VAN and the salience network as the same network[55], although others conceptualize them as distinct networks[56,57].

Shifts in attention can also occur through deliberate cognitive control. Such cognitive control[34] is closely linked to the frontoparietal control network (FPCN)[58,59] (FIG. 2d), which is involved in both internally and externally oriented goal-directed thought[60,61]. The FPCN can couple (that is, display positive functional connectivity) with the DN, to support internally focused deliberate autobiographical planning, or with the DAN, to support externally focused visuospatial planning[60]. We therefore hypothesize that the FPCN implements deliberate constraints on thought. It also seems to mediate the interactions between other networks[57,60].

Finally, cognitive control can be implemented at different timescales[62,63], which may distinguish between the FPCN and another putative control network that has been described in the literature, the cingulo-opercular control network (COCN)[64] (FIG. 2d). Regions of the FPCN show relatively transient activity that is associated with the initiation of cognitive control and short-term adjustments of cognitive control as the demands of a task change from one trial to another; by contrast, regions of the COCN show more temporally sustained activity that may be related to temporally extended cognitive-control processes such as the maintenance of a task set over time[62–64]. The rostrolateral prefrontal cortex (rlPFC) seems to participate in both the FPCN[58,65] and the COCN[62,63].

This overview of large-scale brain networks represents only the current consensus about different networks and their constituent regions. The precise anatomical boundaries and the extent of functional separation[66] between different networks remain active topics of current investigation. There may be several convergent brain zones where multiple networks intersect. For example, the area centred around the temporoparietal junction and inferior parietal lobule and the area centred around the inferior frontal gyrus and opercular region seem to act as such convergence zones. Nonetheless, the evidence for functional specificity in the contributions
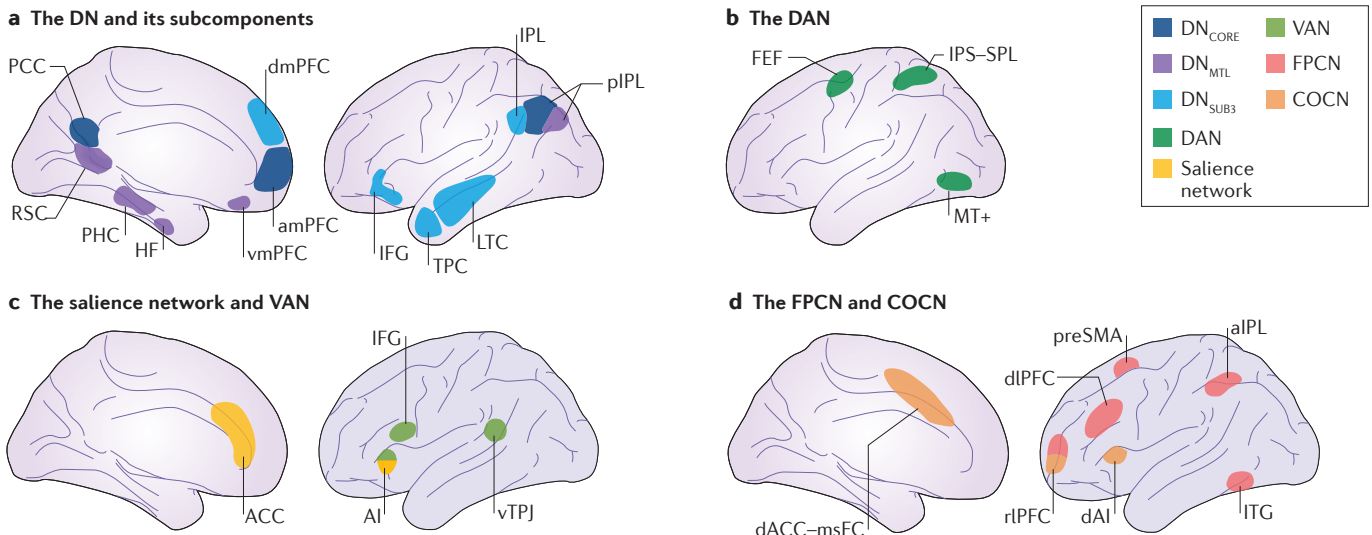

Figure 2 | **Main large-scale brain networks with relevance to spontaneous thought. a** | The default network (DN) is centred on the medial prefrontal cortex (mPFC), the medial parietal cortex and the lateral parietal cortex, and extends into the temporal lobe and lateral PFC. Three subcomponents within the DN have been identified. The first of these subcomponents, the core DN subsystem (DN$_{CORE}$), includes the anterior mPFC (amPFC), posterior cingulate cortex (PCC) and posterior inferior parietal lobule (pIPL). The second subcomponent, the DN subsystem centred around the medial temporal lobe (MTL) (DN$_{MTL}$), includes the hippocampal formation (HF) and parahippocampal cortex (PHC). The DN$_{MTL}$ also includes a number of MTL cortical projections, such as the retrosplenial cortex (RSC), the ventral mPFC (vmPFC) and the pIPL. The third subcomponent, DN$_{SUB3}$, extends more dorsally and includes the dorsomedial PFC (dmPFC), the lateral temporal cortex (LTC) extending into the temporopolar cortex (TPC), and parts of the inferior frontal gyrus (IFG). All three DN subsystems seem to include subsections of the IPL. **b** | The dorsal attention network (DAN) comprises a distributed set of regions centred around the intraparietal sulcus (IPS)–superior parietal lobule (SPL), the dorsal frontal cortex along the precentral sulcus near, or

at, the frontal eye field (FEF) and the middle temporal motion complex (MT+). **c** | The ventral attention network (VAN) comprises a ventral frontal cluster of regions, including the inferior frontal gyrus (IFG), the anterior insula (AI) and the adjacent frontal operculum (not shown); the VAN also includes the ventral temporoparietal junction (vTPJ). Although the VAN is predominantly right lateralized, a bilateral salience network has also been defined. The most prominent regions of the salience network are the AI and the anterior cingulate cortex (ACC). These regions are densely connected with subcortical structures involved in interoception and autonomic functions, which are also considered to be part of the salience network. **d** | Two 'control' networks have been discussed in the literature. The frontoparietal control network (FPCN) includes, most prominently, the dorsolateral PFC (dlPFC) and the anterior IPL (aIPL). Under a broader definition, the FPCN extends to regions including the rostrolateral PFC (rlPFC), the region anterior to the supplementary motor area (preSMA) and the inferior temporal gyrus (ITG). The cingulo-opercular control network (COCN) includes the dorsal ACC (dACC)–medial superior frontal cortex (msFC) and bilateral AI–frontal operculum. The rlPFC contributes to both the FPCN and COCN. dAI, dorsal AI.

of different networks seems to be relatively robust. In the following sections of this Review, we discuss the putative relevance and functionality of different networks with respect to spontaneous thought and its clinical disorders.

Content-based views of mind-wandering

Most empirical research to date has examined mind-wandering from a content-based perspective by assessing the contents of thoughts in terms of their relationship to an ongoing task or activity. In this approach, researchers use thought probes that ask, for example, "are you think-ing about something other than what you are currently doing?" (REF. 21). Answering "yes" to this question would be categorized as being in a state of mind-wandering. Using this approach, research has suggested a striking prevalence of task-unrelated thought in everyday life: it accounts for as much as 30–50% of our waking cognition[15,21,30].

As tasks get easier and external demands on attention become lower, the frequency of task-unrelated thoughts tends to increase[10,12,17] and so does DN recruitment[22]. Because of these parallels, early research into DN functions hypothesized a link between this network and task-unrelated thought[3,7,8]. Initial empirical support for this link came from neuroimaging studies[4,22,67,68] linking the reported frequency of task-unrelated thoughts to DN activation during conditions of low cognitive demand and showing stronger DN activation during highly prac-tised tasks compared with novel tasks in people with a higher propensity for mind-wandering[22].

This initial empirical evidence for a link between the DN and mind-wandering was tentative because it relied on indirect retrospective reports about the overall frequency of mind-wandering or on indirect inferences about its frequency based on data from independent studies. Furthermore, it did not distinguish between task-unrelated and stimulus-independent thought, leav-ing open the possibility that the DN might be involved in task-unrelated but still stimulus-oriented thought[69]. Subsequent research helped to address both of these issues by using online experience sampling measures to capture the moment-by-moment occurrence of specific instances of mind-wandering[23,70]. This research demonstrated con-clusively a consistent link between DN activation and both task-unrelated and stimulus-independent thought.

However, the DN is not the only brain network that is consistently involved in task-unrelated thought. The FPCN, especially the lateral PFC, is also consistently recruited[71]. Indeed, lateral PFC recruitment during rest was one of the earliest observations in functional neuroimaging, dating back to work by Ingvar[72] in the 1970s. It continued to be reported in subsequent stud-ies[3,4,23,67,70,73–77] exploring rest, task-unrelated thought and/or spontaneous thought.

The lateral PFC is closely linked to executive pro-cessing[78–81] and is consistently recruited during difficult tasks involving deliberate task-directed thought[6,79,81,82]. Its recruitment during task-unrelated thought and rest therefore seems counterintuitive and requires an expla-nation. One such explanation is the control failure hypo-thesis[83,84]. According to this hypothesis, task-unrelated thoughts occur because of a failure of executive control

to keep attention on the current task. Once this failure and task-unrelated thoughts have occurred, executive resources are recruited to suppress those thoughts and redirect attention to the task at hand.

Although this theory seems to be plausible, some of its key predictions are at odds with empirical findings. For example, the control failure hypothesis predicts that, when executive resources are reduced, task-unrelated thoughts should increase. However, individuals with higher working-memory capacity (a major component of execu-tive ability) show an increased frequency of task-unrelated thoughts during easy tasks[85] such as breath monitoring or identifying a target among highly dissimilar distractors. Another prediction of this theory is that, with advancing age and associated declines in executive function-ing[86], the frequency of task-unrelated thoughts should increase. Instead, research shows that task-unrelated thought decreases in frequency with advancing age[16,87]. At the neural level, stimulation of executive regions using transcranial direct current stimulation increases task-unrelated thought[88], whereas the control failure hypo-thesis would predict the opposite. Although it is possible that executive resources can, in principle, be used to sup-press task-unrelated thought, it seems unlikely that this is the main role they play during task-unrelated thought.

An alternative explanation is that executive resources are used to direct task-unrelated thoughts towards per-sonal goals[20]. One development of this view, the decou-pling hypothesis[50,89], proposes that executive resources suppress perceptual processing during task-unrelated thought. This suppression serves to decouple attention from the immediate external perceptual environment and thus 'insulates' an internally oriented thought flow against perceptual distractions. The decoupling hypo-thesis is consistent with electroencephalography find-ings of reduced cortical analysis of the external sensory environment during task-unrelated thought[90] and atten-uated sensory responses in visual and auditory cortices during task-unrelated compared with task-related mental states[91]. It is also consistent with fMRI findings showing that, during task-unrelated thought, activation in the posterior cingulate cortex (a key region of the DN_{CORE}) is inversely correlated with activation in the primary sensorimotor and extrastriate visual cortices[26].

However, the decoupling hypothesis equates task-unrelated thought with internally oriented thought. Although task-unrelated thought can sometimes be inter-nally oriented, it can also be externally oriented towards stimuli in the current perceptual environment. In princi-ple, task relatedness, internal versus external orientation and goal directedness are separable dimensions of thought (BOX 2). Nonetheless, most investigations so far have used the terms 'task-unrelated', 'internally oriented,' and 'stimulus-independent' interchangeably[26]. Furthermore, mind-wandering has, so far, been defined[25] largely based on these content-based dimensions of thought. Although mind-wandering is often task unrelated, internally ori-ented and/or stimulus independent, none of these content-based features captures the defining dynamic quality of mind-wandering: the relatively free and spontaneous arising of mental states as the mind wanders.

Constructive mental simulations
Flexible combinations of distinct elements of prior experiences, constructed in the process of imagining a novel (often future-oriented) event.

Lucid dreaming
A type of dreaming during which the dreamer is aware that he or she is currently dreaming and, in some cases, can have deliberate control over dream content and progression.

Creativity
The ability to produce ideas that are both novel (that is, original and unique) and useful (that is, appropriate and meaningful).

Experience sampling
A method in which participants are probed at random intervals and asked to report on aspects of their subjective experience immediately before the probe.

Content-based dimensions of thought
Different ways of categorizing a thought based on its contents, including stimulus dependence (whether the thought is about stimuli that one is currently perceiving), task relatedness (whether the thought is about the current task), modality (visual, auditory, and so on), valence (whether the thought is negative, neutral or positive) or temporal orientation (whether the thought is about the past, present or future).

Mind-wandering as spontaneous thought

Although cognitive neuroscience research has not yet directly investigated thought's spontaneity using experience sampling probes, a growing body of related findings hints at the potential neural basis of spontaneous thought. Not all subnetworks within the DN seem to be involved in spontaneous thought to the same extent (FIG. 3). Although the DN_{CORE} and DN_{SUB3} are more active during task-unrelated than task-related thought and during internally oriented than externally oriented thought, the DN_{MTL} does not seem to be differentially recruited along these dimensions[23,70] (FIG. 3a). Instead, the DN_{MTL} seems to be recruited when deliberate constraints on thought are relatively weak. For example, the DN_{MTL} shows stronger recruitment when participants are unaware that they are having task-unrelated thoughts than when they are aware of them[23] (FIG. 3b). This suggests a link between the DN_{MTL} and spontaneity because, in the absence of meta-awareness (that is, awareness of one's ongoing mental state), deliberate constraints are likely to be minimal.

Overall, a growing body of evidence suggests that the generation of spontaneous thought may be closely linked to the DN_{MTL} and especially its central component, the MTL itself. Converging evidence from humans and rodents suggests that spontaneous memories and spontaneous mental simulations (both of which can be considered types of spontaneous thought), during periods of awake rest, are initiated by the MTL and supported by hippocampal–cortical interactions. Using single-cell recordings in humans, one study[92] found that the spontaneous recall of film clips following a film-viewing period was preceded by an elevated firing rate in many of the same medial temporal neurons that responded while first viewing the film. The DN_{MTL} also seems to be recruited immediately before the spontaneous arising of thoughts, as revealed by a recent fMRI study[93] that used experienced mindfulness practitioners to detect the precise onset of spontaneous thoughts. In another fMRI study[94], differences in resting-state connectivity within the DN_{MTL} predicted the propensity for spontaneous memories and future thoughts during these periods of rest. Furthermore, recent findings[95] suggest that people with an increased propensity to mind-wander in daily life (as measured with a standard trait daydreaming questionnaire) exhibit more variable (that is, more dynamic) functional connectivity within the DN_{MTL} in particular. In rodents, during periods of waking rest, hippocampal place cells demonstrate a replay of previously encountered routes[96–98] and a preplay of future routes that are yet to be visited[99–101].

The hippocampus, which is a central part of the MTL, has long been linked to episodic memory[102,103]. Recent findings have also linked it to a broad range of constructive mental processes such as imagining novel scenarios and situations[43,44,104–106], constructing new spatial scenes[107] and imagining potential future experiences[108]. Based on these findings, it has been proposed that the hippocampus is involved in 'episodic simulation' — the imaginative construction of hypothetical events or scenarios that might occur in one's personal future[109].

Of particular relevance to our dynamic framework is the component process model[110] of episodic memory. According to this model, memory traces are encoded in ensembles of neurons distributed throughout the MTL and neocortex. Such ensembles are groups of spatially distributed neurons capable of firing in a coordinated manner. Hippocampal representations are proposed to have an indexing function[111], capable of reactivating the ensembles that were active during the original experience. During retrieval, cues rapidly and unconsciously trigger the activation of hippocampal representations, which then activate the ensembles that they index[112]. This model also proposes that memory becomes constrained and goal-directed only when

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Box 2 | Varieties of task-unrelated thought

The terms 'task-unrelated', 'stimulus-independent' and 'spontaneous' are sometimes used interchangeably in the cognitive and neuroimaging literature. This usage, however, is problematic because these terms designate separable dimensions of thought. To illustrate this independence, here, we list examples of task-unrelated thought that is either stimulus independent or stimulus oriented. Within each of these categories, we also list examples of task-unrelated thought that is highly constrained (in a deliberate or automatic manner) or spontaneous.

In general, the term 'stimulus' is usually used to mean 'external perceptual stimulus'. In addition, 'stimulus-independent thought' is typically equated with 'internally oriented thought', and 'stimulus-dependent thought' is typically equated with 'externally oriented thought'. Finally, the term 'goal-directed thought' refers to thought that is deliberately directed by any goals, including personal goals that may be unrelated to the task at hand. Although not included in the examples below, the contents of spontaneous thought can also shift between being externally oriented (for example, a forest trail) and being internally oriented (for example, reminiscence about one's childhood).

Stimulus-independent (internally oriented)

Deliberately constrained (goal-directed)

- While in the shower, a bobsledder deliberately and systematically visualizes each turn they will take on an upcoming run.
- While re-painting the walls of their room, a person plans their afternoon, figuring out how to combine multiple errands into a single car ride.

Automatically constrained

- While trying to fall asleep, a job candidate keeps imagining the terrors and triumphs of tomorrow's interview.
- Despite their best attempts to write a research article, a professor keeps fixating on a nasty teaching evaluation.

Spontaneous

- While driving in their car, a writer suddenly thinks of a line for the book they are writing, then remembers that they must pick up dog food on the way home, before reminiscing about the winters of their childhood and fantasizing about the career they might have had as a bobsledder.

Stimulus-oriented (externally oriented)

Deliberately constrained (goal-directed)

- To entertain himself during a boring earnings report, a manager tries to estimate who has the most expensive suit in the room.
- While listening to harsh criticism by her teacher, a student starts counting the tiles on the floor of the classroom as a means to stop herself from crying.

Automatically constrained

- While studying in a quiet library, a student finds herself unable to ignore a buzzing fly.
- A pedestrian loses the thread of his friend's conversation when he cannot help but gawk at a naked man walking down Main Street.

Spontaneous

- While hiking on a forest trail, a woman's thoughts move from the gravel on the path in front of her to a slug crawling up a stump, and then to a leaf floating in a puddle.

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these hippocampal outputs are further processed by slower and conscious control mechanisms mediated by the neocortex[103].

We propose that a similar sequence of processes may operate during episodic retrieval, episodic simulation and constructive mental processes in general. Within our framework (FIG. 4), the hippocampus acts as an internal source of variability in thought by reactivating old or activating novel (re-combined) hippocampal–neocortical ensembles. A transition from the activation of one ensemble to another would correspond to a transition between

mental states. In Jamesian terms, each activated ensemble would be a perching, and the transition from one activated ensemble to another would be a flight.

The DN_{MTL} may also contribute to thought variability by its involvement in contextual associative processing[113,114] (FIG. 3c). The DN_{MTL} may contribute to conceptual variability in the contents of thought over time when one activated ensemble cues the activation of another because they partially overlap at the neural level. This may lead to a stream of conceptually disconnected (but contextually connected) mental states.

There may also be differences within the FPCN in how it contributes to constraining thought through cognitive control. In particular, the rlPFC and the dorsolateral PFC (dlPFC) may have a role in implementing deliberate constraints at different timescales[64] or levels of abstraction[115,116]. The rlPFC is preferentially recruited when thought is broadly constrained towards internal mental events, such as when directing attention towards one's own thoughts and away from one's perceptual sensations[117]. The rlPFC is also preferentially recruited when thought is guided towards highly abstract concepts, such as during the solving of anagrams that are known to subjects to have highly abstract nouns as their solutions[115]. This suggests that the rlPFC may be involved in an abstract 'top-level management' control, constraining thought in a relatively general, nonspecific manner: for example, when the goal of thinking is to generate novel ideas for an essay topic, without limiting the nature of ideas any further than their suitability as an essay topic. This top-level control may implement relatively weak- or medium-level deliberate constraints on thought, thus allowing for some degree of spontaneous variability. By contrast, the dlPFC may be better conceptualized as being involved in 'mid-level management' — carrying out adaptive online adjustments in cognitive control based on relatively specific rules[33,34] and in direct response to specific feedback[63,118]. This mid-level control may result in some of the strongest deliberate constraints on thought.

We propose that automatic constraints on thought can be exerted by multiple brain networks and structures, such as the DN_{CORE}, the salience networks (including the VAN) and the DAN (FIG. 4). The FPCN can exert deliberate constraints on thought by flexibly coupling with the DN_{CORE}, the DAN or the salience networks, thus reinforcing or reducing the automatic constraints being exerted by the DN_{CORE}, the DAN or the salience networks. The level and type of constraints can change dynamically. For example, thought may at first be spontaneous and therefore subject to relatively weak constraints, then it may shift to become highly automatically constrained, and then it may shift again to become highly deliberately constrained (FIG. 5). We propose that these fluctuations in the level and type of constraints on thought correspond to changing interactions between large-scale brain networks (FIG. 5).

Whereas deliberate constraints are relatively well characterized and specifically linked to executive functions and control networks, automatic constraints are much more diverse and therefore probably subserved by diverse neural correlates. It is also likely that the neural

a Areas more active during task-unrelated than during task-related thoughts
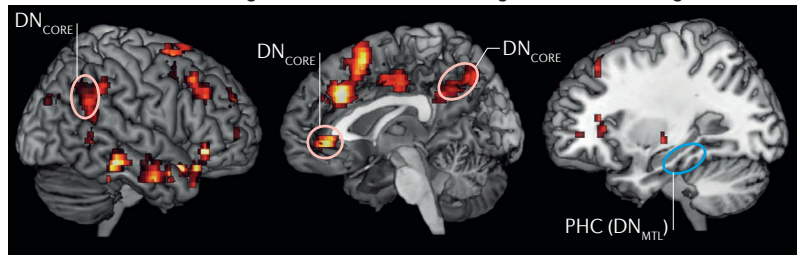
b Areas more active when unaware than when aware of task-unrelated thoughts
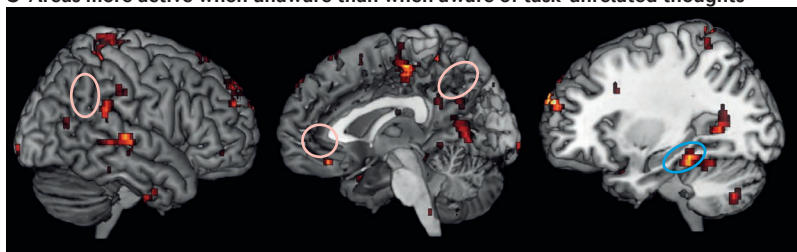
c Neural mechanisms of contextual associative processing
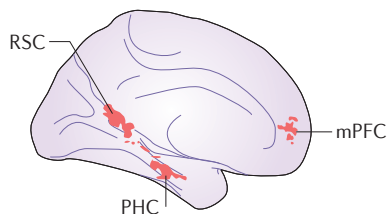
Figure 3 | **Different patterns of recruitment in the DN_{CORE} and DN_{MTL} during mind-wandering. a** | Regions within the core default network (DN) subsystem (DN_{CORE}) are more active during task-unrelated thought than during task-related thought, whereas regions within the DN subsystem centred around the medial temporal lobe (MTL) (DN_{MTL}) show similar levels of activity for task-unrelated and task-related thought. The data are from a functional MRI study[23] that used experience sampling during an ongoing task, the sustained attention to response task (SART). **b** | Regions within the DN_{MTL}, including the parahippocampal cortex (PHC), are more active when participants are unaware of their task-unrelated thoughts than when they are aware of them. Lack of awareness is likely to be associated with minimal constraints on thought, suggesting a specific link between DN_{MTL} and spontaneity. By contrast, regions within the DN_{CORE} show similar levels of activity for unaware and aware task-unrelated thought. The data are from the same study[23] as in part **a. c** | The DN_{MTL} may also contribute to spontaneous thought by its involvement in contextual associative processing. A network for contextual associative processing has been identified[113,114] that closely resembles the DN_{MTL} and includes the PHC, the retrosplenial cortex (RSC) with its associated medial parietal cortex, and the medial prefrontal cortex (mPFC). Areas within this network show greater activation when people see pictures of objects that elicit relatively strong contextual associations (for example, a traffic light) compared with pictures of objects that are not unique to any particular context and are therefore not highly associative (for example, a bag). Part **c** is adapted with permission from REF. 114, Elsevier.
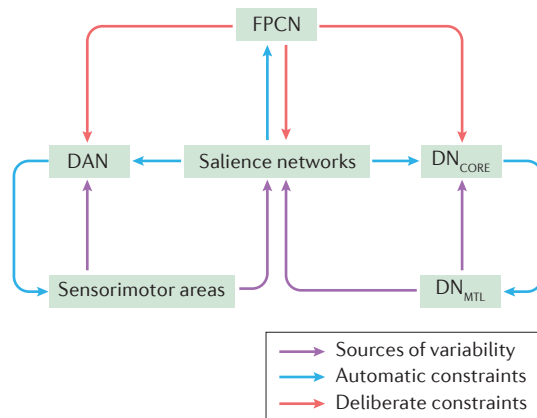
Figure 4 | **Neural model of the interactions among sources of variability, automatic constraints and deliberate constraints.** Arrows represent the influences that large-scale networks have on the dynamics of thought: networks can be sources of variability (in purple), sources of automatic constraints (in blue) or sources of deliberate constraints (in red). The default network (DN) subsystem centred around the medial temporal lobe (MTL) (DN_{MTL}) and sensorimotor areas can act as sources of variability in thought content over time. The salience networks, the dorsal attention network (DAN) and the core DN subsystem (DN_{CORE}) can exert automatic constraints on the output of the DN_{MTL} and sensorimotor areas, thus limiting the variability of thought and increasing its stability over time. The frontoparietal control network (FPCN) can exert deliberate constraints on thought by flexibly coupling with the DN_{CORE}, the DAN or the salience networks, thus reinforcing or reducing the automatic constraints being exerted by the DN_{CORE}, the DAN or the salience networks. The putative role of each network is meant to be illustrative rather than exhaustive. The model includes only those interactions that are relatively well understood given the current state of research.

basis of automatic constraints extends beyond the networks that we discuss here. For example, the basal ganglia and their associated cortico–thalamic–striatal circuits are known to be crucially involved in habit formation[119] and may exert habitual automatic constraints on thought (an excess of which may be linked to obsessive–compulsive disorder[120]). Therefore, an important goal for future research is to improve our knowledge of different types of automatic constraints and their neural basis. As we discuss next, dysfunctions in automatic constraints may be a common factor across multiple mental health disorders.

Clinical implications

Spontaneous thought is altered in a wide range of clinical conditions, including depression, anxiety, attention deficit hyperactivity disorder (ADHD) and schizophrenia. We propose that clinically significant alterations in spontaneous thought can be subdivided into two major categories: those that are marked by excessive variability of thought contents over time and those that are marked by excessive stability.

Within our framework, thought becomes spontaneous and more variable when deliberate and automatic constraints are relaxed. Whereas excessive constraints

may reduce the dynamic flow of thoughts, excessive variability may prevent thoughts from developing coherence (that is, meaningful interconnectedness among successive mental states). Therefore, both excessive constraints and excessive variability, especially when they become chronic, might have detrimental effects on cognitive functioning and emotional well-being.

Depression and rumination. Overall, depression seems to be characterized by excessive stability in thought. It is marked by increased elaboration of negative information and by difficulties in disengaging from negative material such as negative words or pictures[121,122]. One hallmark of depression is rumination, which is defined as "repetitively and passively focusing on symptoms of distress" and remaining "fixated" on one's problems and one's feelings about them[123]. People with depression experience thoughts that tend to be inflexible, perseverative[124] and characterized by excessively self-focused, mostly negative content[125,126]. Rumination is largely involuntary: individuals with depression may want to stop themselves from ruminating but are often unable to do so, suggesting that the constraints on thought in rumination are primarily automatic.

When engaged in experimental tasks, individuals with depression show several differences in neural recruitment compared with healthy controls. The DN shows greater activation in individuals with depression across a range of tasks[127,128]. Moreover, people with depression show greater activation of the salience network (specifically, the frontal insula, dorsal anterior cingulate cortex and amygdala) but lower activation of the FPCN (specifically, the dlPFC and dorsal caudate) when they are presented with negative stimuli[129]. There is also enhanced task-related coupling between the DN and salience regions in individuals with subclinical depression[130]. These results are consistent with our hypothesis that depression involves a preponderance of automatic affective constraints on thought.

Individuals with depression also show altered patterns of resting-state functional connectivity. A recent meta-analysis[131] found that, compared with healthy controls, patients with depression show increased connectivity within the DN and reduced connectivity within the FPCN. Moreover, in cases of depression, the FPCN shows increased coupling with the DN but decreased coupling with the DAN, which may reflect depressive biases towards internal thoughts at the cost of engaging with the external world[131]. We hypothesize that an overly connected DN allows the DN_{CORE} to place greater automatic constraints on the DN_{MTL}, promoting an overly constrained thought flow with an exaggerated internal orientation. Consistent with this idea, recent findings[132] suggest that patterns of resting-state connectivity in people with depression tend to be less variable over time, particularly between the medial PFC (within the DN_{CORE}) and the parahippocampus (within the DN_{MTL}).

Anxiety disorders. Like depression, anxiety disorders are characterized by repetitive negative thoughts[124,133], often accompanied by severe worry about events that might happen in the future[134]. There are both commonalities
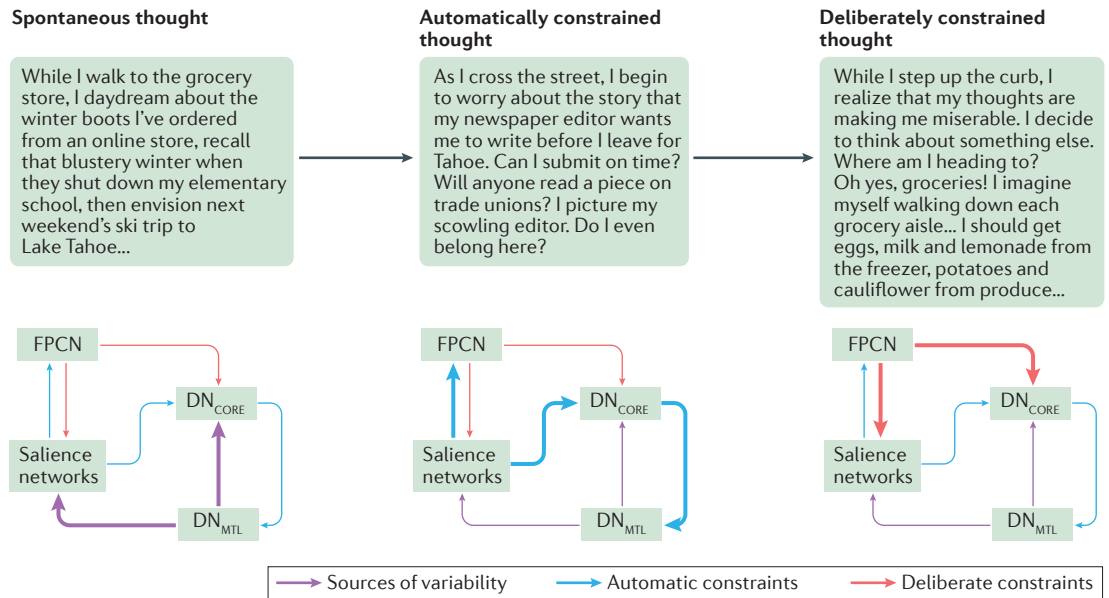
Figure 5 | **Fluctuations in the level and type of constraints may correspond to dynamically changing interactions between large-scale brain networks.** In this example, an internally oriented stream of thought, described from a person's subjective perspective, transitions from spontaneous thought to automatically constrained thought, and then to deliberately constrained thought. We propose that each transition corresponds to changing interactions among large-scale brain networks. During spontaneous, internally oriented thought, the default network (DN) subsystem centred around the medial temporal lobe (MTL) (DN_{MTL}) exerts a relatively strong diversifying influence on the stream of thought, in the context of relatively low deliberate and automatic constraints exerted by the frontoparietal control network (FPCN), core DN subsystem (DN_{CORE}) and salience networks. During automatically constrained, internally oriented thought, the salience networks and the DN_{CORE} exert relatively strong automatic constraints on thought, in the context of relatively weak internal sources of variability from the DN_{MTL} and relatively weak deliberate sources of constraint from the FPCN. Finally, during deliberately constrained, internally oriented thought, the FPCN exerts strong deliberate constraints on thought, in the context of relatively weak internal sources of variability from the DN_{MTL} and relatively weak automatic constraints by the DN_{CORE} and salience networks. Arrows represent influences on the dynamics of thought: sources of variability (in purple), automatic constraints (in blue) and deliberate constraints (in red). The thickness of an arrow represents the hypothesized relative strength of these influences during the corresponding part in the stream of thought.

and differences between anxiety and depression[135]. Like depression, anxiety is associated with attentional biases to consciously perceived stimuli[121,136]. However, patients with anxiety show biased processing of subliminally presented threat-related stimuli, whereas individuals with depression generally do not[121,122]. This suggests that anxiety biases begin in relatively early, orienting stages of information processing, before awareness of perceptual stimuli[137], whereas depressive biases occur primarily at later stages of processing involving the elaboration (that is, the conceptual interpretation) of perceptual information[122].

Within our framework, both anxiety and depression are marked by excessive automatic constraints on thought. These constraints may differ, however, in terms of the level of cognitive processing at which they begin. Consistent with this idea, anxiety disorders, like depression, are marked by alterations in recruitment and functional connectivity within the DN, FPCN and salience network[135,138,139]. What seems to be more pronounced in anxiety, however, are functional alterations in subcortical structures and their interactions with the other networks. For instance, generalized anxiety disorder is associated with disrupted subregional functional connectivity within the amygdala, which also shows enhanced connectivity with the FPCN but reduced connectivity

with the salience network[138]. In addition, the amygdala and the globus pallidus show increased activation across studies when individuals with specific phobias are presented with phobic stimuli[139]. Finally, a recent study[135] examined resting-state fMRI connectivity in individuals with anxiety disorder, depression, both anxiety and depression (comorbid), or neither anxiety nor depression (control subjects). In this study, greater severity of anxiety-specific symptoms was associated with stronger functional connectivity between the ventral striatum and subgenual anterior cingulate cortex, whereas people with depression had reduced connectivity in the same circuit compared with people without depression. Because here we focus on large-scale cortical networks, our framework does not currently highlight the specific contributions of these subcortical structures and their possible role in implementing automatic constraints. However, these topics undoubtedly remain important directions for future theoretical developments.

ADHD. Within our framework, ADHD is a disorder marked by an excessive variability in thought movement. Clinically, ADHD is characterized by a pattern of inattention and/or hyperactivity/impulsivity, which can occur in both children and adults[140]. It is associated with broad

impairments in executive functions[141,142], manifesting as lapses in attention and heightened intra-individual (that is, within-subject) variability in reaction time on cognitive tasks[143]. Failures to sustain attention on a task goal may relate to another characteristic of ADHD: excessive task-unrelated thoughts[144,145]. Spontaneous thought in ADHD has not yet been explored directly using experience sampling, but, based on our framework, we would predict heightened variability of thought content across time.

Neural alterations associated with ADHD[146–148] are consistent with it being a disorder marked by reduced constraints on thought. Task-related fMRI studies indicate that ADHD is associated with reduced activation of the FPCN and DAN[147,149], and failures to deactivate regions within the DN[150,151]. In contrast to studies focusing on depression, resting-state connectivity studies in ADHD[152–157] generally report decreased within-network functional connectivity in the DN and DAN, as well as weaker anti-correlations between key regions of the DN and control networks.

ADHD has a strong developmental component[140], and many of the neural alterations that are present in adults with ADHD are also detectable in affected children[149,151,154]. During typical development, regions within large-scale brain networks, such as the DN, are initially only sparsely connected and gradually mature into a cohesive, interconnected network[158]. Children with ADHD show a maturational delay, which is characterized by hypo-connectivity within the DN and weaker anti-correlations between key regions of the DN and control networks[154,156,159,160]. Crucially, resting-state functional connectivity in ADHD varies across DN subsystems: one study[161] found increased connectivity within the DN_{MTL} but decreased connectivity within the DN_{CORE}, consistent with an increased generation of spontaneous mental content in ADHD (from the DN_{MTL}) combined with decreased automatic constraints on thought (from the DN_{CORE}). However, these results need to be interpreted with caution because motion-induced fMRI artefacts have been shown[162,163] to have significant influence on resting-state functional connectivity findings in ADHD, especially in younger populations.

In summary, the patterns of neural alterations in ADHD suggest a general reduction in both automatic and deliberate constraints on thought, coupled with a possible increase in DN_{MTL}-derived sources of variability. Our account extends the influential hypothesis[164] that patients with ADHD are unable to suppress internally oriented cognition that is supported by the DN. This hypothesis explains why ADHD is associated with weaker anti-correlations between the DN and other networks but not why the disorder is associated with reduced connectivity within some DN subsystems. Our model explains these results, as it suggests that ADHD reflects a reduction in constraints from sources both within and outside of the DN.

Psychotic disorders. Psychotic disorders, including schizophrenia, schizoaffective disorder and psychotic bipolar disorder, are characterized by a profound disruption of thought. The symptoms of such disorders include thought disorganization, hallucinations and delusions[140]. Psychotic disorders are also characterized by notable impairments in executive functioning and processing of semantic information[165]. Psychotic thought can be marked by frequent and abrupt leaps from one topic to another[166] or by stereotyped thinking, including rigid, repetitious or barren thought content[167]. Psychotic disorders may therefore be associated with both excessive variability and excessive stability of thought, which may be present in different psychotic presentations across individuals or may occur at different times within the same individual.

At the neural level, schizophrenia is associated with widespread structural and functional brain abnormalities and with significant reductions in both grey and white matter[168]. Progressive grey-matter reductions can occur throughout the brain but are found most consistently in salience network regions, the FPCN (especially the dlPFC), and the DN_{MTL} and DN_{CORE} regions[169–171]. Whereas grey-matter alterations may be partially linked to antipsychotic drug treatments[169,172], white-matter abnormalities seem to precede treatment and may therefore be linked most directly to the disease itself[168].

Consistent with these findings, fMRI studies of psychotic disorders reveal a pattern of global dysconnectivity[173,174]. In both schizophrenia and bipolar disorder, there is reduced global functional connectivity[174]. In schizophrenia, the dlPFC shows reduced connectivity with other lateral PFC regions but increased long-range connectivity with non-FPCN regions[175], suggesting an impairment of FPCN integrity. Consistent with this finding, functional connectivity within the FPCN is reduced[176]. Within our framework, this disruption of FPCN integrity suggests that deliberate constraints on thought may still be present, but they may lack coherence and logical structure.

Schizophrenia is also associated with disruptions of connectivity within the DN[127,177]. There may be greater connectivity within the DN_{CORE} (REFS 178,179) and weaker anti-correlations between the DN and DAN during both rest and working-memory tasks[127]. Finally, there seems to be a failure of the salience network to appropriately regulate the interactions between the DN and FPCN[180].

We hypothesize that there is an overall dysregulation of both deliberate and automatic constraints on thought in psychotic disorders. There may also be a blurring between external (visual, auditory and somatosensory) and internal (DN_{MTL}) sources of variability, which in turn could be linked to a breakdown of the typical network-based functional brain organization that maintains a relative functional segregation between the processing of internal and external information.

Summary and future directions

Mind-wandering has recently become a prominent topic of research within cognitive neuroscience and psychology. However, its dynamics have been all but forgotten. Rather than emphasizing the spontaneous flow of thought, most research has instead used the terms 'mind-wandering' and 'spontaneous' as loose synonyms

for 'task-unrelated' or 'stimulus-independent'. Our framework offers explicit definitions of spontaneous thought and mind-wandering that capture those largely ignored dynamics. In doing so, we lend conceptual clarity to numerous issues. We draw conceptual distinctions between the dimensions of spontaneity, task relatedness and stimulus relatedness. Our framework can also tease apart antithetical phenomena such as mind-wandering and rumination, which seem to be indistinguishable if we focus on the static contents of thoughts to the exclusion of its dynamics. We argue that mind-wandering is best understood as a member of a family of spontaneous-thought processes — a family that also includes creative thought and dreaming. Finally, we also locate spontaneous thought within a broader conceptual space that allows its comparison to goal-directed thought, as well as to clinical alterations that make thought excessively constrained — such as in rumination and anxiety — or excessively variable — such as in ADHD.

Our conceptual framework is empirically grounded and thus makes falsifiable predictions. Overall, it predicts that fluctuations between spontaneous, automatically constrained and deliberately constrained thought correspond to changes in the interactions between large-scale brain networks. Furthermore, divisions within these large-scale networks are predicted to have different influences on the dynamics of thought. Thus, we predict that the DN_{CORE} would show increased recruitment as automatic constraints on internally oriented thought increase, whereas the DN_{MTL} would show decreased recruitment as either deliberate or automatic constraints on thought increase.

One future direction of development for our framework is to enumerate the types of automatic constraints and link them to their neural substrates. We have focused here on constraints from affective salience, which are implemented, in part, by the salience network and have clear implications for disease. However, other forms of automatic constraints, such as habits of attention that depend on cortico–thalamic–striatal circuits or neuromodulatory influences on thought by midbrain mechanisms such as the locus coeruleus noradrenaline system[181], are also likely to be of theoretical and clinical significance. Elucidating how automatic constraints are implemented could improve our understanding of how to de-automatize[188] them when they become detrimental to well-being, as in clinical conditions, or how to beneficially harness already existing automatic constrains[182], as in the case of creative thinking. Future research will also be needed to clarify the role of the DN_{SUB3} in the dynamics of thought. Regions within the DN_{SUB3} have been linked to the processing of social, semantic and emotional information, but it remains unclear how they contribute to the constraining and diversifying of thought.

Future research may particularly benefit from a neurophenomenological approach[189] that combines online experience sampling or first-person measures of ongoing thought dynamics with measures of neural activity. Such approaches may greatly benefit clinical investigations, from which a wealth of information can be gathered regarding the subjective experiences associated with disruptions in thought dynamics. To do so, however, reliable methods need to be develped for measuring the extent to which individuals' thoughts unfold in a spontaneous, automatically constrained or goal-directed manner. The development of such methods, combined with theoretical, empirical and neuroscientific advances such as those that we have reviewed here, may one day unfurl the mystery that captivated William James more than a century ago: what do the 'flights of the mind' look like, and can we ever observe them?

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