

A neural model of mind wandering

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Abstract

The role of the default-mode network in the emergence of mind wandering and task-unrelated thought has been studied extensively. In parallel work, mind wandering has been associated with neuromodulation via the locus coeruleus norepinephrine system. Here, we propose a neural model that links the two systems in an integrative framework. The model attempts to explain how dynamic changes in brain systems give rise to the subjective experience of mind wandering. The model implies a neural and conceptual distinction between an off-focus state and an active mind wandering state, and provides a potential neural grounding for well-known cognitive theories of mind wandering. Finally, the proposed neural model of mind wandering generates precise, testable predictions at neural and behavioral levels.

Keywords: mind wandering, default-mode network, locus-coeruleus, norepinephrine, adaptive-gain theory, gain-modulation

Mind wandering and the brain

Mind wandering, or engaging in trains of thought that are unrelated (or unhelpful) to current task goals, is common in daily life [1]. In recent years, mind wandering has received considerable attention in the cognitive neurosciences, with a particular focus on uncovering its neural origins. Because mind wandering appears to be a pervasive state of mental functioning, exploring its underlying mechanisms may tell us much about the human brain. In particular, understanding the causes of the attentional fluctuations that underlie mind wandering can help to identify separate brain states in which information processing is differentially affected.

The Default-Mode Network (DMN) is strongly implicated in mind wandering [2–4]. The DMN is one of the most widely studied intrinsic connectivity networks (ICNs, [5]) and includes nodes such as the medial prefrontal cortex (mPFC), the parietal cingulate cortex (PCC), precuneus, and both angular gyri. These regions are reliably activated in the absence of a task (i.e., resting-state fMRI sessions; for review, see [6]), though it is unlikely that the DMN is a purely task-negative network [7–9]. The DMN is also involved in autobiographical planning and internally guided thoughts [10,11]. Generally, activity in the core DMN nodes is positively related to mind wandering as indicated by introspective thought sampling and attentional lapses in the form of behavioral errors [3,12,13]).

Simultaneously, a second neural system - the locus coeruleus norepinephrine (LC-NE) system - has also been studied as a potential neural modulator of mind wandering [4,14,15]. Norepinephrine is assumed to control an alerting system that produces and maintains optimal levels of vigilance and performance [16,17]. A great deal of research has investigated the role of norepinephrine within the LC-NE system in supporting sustained attention (for review, see [18,19]) or attentional lapses [20]. The dynamics of the LC-NE system are commonly

separated into slow, tonic fluctuations and fast, phasic responses to stimuli that are connected via an inverse U-shape relationship: When tonic LC activity is low or high, performance-relevant phasic responses are attenuated. Measuring these dynamics is difficult because of the small size of the LC (see Box 1). Instead, activity of the LC-NE system is commonly operationalized with measures derived from the pupil diameter. This operationalization is based on correlations between simultaneously recorded neural activity and pupil diameter [18], and although this link has been somewhat speculative [21,22] the relationship between LC-NE system activity and pupil diameter was recently substantiated with electrophysiological measures in non-human primates [23]. In addition, several studies have investigated pupil diameter in a mind-wandering context: An increase in tonic pupil diameter precedes mind wandering-related errors [14], and a decrease in the phasic pupil response to stimulation is observed during episodes of mind wandering [4]. These findings have been taken as evidence for a role of the LC-NE system in mind wandering.

An intermediate level of tonic LC activity is likely required for optimal information processing; decreased or increased tonic levels are counterproductive in the sense that performance on a primary task suffers. The role of tonic LC-NE activity has been conceptualized in terms of an exploration-exploitation tradeoff [18]. In this framework, intermediate levels of tonic norepinephrine help to efficiently solve the task at hand because transient bursts in norepinephrine allow efficient selection of the most salient action in a multi-layered neural network [24]. In this sense, intermediate levels of LC-NE activity are optimal. If tonic LC-NE levels increase relative to the optimum, the brain enters an exploratory mode where incidentally high activations can evoke response patterns that otherwise would not be strong enough to cross threshold.

Functional connectivity and gain modulation of the LC-NE system may also be linked. Using large-scale simulations, a recent paper [25] showed that increases in neural gain entailed stronger functional connectivity. This finding was validated experimentally: blocks with increased baseline pupil diameter had stronger functional connectivity between brain regions. As neural gain increases there is a shift from widely distributed patterns of neural processing to tightly clustered patterns dominated by the strongest connections. Because this high-gain mode has also been characterized as facilitating exploration [18], it can be interpreted as an unstable state in which all highly interconnected networks can potentially become dominant and drive behavior. This notion is similar to the "network reset" theory of phasic LC-NE functioning proposed on the basis of experimental work in rodents and non-human primates [26]. Therefore, while short, phasic increases in LC-NE promote optimal responding by facilitating action selection, tonically high levels may cause incidental activations in task-unrelated networks to become dominant, hence shifting the focus of attention away from the task.

We argue that recent findings concerning the interaction of different brain networks can help to further specify this view of processing in the high-gain mode of mind wandering [27–29]. A study investigating the convergence of neural networks to local brain areas [27] provided evidence for the simultaneous "echoing" of signals from different ICNs within subparts of specific brain structures. This means the temporal dynamics of many independent ICNs were locally represented in spatially separate subparts of the PCC [29] and other areas including the mPFC [27], which raises the intriguing possibility that these nodes might serve as a global workspace [30,31]. Notably, the most prominent multi-network echo-structures - the PCC and mPFC - compose the core nodes of the DMN, which is consistent with existing results that the PCC and mPFC are integrating, transmodal nodes [32]. These findings

suggest the DMN consists of two subnetworks - the dorsal medial (DM) and medial temporal lobe (MTL) subsystems – which are connected and coordinated by two core hub structures, the mPFC and the PCC. This idea is further corroborated by research on the widespread functional and anatomical connectivity of the PCC, supporting its role as a cortical hub [33].

Taken together, rather than being a unified system, the core nodes of the DMN might reflect a summation of converging activity from different ICNs. An important implication is a reinterpretation of the frequently observed task-related deactivation of the core DMN nodes during experimental tasks. Rather than being evidence for the direct relationship of DMN activity and mind wandering, task-related DMN deactivations could be a mere side effect of a lower number of functionally specific ICNs active during the processing of most simple experimental tasks.

A neural model of mind wandering

We propose a neural model of the emergence of mind wandering that integrates findings regarding ICNs and the LC-NE system. A key feature of our proposal is a movement away from the idea that the core DMN nodes PCC and mPFC are directly involved in mind wandering and toward a reinterpretation of these nodes as integrative, transmodal processing units. These units adjust their activity according to the functionally specific large-scale networks that converge onto them; this would mean that the PCC and mPFC are simply common 'flags' of other, broader network processes. Instead, we propose that the driving force behind attentional focus is the LC-NE system: norepinephrine fluctuations determine a global processing state that influences efficiency in solving a task or engaging in mind wandering. As a consequence, our model proposes a fundamental difference between an exploratory "off-focus" state and active mind wandering.

Figure 1 illustrates the proposed model and Table 1 presents predictions of the model. When a participant starts performing an experimental task, engagement and motivation is initially high. This is reflected in an intermediate level of LC activity resulting in optimal neural gain (Figure 1, bottom left). In this state, brain networks that are necessary to efficiently solve the task are active (e.g., the dorsal attention network) while other networks that mainly involve functions unrelated to the task are deactivated (e.g., networks involved in memory retrieval or introspection). Because relatively few networks converge on the transmodal hub nodes PCC and mPFC (only those few activated by a simple experimental task), these nodes show relative deactivation. Because both core regions (PCC, mPFC) and subnetworks (DM, MTL) of the DMN are weakly involved, this state shows a general deactivation of the DMN.

Attention is limited in duration and constant re-engagement or refocusing of the system is required, previously described as an "endogeneously controlled refresh system" [34]. Thus, the focus of attention is periodically broadened, accompanied by a more exploratory state reflected in higher levels of tonic norepinephrine and, hence, high neural gain (Figure 1, top). The off-focus state is also accompanied by higher functional connectivity [25] and higher activity of the DMN. This effect is due to the convergence of the simultaneous activity of many different ICNs involved in the different cognitive functions corresponding to the exploratory nature of the off-focus state. Because high gain increases functional connectivity within and between networks, activity from many networks converges on the transmodal hub nodes PCC and mPFC, resulting in a relative increase of activation in these nodes and episodes of less efficient task processing [12]. Activation of the transmodal nodes allows selection of a new behavioral goal (i.e., exploitation), which may be to return to task processing or engage in mind wandering.

The probability of engaging in task-unrelated thoughts (or mind wandering) increases when the perceived attractiveness of internal processing exceeds that of actively solving the task (Figure 1, bottom right). This might happen, for example, when thoughts turn to a pressing, subjectively important issue (e.g., a "current concern" [35]) or when motivation has declined due to prolonged exposure to a monotonous task. In this way, the concentration on an internal goal during mind wandering is similar to the concentration on an external experimental goal in the on-task state. Neurally, the ICNs corresponding to the functions involved in pursuit of the internal goal are primarily engaged (e.g., the MTL subsystem of the DMN if the content of mind wandering involves projection of the self into the future [32]). As with the on-task state, during mind wandering functional connectivity would be reduced due to the differential engagement of relatively few networks and the transmodal nodes PCC and mPFC are expected to show reduced activity relative to the off-focus state. In addition, we expect to see transient bursts of LC-NE activity, albeit not locked to external stimuli but to internal events, and hence difficult to measure.

Over the course of the experiment, the participant switches between the on-task and mind wandering states. We argue, however, that it is always necessary to proceed through the proposed off-focus state. Recent research has shown that mind wandering consists of a complex, multi-faceted pattern involving episodic thought, emotion, executive control and meta-awareness in a component process account [36] featuring intricate combinations of corresponding neural responses [37]. Furthermore, intention during mind wandering has recently been identified as a key dimension with great explanatory power [38–40]. Our model is less concerned with such precise specification of the mind-wandering state and instead emphasizes the dynamics of the transitions between different attentional states. Qualitatively distinct types of mind wandering are implemented in our model as separate brain-states

involving different, specialized brain networks. Therefore, the mind-wandering state proposed in our model is not a unitary state; it represents a collection of many different states that share the feature of internally guided cognition, each with potentially different goals, meta-awareness and emotional associations. As a consequence, shifting between qualitatively different types of mind wandering would also involve a transition through the proposed off-focus state and back to the mind wandering state.

Implications of the model

Our model integrates converging empirical findings into a cogent theory that lays the foundation for the next wave of hypothesis-driven research into the neural underpinning of mind wandering. First, the model leads to specific, testable predictions at the neural and behavioral level. Second, it provides a working hypothesis to resolve opposing views. Third, it is consistent with existing, largely qualitative, cognitive perspectives on mind wandering.

The model leads to a set of predictions to guide future research into mind wandering in particular and attention in general (Table 1). The most important implication of the model is that the assumption of a unified concept of mind wandering is an oversimplification. Observed behavior and brain activity studied under the label of mind wandering might arise from the proposed off-focus state or the active mind wandering state. As a consequence, studies must carefully specify which of these phenomena is being investigated.

The model also resolves previous inconsistencies in the exploration-exploitation tradeoff, as well as other paradoxical findings recently described in relation to the DMN. Several recent studies found that activity in the DMN is inversely related to measures of behavioral variability (i.e., poorer task performance) [41–43]. For example, in a finger-tapping task, increased tap variability was associated with reduced DMN activity [43] even

though behavioral variability is consistently associated with mind wandering [44,45]. Finger-tapping does not feature any external stimulation and therefore is prone to high levels of mind wandering. Our model links an active state of mind wandering to reduced activation in the PCC/mPFC and poor task performance (Table 1), which would explain these finger-tapping findings. In contrast, studies that found a positive correlation between mind wandering and PCC/mPFC activity used sustained attention tasks where mind wandering was sampled with thought-probes [2–4,13]. In such a setting, it is likely that episodes of mind wandering are relatively sparse and most thought probes where participants indicated they were off-task likely mirrored the state we described as off-focus (exploratory) in this model.

The tripartite model describes mind wandering (but not the transient off-focus state) as an active, goal oriented state in which internally guided cognition is pursued. This conceptualization fits well with findings indicating that brain networks involved in cognitive control (e.g., the fronto-parietal network) are also active during episodes of mind wandering [3,46–48] indicating that these networks are involved in actively guiding internal trains of thoughts or protecting it against external stimuli.

The model distinguishes between different on-task, off-focus and mind-wandering states, which aligns with the general consensus among researchers that there are different stages of mind wandering. One popular theory of mind wandering is the perceptual decoupling hypothesis. Several studies have shown that mind wandering results in a loss of sensitivity to sensory stimuli [11,49] and that the DMN is involved in this process [10]. The model we propose here can be interpreted as a neural implementation of the perceptual decoupling hypothesis, where coupling with the visual and saliency networks is reduced in favor of the networks involved in mind wandering.

Our neural model is also consistent with an insightful introspection of the phenomenon that proposes a hierarchical set of qualitatively different levels of mind wandering [50]. These authors proposed that an episode of mind wandering starts with a shallow detachment from the current task not unlike the partial detachment of our off-focus state. This state has also been referred to as "tuning out" [51] and has been described as allowing almost unimpaired performance in the primary experimental task, albeit characterized by increased variability. In a second, deeper state of mind wandering, participants continue doing the task on a superficial level while actively engaging in task-unrelated thoughts; "zoning out", which corresponds to our exploitation-like state when internal goals are being pursued. The deepest level of mind wandering features an almost total lack of responsiveness to task-related stimuli, which in our model would correspond to a strong commitment to internal goals resulting in highly impaired performance.

Concluding remarks

The neural correlates of attentional fluctuations and mind wandering are complex, involving regionally specific activity fluctuations, dynamic connectivity fluctuations, and neuromodulatory effects. We argue that understanding this complex pattern of results necessitates theoretical and methodological integration of all relevant effects in a comprehensive model (refer to Box: Outstanding Questions). Here, we proposed an empirically and theoretically-driven framework that has the potential to explain results from all of these measures. We believe that focusing on one of the neural measures in isolation can lead to an oversimplified pattern of results. It is essential for future studies to simultaneously collect data reflecting the involvement of the different neural components, which will require developing better neuroimaging protocols. It is, for example, notoriously difficult to measure

BOLD activity in the LC using fMRI (Box 1), even though this is highly desirable to better understand the impact of the LC-NE system on mind wandering in particular and goal-directed cognition more generally. It is also necessary to develop sophisticated methods of analysis that integrate the separate measures in a formal framework and relate them to behavior (Box 2). Comprehensive, data-based models of mind wandering will be also be useful to those who are not studying the intricate phenomenon of mind wandering. In experiments designed to investigate other cognitive processes (e.g., decision making [52]), mind wandering will inevitably occur and obfuscate the phenomenon under investigation. In these cases, isolating and eliminating this source of noise using a suitable model (of mind wandering) can reveal new insights into the actual cognitive constructs under investigation.

References

- 1 Killingsworth, M.A. and Gilbert, D.T. (2010) A wandering mind is an unhappy mind. *Science* 330, 932
- 2 Christoff, K. (2012) Undirected thought: neural determinants and correlates. *Brain Res* 1428, 51–59
- 3 Christoff, K. *et al.* (2009) Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc Natl Acad Sci U A* 106, 8719–8724
- 4 Mittner, M. *et al.* (2014) When the Brain Takes a Break: A Model-Based Analysis of Mind Wandering. *J. Neurosci.* 34, 16286–16295
- 5 Smith, S.M. *et al.* (2009) Correspondence of the brain’s functional architecture during activation and rest. *Proc Natl Acad Sci U A* 106, 13040–13045
- 6 Buckner, R.L. *et al.* (2008) The brain’s default network: anatomy, function, and relevance to disease. *Ann N Acad Sci* 1124, 1–38
- 7 Vatansever, D. *et al.* (2015) Default Mode Dynamics for Global Functional Integration. *J. Neurosci.* 35, 15254–15262
- 8 Konishi, M. *et al.* (2015) Shaped by the Past: The Default Mode Network Supports Cognition that Is Independent of Immediate Perceptual Input. *PLOS ONE* 10, e0132209
- 9 Crittenden, B.M. *et al.* (2015) Recruitment of the default mode network during a demanding act of executive control. *eLife* 4, e06481
- 10 Andrews-Hanna, J.R. *et al.* (2010) Evidence for the default network’s role in spontaneous cognition. *J Neurophysiol* 104, 322–335
- 11 Smallwood, J. *et al.* (2013) Escaping the here and now: evidence for a role of the default mode network in perceptually decoupled thought. *Neuroimage* 69, 120–125

- 12 Weissman, D.H. *et al.* (2006) The neural bases of momentary lapses in attention. *Nat Neurosci* 9, 971–978
- 10 Mason, M.F. *et al.* (2007) Wandering minds: the default network and stimulus-independent thought. *Science* 315, 393–395
- 14 Smallwood, J. *et al.* (2011) Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. *PLoS One* 6, e18298
- 15 Smallwood, J. *et al.* (2012) Insulation for daydreams: a role for tonic norepinephrine in the facilitation of internally guided thought. *PLoS One* 7, e33706
- 16 Posner, M. and Petersen, S. (1990) The attention system of the human brain. *Annu Rev Neurosci* 13, 25–42
- 17 Petersen, S.E. and Posner, M.I. (2012) The attention system of the human brain: 20 years after. *Annu Rev Neurosci* 35, 73–89
- 18 Aston-Jones, G. and Cohen, J.D. (2005) An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annu Rev Neurosci* 28, 403–450
- 19 Sara, S.J. and Bouret, S. (2012) Orienting and reorienting: the locus coeruleus mediates cognition through arousal. *Neuron* 76, 130–141
- 20 Smith, A. and Nutt, D. (1996) Noradrenaline and attention lapses. *Nature* 380, 291
- 21 Nieuwenhuis, S. *et al.* (2010) The anatomical and functional relationship between the P3 and autonomic components of the orienting response. *Psychophysiology* DOI: 10.1111/j.1469-8986.2010.01057.x
- 22 Nieuwenhuis, S. *et al.* (2005) Decision making, the P3, and the locus coeruleus-norepinephrine system. *Psychol Bull* 131, 510–532

- 23 Joshi, S. *et al.* (2016) Relationships between pupil diameter and neuronal activity in the locus coeruleus, colliculi, and cingulate cortex. *Neuron* 89, 221–234
- 24 Usher, M. *et al.* (1999) The role of locus coeruleus in the regulation of cognitive performance. *Science* 283, 549–554
- 25 Eldar, E. *et al.* (2013) The effects of neural gain on attention and learning. *Nat Neurosci* 16, 1146–1153
- 26 Bouret, S. and Sara, S.J. (2005) Network reset: a simplified overarching theory of locus coeruleus noradrenaline function. *Trends Neurosci* 28, 574–582
- 27 Braga, R.M. *et al.* (2013) Echoes of the Brain within Default Mode, Association, and Heteromodal Cortices. *J. Neurosci.* 33, 14031–14039
- 28 Leech, R. *et al.* (2011) Fractionating the default mode network: distinct contributions of the ventral and dorsal posterior cingulate cortex to cognitive control. *J. Neurosci.* 31, 3217–3224
- 29 Leech, R. *et al.* (2012) Echoes of the brain within the posterior cingulate cortex. *J. Neurosci.* 32, 215–222
- 30 Baars, B.J. (2002) The conscious access hypothesis: origins and recent evidence. *Trends Cogn. Sci.* 6, 47–52
- 31 Dehaene, S. and Changeux, J.-P. (2011) Experimental and Theoretical Approaches to Conscious Processing. *Neuron* 70, 200–227
- 32 Andrews-Hanna, J.R. *et al.* (2010) Functional-anatomic fractionation of the brain’s default network. *Neuron* 65, 550–562
- 33 Hagmann, P. *et al.* (2008) Mapping the Structural Core of Human Cerebral Cortex. *PLoS Biol* 6, e159

- 34 Langner, R. and Eickhoff, S.B. (2013) Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychol Bull* 139, 870–900
- 35 Klinger, E. and Cox, W.M. (2011) Motivation and the Goal Theory of Current Concerns. In *Handbook of Motivational Counseling* (Cox, W. M. and Klinger, E., eds), pp. 1–47, John Wiley & Sons, Ltd
- 36 Smallwood, J. and Schooler, J.W. (2015) The Science of Mind Wandering: Empirically Navigating the Stream of Consciousness. *Annu. Rev. Psychol.* 66, 487–518
- 37 Smallwood, J. *et al.* (2016) Representing Representation: Integration between the Temporal Lobe and the Posterior Cingulate Influences the Content and Form of Spontaneous Thought. *PLOS ONE* 11, e0152272
- 38 Paul Seli *et al.* (accepted) Mind-Wandering With and Without Intention. *Trends Cogn. Sci.*
- 39 Seli, P. *et al.* (2016) On the Necessity of Distinguishing Between Unintentional and Intentional Mind Wandering. *Psychol. Sci.* 27, 685–691
- 40 Seli, P. *et al.* (2015) On the relation between motivation and retention in educational contexts: The role of intentional and unintentional mind wandering. *Psychon. Bull. Rev.* DOI: 10.3758/s13423-015-0979-0
- 41 Esterman, M. *et al.* (2012) In the Zone or Zoning Out? Tracking Behavioral and Neural Fluctuations During Sustained Attention. *Cereb Cortex* DOI: 10.1093/cercor/bhs261
- 42 Esterman, M. *et al.* (2014) Intrinsic fluctuations in sustained attention and distractor processing. *J Neurosci* 34, 1724–1730
- 43 Kucyi, A. *et al.* (2016) Dynamic brain network correlates of spontaneous fluctuations in attention. *Cereb. Cortex*

- 44 Seli, P. *et al.* (2012) Wandering Minds and Wavering Rhythms: Linking Mind Wandering and Behavioral Variability. *J Exp Psychol Hum Percept Perform* DOI: 10.1037/a0030954
- 45 Bastian, M. and Sackur, J. (2013) Mind wandering at the fingertips: Automatic parsing of subjective states based on response time variability. *Front. Psychol.* 4, doi: 10.3389/fpsyg.2013.00573
- 46 Dumontheil, I. *et al.* (2010) Recruitment of lateral rostral prefrontal cortex in spontaneous and task-related thoughts. *Q J Exp Psychol Hove* 63, 1740–1756
- 47 Smallwood, J. *et al.* (2012) Cooperation between the default mode network and the frontal-parietal network in the production of an internal train of thought. *Brain Res* 1428, 60–70
- 48 Fox, K.C.R. *et al.* (2015) The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *NeuroImage* 111, 611–621
- 49 Schooler, J.W. *et al.* (2011) Meta-awareness, perceptual decoupling and the wandering mind. *Trends Cogn Sci* 15, 319–326
- 50 Cheyne, J.A. *et al.* (2009) Anatomy of an error: a bidirectional state model of task engagement/disengagement and attention-related errors. *Cognition* 111, 98–113
- 51 Schooler, J.W. (2002) Re-representing consciousness: dissociations between experience and meta-consciousness. *Trends Cogn Sci* 6, 339–344
- 52 Forstmann, B. *et al.* (2016) Sequential sampling models in cognitive neuroscience: Advantages, applications, and extensions. *Annu Rev Psych* 67, 641–666
- 53 Ward, A.F. and Wegner, D.M. (2013) Mind-blanking: when the mind goes away. *Front. Psychol.* 4,

- 54 Sasaki, M. *et al.* (2006) Neuromelanin magnetic resonance imaging of locus ceruleus and substantia nigra in Parkinson's disease. *Neuroreport* 17, 1215–1218
- 55 Keren, N.I. *et al.* (2009) In vivo mapping of the human locus coeruleus. *NeuroImage* 47, 1261–1267
- 56 Keren, N.I. *et al.* (2015) Histologic validation of locus coeruleus MRI contrast in post-mortem tissue. *NeuroImage* 113, 235–245
- 57 Hawkins, G. *et al.* (2015) Toward a model-based cognitive neuroscience of mind wandering. *Neuroscience* 310, 290–305
- 58 Rabiner, L.R. (1989) A tutorial on hidden Markov models and selected applications in speech recognition. *Proc. IEEE* 77, 257–286
- 59 Visser, I. (2011) Seven things to remember about hidden Markov models: A tutorial on Markovian models for time series. *J. Math. Psychol.* 55, 403–415
- 60 Forstmann, B.U. and Wagenmakers, E.-J., eds. (2015) *An Introduction to Model-Based Cognitive Neuroscience*, Springer New York.

Trends

- Large-scale brain networks are important for goal-directed cognition. The default mode network (DMN) is central to mind wandering.
- The locus coeruleus norepinephrine (LC-NE) system is a potential neural modulator of mind wandering. The LC-NE system adaptively gates the transition between exploring new avenues and exploiting existing ones, known as the exploration-exploitation tradeoff.
- We propose the DMN and LC-NE systems interact to give rise to the subjective phenomenon of mind wandering.

Outstanding Questions

- What are suitable experimental paradigms to empirically discriminate the off-focus and mind-wandering states? Can a model-selection procedure based on, for example, a Hidden Markov assumption, provide evidence for the dynamical switching mediated by the off-focus state?
- How are the components of the component-process account of mind wandering [36] related to the off-focus and mind-wandering states? How is executive control and meta-awareness related to these states?
- Can the phenomenon of mind-blanking [53] be explained in terms of prolonged time in the off-focus state?
- Is it possible to replace introspective measures of mind wandering with more objective, neural-based measures?
- How are the identified electrophysiological and neuroimaging correlates of mind wandering related and can they be simultaneously measured and modeled?
- What is the best way to quantify tonic and phasic LC-NE parameters using pupillometric signals? Can these measures be validated using in-vivo imaging of the human LC?
- On what time-scale do the temporal dynamics of the human attentional system operate? Is it possible to capture them using dynamical extensions of cognitive process models?
- Can mind wandering be actively influenced by pharmacology or brain stimulation, and what are the implications for related psychopathological conditions?

Box 1. High-fidelity imaging of the locus coeruleus.

The locus coeruleus (LC) is a pontine nucleus comprised of a small group of cells with widespread projections throughout the central nervous system. Because of its small size and location deep within the brain, signal from the LC is difficult to acquire. Using structural magnetic resonance imaging, the LC cannot be seen on standard structural scans [54]; LC-tailored MRI structural sequences are required to accurately localize the LC. Recently, the first in vivo anatomical map of the human LC in standard space was created [55] using a T1-TSE sequence [54] that exploited the increased contrast that the presence of neuromelanin in the LC offers. This method was later validated with post-mortem scans and histology ([56], see Figure I).

Probabilistic maps of the LC in standard space can be used to provide an accurate region of interest (ROI) for the investigation of LC signal. However, the position of the LC might vary between individuals to such an extent that standard-space probabilistic LC maps may not provide sufficient spatial precision. This problem is exacerbated by other factors such as age-related alterations in LC signal [54]. To obtain a more precise ROI of the LC, future studies would benefit from acquiring an individual, LC-tailored (e.g., the T1-TSE) sequence for each participant.

Box 2. Cognitive Effects of Mind Wandering.

Mind wandering impairs performance in ongoing behavioral tasks, leading to higher error rates and more variable response times (e.g., [45,50]). Recent work has attempted to understand mind-wandering induced changes in behavior as the observed output of a change in latent task processing, via quantitative cognitive process models (for review, see [57]). Quantitative cognitive process models decompose observed variables, such as choices and response times, into latent components of processing that are typically of greater theoretical interest, such as information processing efficiency and cautiousness. In this way, cognitive models can address questions regarding how and why mind wandering affects observed performance during task completion.

Recent work has implemented cognitive process models in a model-based cognitive neuroscience framework. This allows mind wandering to be conceived as a neural state or process - as outlined in this Opinion - that affects the latent components of cognitive process models, which in turn affects observed behavior. To date, only one study has taken the first step toward an integrated model-based cognitive neuroscience of mind wandering ([4], Figure II). The general approach in this study can be extended to empirically test the tripartite neural model of mind wandering proposed in the main text. This extension requires development of a dynamical component (e.g., a Hidden Markov assumption [58,59]) that describes the transitions between the three states, and an experimental paradigm that can discriminate the off-focus and mind-wandering states. Not only will this allow experimental validation of the neural theory of mind wandering, but also quantitative study of the effect of the three neural states on cognition and behavior (cf. Table 1).

Figure Titles and Captions

Figure 1: Conceptual illustration of the proposed neural model of mind wandering.

When neural gain is intermediate, the participant shows optimal performance (on-task) or deliberate pursuit of internal goals (mind-wandering). In these states the transmodal hub nodes of the DMN, PCC and mPFC (red), are connected to few networks involved in performing the task; for example, the dorsal attention network (DAN; blue) during the on-task state and the MTL subsystem of the DMN (green) during the mind wandering state. During periods of increased neural gain, participants (subconsciously) consider engaging in other activities, which we term "exploration". Exploration is reflected in stronger activation and simultaneous connectivity of PCC and mPFC to many distinct brain networks (off-focus). Regions: DAN, middle frontal gyrus, frontal eye field, superior parietal lobule (blue, left to right); MTL subsystem, ventral medial PFC, hippocampal formation, posterior inferior parietal lobule (green, left to right); mPFC, PCC (red, left to right).

Figure I: Axial view of the human LC. The LC is depicted in (a) a post-mortem histological brainstem section, and (b) an in vivo T1-TSE scan. LC-tailored MRI scanning of this area was performed and the position of the LC was validated using a histological approach [55]. Image taken with permission from [55].

Figure II: Overview of a model-based cognitive neuroscience approach to mind wandering [4]. Neural data (fMRI, pupil diameter) were preprocessed to extract theoretically relevant features for use in a machine learning classifier. Self-reported ratings of mind wandering were obtained during task completion for use as training labels in the classifier. After training the classifier, behavioral trials were assigned to on-task or off-task states,

permitting quantitatively precise tests of the neural and behavioral signature of the two states.

Figure reproduced with permission from [4].