Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Psychology

Models of sustained attention

Michael Esterman[1,2] and David Rothlein[1]

Attention is not constant, but fluctuates from moment-to-moment. Multiple neurocognitive factors contribute to these fluctuations, acting to help us get 'in the zone' as well as pulling us away from this optimal and fleeting state. Models of arousal, mind wandering, cognitive resource allocation, and effort have consequences for this fundamental process. Integrating these models with an understanding of how attentional fluctuations impact information processing—from stimulus to motor representations—will help to reveal the causes and consequences of these fluctuations. This integrated perspective has implications for a range of clinical populations and cognitive processes that rely on attention.

Addresses
[1] Boston Attention and Learning Laboratory, VA Boston Healthcare System, United States
[2] Department of Psychiatry, Boston University School of Medicine, United States

Corresponding author: Esterman, Michael (esterman@bu.edu)

Current Opinion in Psychology 2019, **29**:174–180

This review comes from a themed issue on **Attention and perception**

Edited by **Sarah Shomstein**, **Andrew Leber** and **Joy Geng**

https://doi.org/10.1016/j.copsyc.2019.03.005

2352-250X/© 2018 Elsevier Inc. All rights reserved.

The ability to sustain attention is critical to most everyday tasks with real world implications that impact academic outcomes [1], safety, social communication, and mental health. Despite this, sustained attention is generally less studied than transient aspects of attention like shifting, dividing and attentional selection. What distinguishes investigations into sustained attention is the focus on performance on a single task over time, with the goal of explaining both the fluctuations within an individual as well as the individual differences in overall ability to maintain stable task performance. Until recently [2•], sustained attention research often failed to appreciate that performance fluctuates within an individual from moment-to-moment, and that these fluctuations have heterogeneous causes, each of which may impact the stream of task-directed information processing uniquely. As we will describe in a novel framework, the underlying causes of performance fluctuations are multifaceted, and are informed by research into mind wandering, arousal, motivation, effort, reward, as well as the information processing theories that underlie transient attention research. The proposed framework below indicates that a wide breadth of cognitive processes are relevant to sustained attention, thus the underlying neural architecture is, unsurprisingly, highly distributed [2•]. Further, the proposed framework may also help explain why sustained attention deficits are so ubiquitous in clinical populations, as well as link different clinical disorders to different mechanisms of dysfunction. Understanding why attention fluctuates within and across individuals will ultimately lead to a more dynamic and integrated understanding of other aspects of cognition and brain functioning in health and disease.

Empirical findings: decrements and fluctuations

Research into sustained attention was first characterized by Mackworth in 1948 [3], and was developed as a scientific discipline by the human factors research community [4]. These initial paradigms involved the detection of rare targets amongst non-targets, over long durations (minutes to hours) and was essential to the characterization of vigilance decrements, or performance decline over time. Vigilance decrements along with subjective reports have promoted a theory that sustained attention uses a limited resource that can be depleted [4]. However, what comprises this resource has been a matter of much debate and skepticism (for discussions see Refs. [5–8,9•,10]). Many paradoxical findings, such as the fact that easier tasks can sometime lead to greater vigilance decrements [11,12], as well as the demonstrable role of motivation in sustaining attention [8,13], has cast doubt on this strict resource depletion model.

Beyond decrements over time, attention, and cognitive functioning more broadly, oscillates over multiple timescales from daily (homeostatic, circadian, sleep) to subsecond variations [14,15], and this temporal structure in behavior may be related to temporal structure in ongoing neural activity [16,17]. The past few decades saw the development of new methods to characterize fluctuations in a temporal range relevant to sustained attention, on the order of seconds to minutes [18–20].

The most straightforward way to measure attentional fluctuations during sustained attention is by moment-to-moment measures of performance. Sustained attention tasks that require continuous responses [21,22], such as not-X CPTs requiring a response for frequent non-targets and response inhibition for rare targets, sample reaction times continuously at a high rate (e.g. 1 Hz). Examining the trial-to-trial variability of RTs has enabled researchers to track fluctuations in performance with a high degree of temporal resolution. Accordingly, our lab recently introduced a method to explore intraindividual fluctuations in reaction time, called the variance time course (VTC) [18,23–25,26••,27–30]. Specifically, we examined moment-to-moment deviation from the mean RT, during the gradual onset continuous performance task (gradCPT), a not-X CPT with gradually and rapidly fading scene images. Analysis of the VTC has revealed that attention fluctuates between periods of low variability, high accuracy, and small error-related adjustments ('in the zone' attentional state), and periods of higher variability, lower accuracy, and larger error-related adjustments ('out of the zone' attentional state), across multiple tasks [18,24,25]. These fluctuations in variability are largely independent of vigilance decrements [13,18] (see Figure 1).

Neurocognitive models

We have outlined two broad categories of empirical findings relating to sustained attention: decrements and fluctuations. Below we will describe neurocognitive models that set out to explain core factors that relate to sustained attention (see Figure 2).

Figure 1

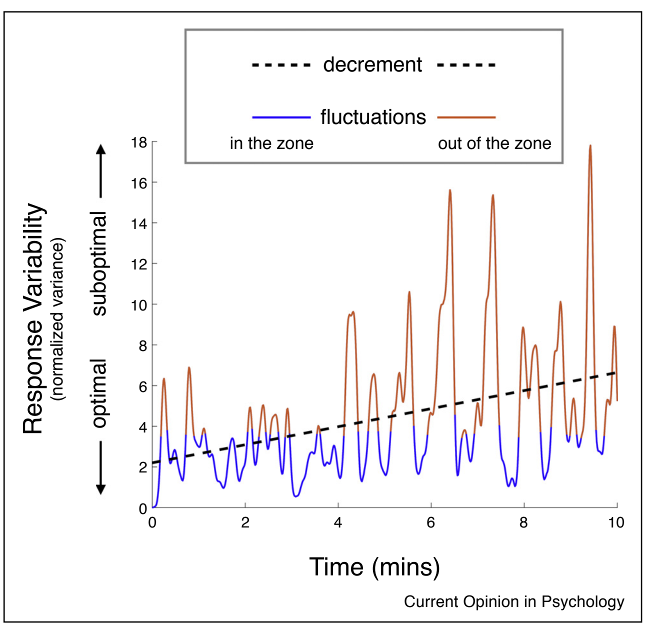


Illustration of attentional fluctuations and vigilance decrements. In this sample performance on a sustained attention task (i.e. gradCPT), performance (response variability, *y*-axis) worsens linearly across 10-min of task (vigilance decrement, dashed line). Additionally, performance fluctuates from moment-to-moment between stable (in the zone; blue) and variable (out of the zone; orange) periods.

Arousal model

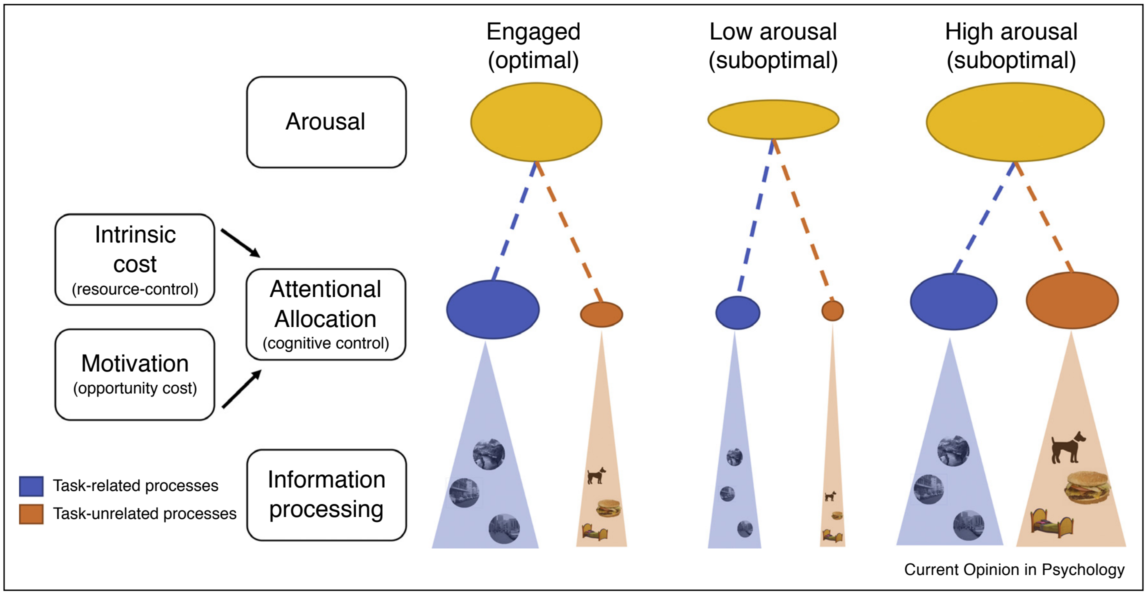
Optimal physiological arousal is critical for attention and a major contributor to arousal is the locus-coeruleus (LC) noradranergic system (for review see Refs. [31,32]). It has been demonstrated that low tonic LC activity is associated with low task engagement due to hypoarousal, while high tonic LC activity results in low task engagement due to hyperarousal and distractibility. Importantly, both suboptimal arousal states are associated with weak LC responses to task relevant stimuli (phasic responses). This has led to a classic inverted U-shaped function to describe the relationship between performance and arousal (Yerkes Dodson).

The effects of arousal are thought to impact sustained attention via LC-norepinephrine neuromodulation of frontal-parietal control regions [32,33]. Specifically, these neuromodulatory projections, at intermediate levels of LC activity, are thought to reduce background noise, and enhance neural (phasic) responses to salient stimuli, thus enhancing task-related information processing capacity and reducing signal-to-noise ratios. Recent support for the idea that arousal can have dissociable effects on sustained attention come from studies using pupillometry (a proxy for LC activity) to investigate the role of arousal in fluctuations of both objective and subjective measures of sustained attention. Specifically, several studies from Unsworth and colleagues found that mind-wandering states were associated with small pretrial tonic pupil diameters (lower arousal) and externally distracted states were associated with larger pretrial tonic pupil diameters (higher arousal) [34,35••]. Importantly, both were associated with similar behavioral/objective measures of attention (slower RTs), and smaller task-evoked phasic pupillary responses [34,35••,36]. Further, these pupillary indices of arousal tracked changes in performance over time (vigilance decrements) [35••]. Other evidence for the contribution of arousal to sustained attention comes from an experimental manipulation of arousal via the threat of shock, which enhanced sustained attention and reduced fluctuations [37]. Overall, these studies indicate that suboptimal arousal, potentially via its modulation of flexible control cortices, can account for different types of lapses of attention.

Attentional allocation

While arousal can be thought of as the baseline amount of attentional resources available to be allocated toward a given task, performance on a task is not solely a function of resource availability but also how that resource is allocated. Thought probes during sustained attention tasks (for review see Ref. [38]) have demonstrated that subjective reports of the degree to which attention is directed to the task (versus task-unrelated or stimulus-unrelated thoughts) correlate with objective measures of performance [34,39,40]. Broadly, mind wandering during a cognitive task is thought to represent task-unrelated and

Figure 2



Task performance is modulated by arousal, attentional allocation and information processing. During an optimal attentional state (for the gradCPT in this example), arousal will enable a sufficient degree of cognitive/attentional resources (yellow) and cognitive control will determine the proportion of the available resources that will be dedicated to the task, which is impacted by the intrinsic cost of control as well as motivation. In a low arousal state, there are less cognitive resources to be allocated and thus task performance may be suboptimal, even if those resources are primarily dedicated to the task. In a high-arousal/distracted state, there may be sufficient resources but attention will be less selective, as it is directed toward task-unrelated mental processes as well.

stimulus unrelated thoughts that impair ongoing performance. Recent studies of mind wandering reveal a heterogeneous process that includes a number of distinct dimensions and enable finer parsing [41,42•]. Most relevant to understanding sustained attention, the intentionality of mind wandering has been highlighted as an important distinction [43,44]. Finer characterization of intentional versus unintentional mind wandering has revealed that each can be differentially influenced by task difficulty, such that intentional mind wandering decreases with task difficulty, while unintentional mind wandering shows the opposite pattern [44] (Although see Ref. [45]). Further, motivation can differentially impact the ratio of intentional versus unintentional mind wandering [46]. Carefully designed subjective thought probes, combined with a number of the other experimental techniques described in this review, including dynamic variability measures and pupillometry measures [34,39] are helping to characterize the relationship between mind wandering and sustained attention.

Control model

The notion that task-unrelated thoughts can be intentional or unintentional alludes to the critical role cognitive control plays in sustaining attention to a task. To further explain how cognitive resources are allocated, several antagonistic theories propose that the exertion of cognitive control carries an intrinsic cost [9•,10,47]. The resource-control theory, developed from findings suggesting that mind wandering (self-generated thought) is the default state for individuals, proposes that there is a continuous bias for attentional resources to be directed toward mind wandering [47]. This model predicts that brain regions associated with attentional control (frontal-parietal and dorsal attention networks) versus mind wandering (default mode network) should both fluctuate in time with sustained attention performance, and that they should be inversely related. Further, it suggests that communication between attentional control regions and default mode regions should optimally be minimized. In support of this prediction, we recently found that greater dorsal attention-default mode coupling was associated with more variable, out-of-the-zone attentional states, suggesting the push-pull relationship between these networks impacts sustained attention [26••] (see also Ref. [25]). As further predicted by these models, periods of increased variability were associated with greater mind wandering [39]. Additionally, attentional lapses were associated with moment-to-moment increases in default mode activity and decreases in dorsal attention activity [21,48]. Finally, individuals with greater attention-default coupling across the entire task tend to have worse overall task performance [48]. Together, this evidence supports models of sustained attention that posit oscillations between ‘default’ and ‘controlled’ states, and these state transitions are reflected in fluctuations in objective measures of performance, subjective reports of mind wandering, and the ongoing dynamics of the dorsal attention and default mode networks during sustained attention tasks.

Opportunity cost model

While the control model provides an account of several empirical findings associated with sustained attention, it does not explain why controlled states are costly (or conversely why default states are preferred). One potential answer comes from the opportunity cost model, which posits that the subjective cost of cognitive control is a function of the subjective value of the current state of mental activity relative to the value of other possible mental activities, such as mind wandering. In other words, sustaining attention to a given task reflects a cost such that the higher the subjective value of possible alternative tasks relative to the current task, the greater the perceived effort [7,49•]. The focus in this theory is thus how cognitive effort is distributed on the basis of reward, valuation, and/or motivation, not diminishing availability. Experimental manipulations of motivation have helped support this model, such that performance-based rewards can enhance sustained attention [8,13,50]. Specifically, we found that by keeping motivation constant during sustained attention, with the promise of a looming potential reward, vigilance decrements were eliminated, and overall attention lapses were reduced [8] (also see Ref. [50]). Further, motivation probes show that when participants are more motivated (intrinsically), they mind wander less [46], and motivation induces strategic shifts toward more sustained and proactive engagement of attentional resources resulting in reduced attentional fluctuations [28,51]. Overall, these studies indicate that motivation and the value of sustaining attention contributes to performance fluctuations.

Information processing perspective

The previous models have all conceptualized attention as a resource that is in some way limited and thus must be allocated. However, what it means for attention to be allocated to a particular task versus task unrelated thoughts is also of central importance. Attention is thought to facilitate both the representation of task-relevant stimuli and the communication of these representations across large-scale brain networks [26••,52–56]. Recently, using the gradCPT, dynamic measures of variability within-subject, and fMRI, our lab demonstrated that in-the-zone periods were associated with increased fidelity, or reliability of visual representations as well as more effective communication of this information between visual and attentional control regions of the brain [26••]. Interestingly, the effects of motivation on information processing were orthogonal, such that there was increased communication of stimulus information between attentional networks and the default mode network—which is associated with internal mentation—during rewarded (high-motivation) trials. This suggests that when motivated, participants’ internal thoughts may in fact be more stimulus-related. Using EEG and naturalistic stimuli, another study found that attention enhances reliability of stimulus-specific patterns of brain activity, with separable effects based on manipulations of task-unrelated thoughts versus the engaging nature of the stimuli (i.e. motivation) [57]. Similarly, manipulations of top-down versus bottom-up attentional factors (such as visual interruption and task-relevance) had differential effects on the reliability of stimulus representations using fMRI [58]. Further, the use of specific information-based visual processing strategies has been associated with individual differences in sustained attention [59]. These studies suggest that information processing models can differentiate multiple states of optimal sustained attention, due to intrinsic/natural fluctuations, versus changes in external motivation and effort. These sophisticated neuroimaging approaches provide a more direct way to measure stimulus-specific processing than traditional functional activity/connectivity, which does not isolate stimulus-related from stimulus-unrelated information processing. In fact, we find that the two types of analyses can dissociate, such that greater overall activation in the dorsal attention network can be associated with weaker fidelity of visual representations [30,48]. Similarly, greater representational connectivity between dorsal attention and default mode (stimulus-specific communication) can co-occur alongside weaker functional connectivity (stimulus-unrelated communication) [26••].

In a related efficiency model, optimal sustained is thought to be a state in which information processing is accomplished with the minimum effort and computational resources. In support of this model, we have demonstrated that in-the-zone periods of stable and accurate behavior are associated with greater visual processing efficiency. Specifically, we find that processing of task-unrelated information is more extensive during these in-the-zone periods, akin to states of lower perceptual load [30]. Further, activation of attention-related brain regions tends to be higher during out-of-the-zone periods, potentially reflecting an inefficient mode of information processing [25,30,48]. Additionally, these optimal periods, compared to suboptimal periods were more negatively impacted by transcranial magnetic stimulation to dorsal attention regions, again indicating that optimal sustained attention is accomplished by efficient recruitment of top–down control [27]. One interpretation of the efficiency model is that one optimal attentional state may be more ‘effortless’, potentially related to the idea of flow [2•,18].

Future directions

These models (Figure 2) have implications for understanding attentional and cognitive dysfunction across a range of clinical populations. For example, sustained attentional impairments in ADHD have been conceptualized as deficits in arousal, motivation [60], and interactions between control and mind wandering systems [61], which could potentially explain the heterogeneity of the disorder [62]. Similarly, attentional impairments due to trauma [63–68] have been linked to both dysregulated arousal and decreased motivation due to anhedonia [69,70]. Age-related impairments in attention [29,71] may be critically linked to arousal/LC function [72]. In contrast to neuropsychiatric disorders, age-related attention problems are actually accompanied by mind wandering decreases and motivation increases [73].

In addition to further characterizing heterogeneous impairments in sustained attention, these models have the potential to inform interventions, as remediation may require a more targeted approach [74]. Interventions that target sustained attention are likely to generalize to other aspects of cognition. Van Vleet *et al.* [75] found that two weeks of a sustained attention training in older adults leads to improved working memory span and verbal fluency, further demonstrating that sustained attention underlies numerous other cognitive functions. This is consistent with recent studies that have highlighted how fluctuations in sustained attention underlie failures of working memory [32,76,77] and long-term memory encoding [78,79]. Even online feedback can reduce attentional lapses and improve working memory, potentially via arousal and/or motivational mechanisms [80].

In sum, a better appreciation for the multiple neurocognitive factors that impact the ability to sustain attention has broad implications for cognitive psychology, clinical psychology, and neuroscience. Developing novel, integrative, and reliable paradigms that can compare the relative contributions of the above the models, including neuroimaging, pupillometry, experience sampling, and individual differences will ultimately advance our understanding of sustained attention.

Conflict of interest statement

Nothing declared.

Acknowledgements

This research was supported by a Merit Review Award from the Department of Veterans Affairs Clinical Sciences Research and Development (I01CX001653) and a SPiRE Award from the Veterans Affairs Rehabilitation Research and Development (I21RX002737) to ME.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Isbell E, Calkins SD, Swingler MM, Leerkes EM: **Attentional fluctuations in preschoolers: direct and indirect relations with task accuracy, academic readiness, and school performance**. *J Exp Child Psychol* 2018, **167**:388-403 http://dx.doi.org/10.1016/j.jecp.2017.11.013.

2. • Fortenbaugh FC, Degutis J, Esterman M: **Recent theoretical, neural, and clinical advances in sustained attention research**. *Ann N Y Acad Sci* 2017, **1396**:70-91 http://dx.doi.org/10.1111/nyas.13318.

This review highlights neural models of sustained attention integrating many of the psychological models highlighted in the current report, and discusses the translational implications.

3. Mackworth NH: **The breakdown of vigilance during prolonged visual search**. *Q J Exp Psychol* 1948, **1**:6-21 http://dx.doi.org/10.1080/17470214808416738.

4. Parasuraman R, Warm JS, Dember WN: **Vigilance: taxonomy and utility**. *Ergonomics and Human Factors Recent Research*. New York, NY: Springer; 1987, 11-32 http://dx.doi.org/10.1007/978-1-4612-4756-2_2.

5. Muraven M, Baumeister RF: **Self-regulation and depletion of limited resources: does self-control resemble a muscle?** *Psychol Bull* 2000, **126**:247-259 http://dx.doi.org/10.1037/0033-2909.126.2.247.

6. Inzlicht M, Schmeichel BJ, Macrae CN: **Why self-control seems (but may not be) limited**. *Trends Cogn Sci* 2014, **18**:127-133 http://dx.doi.org/10.1016/j.tics.2013.12.009.

7. Kurzban R, Duckworth A, Kable JW, Myers J: **An opportunity cost model of subjective effort and task performance**. *Behav Brain Sci* 2013, **36**:661-679 http://dx.doi.org/10.1017/S0140525X12003196.

8. Esterman M, Grosso M, Liu G, Mitko A, Morris R, DeGutis J: **Anticipation of monetary reward can attenuate the vigilance decrement**. *PLoS One* 2016, **11**:e0159741 http://dx.doi.org/10.1371/journal.pone.0159741.

9. • Shenhav A, Musslick S, Lieder F, Kool W, Griffiths TL, Cohen JD, Botvinick MM: **Toward a rational and mechanistic account of mental effort**. *Annu Rev Neurosci* 2017, **40**:99-124 http://dx.doi.org/10.1146/annurev-neuro-072116-031526.

This review explores computational, psychological, and neuroscience perspectives on cognitive effort, and proposes an information processing perspective.

10. Botvinick M, Braver T: **Motivation and cognitive control: from behavior to neural mechanism**. *Annu Rev Psychol* 2015, **66**:83-115 http://dx.doi.org/10.1146/annurev-psych-010814-015044.

11. Pattyn N, Neyt X, Henderickx D, Soetens E: **Psychophysiological investigation of vigilance decrement: Boredom or cognitive fatigue?** *Physiol Behav* 2008, **93**:369-378 http://dx.doi.org/10.1016/j.physbeh.2007.09.016.

12. Ralph BCW, Onderwater K, Thomson DR, Smilek D: **Disrupting monotony while increasing demand: benefits of rest and intervening tasks on vigilance**. *Psychol Res* 2017, **81**:432-444 http://dx.doi.org/10.1007/s00426-016-0752-7.

13. Esterman M, Reagan A, Liu G, Turner C, DeGutis J: **Reward reveals dissociable aspects of sustained attention**. *J Exp Psychol Gen* 2014, **143**:2287-2295 http://dx.doi.org/10.1037/xge0000019.

14. Landau AN, Fries P: **Attention samples stimuli rhythmically**. *Curr Biol* 2012, **22**:1000-1004 http://dx.doi.org/10.1016/j.cub.2012.03.054.

15. Helfrich RF, Fiebelkorn IC, Szczepanski SM, Lin JJ, Parvizi J, Knight RT, Kastner S: **Neural mechanisms of sustained attention are rhythmic**. *Neuron* 2018, **99**:854-865.e5 http://dx.doi.org/10.1016/j.neuron.2018.07.032.

16. Palva JM, Zhigalov A, Hirvonen J, Korhonen O, Linkenkaer-Hansen K, Palva S: **Neuronal long-range temporal correlations and avalanche dynamics are correlated with behavioral scaling laws**. *Proc Natl Acad Sci U S A* 2013, **110**:3585-3590 http://dx.doi.org/10.1073/pnas.1216855110.

17. Clayton MS, Yeung N, Cohen Kadosh R: **The roles of cortical oscillations in sustained attention**. *Trends Cogn Sci* 2015, **19**:188-195 http://dx.doi.org/10.1016/j.tics.2015.02.004.

18. Esterman M, Noonan SK, Rosenberg M, Degutis J: **In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention**. *Cereb Cortex* 2013, **23**:2712-2723 http://dx.doi.org/10.1093/cercor/bhs261.

19. Di Martino A, Ghaffari M, Curchack J, Reiss P, Hyde C, Vannucci M, Petkova E, Klein DF, Castellanos FX: **Decomposing intra-subject variability in children with attention-deficit/hyperactivity disorder**. *Biol Psychiatry* 2008, **64**:607-614 http://dx.doi.org/10.1016/j.biopsych.2008.03.008.

20. Irrmischer M, Natalie van der Wal C, Mansvelder HD, Linkenkaer-Hansen K: **Negative mood and mind wandering increase long-range temporal correlations in attention fluctuations**. *PLoS One* 2018, **13**:e0196907 http://dx.doi.org/10.1371/journal.pone.0196907.

21. Robertson IH, Manly T, Andrade J, Baddeley BT, Yiend J: **"Oops!": performance correlates of everyday attentional failures in traumatic brain injured and normal subjects**. *Neuropsychologia* 1997, **35**:747-758 http://dx.doi.org/10.1016/S0028-3932(97)00015-8.

22. Riccio CA, Reynolds CR, Lowe P, Moore JJ: **The continuous performance test: A window on the neural substrates for attention?** *Arch Clin Neuropsychol* 2002, **17**:235-272 http://dx.doi.org/10.1016/S0887-6177(01)00111-1.

23. Rosenberg M, Noonan S, DeGutis J, Esterman M: **Sustaining visual attention in the face of distraction: a novel gradual-onset continuous performance task**. *Atten Percept Psychophys* 2013, **75**:426-439 http://dx.doi.org/10.3758/s13414-012-0413-x.

24. Rosenberg MD, Finn ES, Constable RT, Chun MM: **Predicting moment-to-moment attentional state**. *Neuroimage* 2015, **114**:249-256 http://dx.doi.org/10.1016/j.neuroimage.2015.03.032.

25. Kucyi A, Hove MJ, Esterman M, Hutchison RM, Valera EM: **Dynamic brain network correlates of spontaneous fluctuations in attention**. *Cereb Cortex* 2017, **27**:1831-1840 http://dx.doi.org/10.1093/cercor/bhw029.

26. •• Rothlein D, Degutis J, Esterman M: **Attentional fluctuations influence the neural fidelity and connectivity of stimulus representations**. *J Cogn Neurosci* 2018, **30**:1209-1228 http://dx.doi.org/10.1162/jocn_a_01306.

This study introduces an information processing perspective on attentional fluctuations, incorporating a novel method of measuring the neural impact of states of attention and motivation on stimulus processing. Results indicate that intrinsic and motivation-based fluctuations have different consequences for information processing.

27. Esterman M, Liu G, Okabe H, Reagan A, Thai M, DeGutis J: **Frontal eye field involvement in sustaining visual attention: evidence from transcranial magnetic stimulation**. *Neuroimage* 2015, **111**:542-548 http://dx.doi.org/10.1016/j.neuroimage.2015.01.044.

28. Esterman M, Poole V, Liu G, DeGutis J: **Modulating reward induces differential neurocognitive approaches to sustained attention**. *Cereb Cortex* 2017, **27**:4022-4032 http://dx.doi.org/10.1093/cercor/bhw214.

29. Fortenbaugh FC, Degutis J, Germine L, Wilmer JB, Grosso M, Russo K, Esterman M: **Sustained attention across the life span in a sample of 10,000: dissociating ability and strategy**. *Psychol Sci* 2015, **26**:1497-1510 http://dx.doi.org/10.1177/0956797615594896.

30. Esterman M, Rosenberg MD, Noonan SK: **Intrinsic fluctuations in sustained attention and distractor processing**. *J Neurosci* 2014, **34**:1724-1730 http://dx.doi.org/10.1523/JNEUROSCI.2658-13.2014.

31. Aston-Jones G, Cohen JD: **An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance**. *Annu Rev Neurosci* 2005, **28**:403-450 http://dx.doi.org/10.1146/annurev.neuro.28.061604.135709.

32. Unsworth N, Robison MK: **A locus coeruleus-norepinephrine account of individual differences in working memory capacity and attention control**. *Psychon Bull Rev* 2017, **24**:1282-1311 http://dx.doi.org/10.3758/s13423-016-1220-5.

33. Lenartowicz A, Simpson GV, Cohen MS: **Perspective: causes and functional significance of temporal variations in attention control**. *Front Hum Neurosci* 2013, **7**:381 http://dx.doi.org/10.3389/fnhum.2013.00381.

34. Unsworth N, Robison MK: **Tracking arousal state and mind wandering with pupillometry**. *Cogn Affect Behav Neurosci* 2018, **18**:638-664 http://dx.doi.org/10.3758/s13415-018-0594-4.

35. •• Unsworth N, Robison MK: **Pupillary correlates of lapses of sustained attention**. *Cogn Affect Behav Neurosci* 2016, **16**:601-615 http://dx.doi.org/10.3758/s13415-016-0417-4.

This study examined the extent to which pupillary markers of arousal are related to objective and subjective measures of sustained attention. The results suggested the pupillary markers of arousal are sensitive to different types of lapses of attention.

36. Unsworth N, Robison MK, Miller AL: **Pupillary correlates of fluctuations in sustained attention**. *J Cogn Neurosci* 2018, **30**:1241-1253 http://dx.doi.org/10.1162/jocn_a_01251.

37. Grillon C, Robinson OJ, Mathur A, Ernst M: **Effect of attention control on sustained attention during induced anxiety**. *Cogn Emot* 2016, **30**:700-712 http://dx.doi.org/10.1080/02699931.2015.1024614.

38. Smallwood J, Schooler JW: **The restless mind**. *Psychol Bull* 2006, **132**:946-958 http://dx.doi.org/10.1037/0033-2909.132.6.946.

39. Kucyi A, Esterman M, Riley CS, Valera EM: **Spontaneous default network activity reflects behavioral variability independent of mind-wandering**. *Proc Natl Acad Sci U S A* 2016, **113**:13899-13904 http://dx.doi.org/10.1073/pnas.1611743113.

40. Smallwood J, Davies JB, Heim D, Finnigan F, Sudberry M, O'Connor R, Obonsawin M: **Subjective experience and the attentional lapse: task engagement and disengagement during sustained attention**. *Conscious Cogn* 2004, **13**:657-690 http://dx.doi.org/10.1016/j.concog.2004.06.003.

41. Christoff K, Irving ZC, Fox KCR, Spreng RN, Andrews-Hanna JR: **Mind-wandering as spontaneous thought: a dynamic framework**. *Nat Rev Neurosci* 2016, **17**:718-731 http://dx.doi.org/10.1038/nrn.2016.113.

42. • Seli P, Kane MJ, Smallwood J, Schacter DL, Maillet D, Schooler JW, Smilek D: **Mind-wandering as a natural kind: a family-resemblances view**. *Trends Cogn Sci* 2018, **22**:479-490 http://dx.doi.org/10.1016/j.tics.2018.03.010.

Review of the distinction between intentional and unintentional mind wandering, including the impact of task difficulty, motivation, and individual differences.

43. Seli P, Risko EF, Smilek D, Schacter DL: **Mind-wandering with and without intention**. *Trends Cogn Sci* 2016, **20**:605-617 http://dx.doi.org/10.1016/j.tics.2016.05.010.

Review of the distinction between intentional and unintentional mind wandering, including the impact of task difficulty, motivation, and individual differences.

44. Seli P, Risko EF, Smilek D: **On the necessity of distinguishing between unintentional and intentional mind wandering**. *Psychol Sci* 2016, **27**:685-691 http://dx.doi.org/10.1177/0956797616634068.

45. Seli P, Konishi M, Risko EF, Smilek D: **The role of task difficulty in theoretical accounts of mind wandering**. *Conscious Cogn* 2018, **65**:255-262 http://dx.doi.org/10.1016/j.concog.2018.08.005.

46. Seli P, Cheyne JA, Xu M, Purdon C, Smilek D: **Motivation, intentionality, and mind wandering: implications for assessments of task-unrelated thought**. *J Exp Psychol Learn Mem Cogn* 2015, **41**:1417-1425 http://dx.doi.org/10.1037/xlm0000116.

47. Thomson DR, Besner D, Smilek D: **A resource-control account of sustained attention: evidence from mind-wandering and vigilance paradigms**. *Perspect Psychol Sci* 2015, **10**:82-96 http://dx.doi.org/10.1177/1745691614556681.

48. Fortenbaugh FC, Rothlein D, McGlinchey R, DeGutis J, Esterman M: **Tracking behavioral and neural fluctuations during sustained attention: a robust replication and extension**. *Neuroimage* 2018, **171**:148-164 http://dx.doi.org/10.1016/j.neuroimage.2018.01.002.

49. Kurzban R: **The sense of effort**. *Curr Opin Psychol* 2016, **7**:67-70
• http://dx.doi.org/10.1016/j.copsyc.2015.08.003.
Succinct review of opportunity cost and related models of cognitive effort.

50. Massar SAA, Lim J, Sasmita K, Chee MWL: **Rewards boost sustained attention through higher effort: a value-based decision making approach**. *Biol Psychol* 2016, **120**:21-27 http://dx.doi.org/10.1016/j.biopsycho.2016.07.019.

51. Braver TS: **The variable nature of cognitive control: a dual mechanisms framework**. *Trends Cogn Sci* 2012, **16**:106-113 http://dx.doi.org/10.1016/j.tics.2011.12.010.

52. Buschman TJ, Kastner S: **From behavior to neural dynamics: an integrated theory of attention**. *Neuron* 2015, **88**:127-144 http://dx.doi.org/10.1016/j.neuron.2015.09.017.

53. Desimone R, Duncan J: **Neural mechanisms of selective visual attention**. *Annu Rev Neurosci* 1995, **18**:193-222 http://dx.doi.org/10.1146/annurev.ne.18.030195.001205.

54. Qiao L, Zhang L, Chen A, Egner T: **Dynamic trial-by-trial re-coding of task-set representations in frontoparietal cortex mediates behavioral flexibility**. *J Neurosci* 2017, **37** http://dx.doi.org/10.1523/JNEUROSCI.0935-17.2017 0935-17.

55. Jackson J, Rich AN, Williams MA, Woolgar A: **Feature-selective attention in frontoparietal cortex: Multivoxel codes adjust to prioritize task-relevant information**. *J Cogn Neurosci* 2017, **29**:310-321 http://dx.doi.org/10.1162/jocn_a_01039.

56. Etzel JA, Cole MW, Zacks JM, Kay KN, Braver TS: **Reward motivation enhances task coding in frontoparietal cortex**. *Cereb Cortex* 2016, **26**:1647-1659 http://dx.doi.org/10.1093/cercor/bhu327.

57. Ki JJ, Kelly SP, Parra LC: **Attention strongly modulates reliability of neural responses to naturalistic narrative stimuli**. *J Neurosci* 2016, **36**:3092-3101 http://dx.doi.org/10.1523/JNEUROSCI.2942-15.2016.

58. Long NM, Kuhl BA: **Bottom-up and top-down factors differentially influence stimulus representations across large-scale attentional networks**. *J Neurosci* 2018, **38** http://dx.doi.org/10.1523/JNEUROSCI.2724-17.2018 2724–17.

59. Rothlein D, DeGutis J, Germine L, Wilmer J, McGlinchey R, Esterman M: **Sensitivity to stimulus similarity is associated with greater sustained attention ability**. *Atten Percept Psychophys* 2018, **80**:1390-1408 http://dx.doi.org/10.3758/s13414-018-1504-0.

60. Bubnik MG, Hawk LW, Pelham WE, Waxmonsky JG, Rosch KS: **Reinforcement enhances vigilance among children with ADHD: comparisons to typically developing children and to the effects of methylphenidate**. *J Abnorm Child Psychol* 2015, **43**:149-161 http://dx.doi.org/10.1007/s10802-014-9891-8.

61. Bozhilova N, Michelini G, Kuntsi J, Asherson P: **Mind wandering perspective on ADHD**. *Neurosci Biobehav Rev* 2018, **92**:464-476 http://dx.doi.org/10.1016/j.neubiorev.2018.07.010.

62. Mueller A, Hong DS, Shepard S, Moore T: **Linking ADHD to the neural circuitry of attention**. *Trends Cogn Sci* 2017, **21**:474-488 http://dx.doi.org/10.1016/j.tics.2017.03.009.

63. Aupperle RL, Melrose AJ, Stein MB, Paulus MP: **Executive function and PTSD: disengaging from trauma**. *Neuropharmacology* 2012, **62**:686-694 http://dx.doi.org/10.1016/j.neuropharm.2011.02.008.

64. DeGutis J, Esterman M, McCulloch B, Rosenblatt A, Milberg W, McGlinchey R: **Posttraumatic psychological symptoms are associated with reduced inhibitory control, not general executive dysfunction**. *J Int Neuropsychol Soc* 2015, **21**:342-352 http://dx.doi.org/10.1017/S1355617715000235.

65. Fortenbaugh FC, Corbo V, Poole V, McGlinchey R, Milberg W, Salat D, DeGutis J, Esterman M: **Interpersonal early-life trauma alters amygdala connectivity and sustained attention performance**. *Brain Behav* 2017, **7**:e00684 http://dx.doi.org/10.1002/brb3.684.

66. Lim L, Hart H, Mehta MA, Simmons A, Mirza K, Rubia K: **Neurofunctional abnormalities during sustained attention in severe childhood abuse**. *PLoS One* 2016, **11**:e0165547 http://dx.doi.org/10.1371/journal.pone.0165547.

67. Hart H, Lim L, Mehta MA, Chatzieffraimidou A, Curtis C, Xu X, Breen G, Simmons A, Mirza K, Rubia K: **Reduced functional connectivity of fronto-parietal sustained attention networks in severe childhood abuse**. *PLoS One* 2017, **12**:e0188744 http://dx.doi.org/10.1371/journal.pone.0188744.

68. Esterman M, Fortenbaugh F, Pierce M, Fonda J, Degutis J, Milberg W, McGlinchey R: **Trauma-related psychiatric and behavioral conditions are uniquely associated with sustained attention dysfunction.** *Neuropsychology* (in press).

69. Dutra SJ, Marx BP, McGlinchey R, DeGutis J, Esterman M: **Reward ameliorates posttraumatic stress disorder-related impairment in sustained attention**. *Chronic Stress* 2018, **2** http://dx.doi.org/10.1177/2470547018812400.

70. Nawijn L, van Zuiden M, Frijling JL, Koch SBJ, Veltman DJ, Olff M: **Reward functioning in PTSD: a systematic review exploring the mechanisms underlying anhedonia**. *Neurosci Biobehav Rev* 2015, **51**:189-204 http://dx.doi.org/10.1016/j.neubiorev.2015.01.019.

71. Huntley JD, Hampshire A, Bor D, Owen AM, Howard RJ: **The importance of sustained attention in early Alzheimer's disease**. *Int J Geriatr Psychiatry* 2017, **32**:860-867 http://dx.doi.org/10.1002/gps.4537.

72. Mather M, Harley CW: **The locus coeruleus: essential for maintaining cognitive function and the aging brain.** *Trends Cogn Sci* 2016, **20**:214-226 http://dx.doi.org/10.1016/j.tics.2016.01.001.

73. Seli P, Maillet D, Smilek D, Oakman JM, Schacter DL: **Cognitive aging and the distinction between intentional and unintentional mind wandering**. *Psychol Aging* 2017, **32**:315-324 http://dx.doi.org/10.1037/pag0000172.

74. Esterman M, Thai M, Okabe H, DeGutis J, Saad E, Laganiere SE, Halko MA: **Network-targeted cerebellar transcranial magnetic stimulation improves attentional control**. *Neuroimage* 2017, **156**:190-198 http://dx.doi.org/10.1016/j.neuroimage.2017.05.011.

75. Van Vleet TM, DeGutis JM, Merzenich MM, Simpson GV, Zomet A, Dabit S: **Targeting alertness to improve cognition in older adults: a preliminary report of benefits in executive function and skill acquisition**. *Cortex* 2016, **82**:100-118 http://dx.doi.org/10.1016/j.cortex.2016.05.015.

76. Unsworth N, Robison MK: **The importance of arousal for variation in working memory capacity and attention control: a latent variable pupillometry study**. *J Exp Psychol Learn Mem Cogn* 2017, **43**:1962-1987 http://dx.doi.org/10.1037/xlm0000421.

77. Adam KCS, Mance I, Fukuda K, Vogel EK: **The contribution of attentional lapses to individual differences in visual working memory capacity**. *J Cogn Neurosci* 2015, **27**:1601-1616 http://dx.doi.org/10.1162/jocn_a_00811.

78. deBettencourt MT, Norman KA, Turk-Browne NB: **Forgetting from lapses of sustained attention**. *Psychon Bull Rev* 2018, **25**:605-611 http://dx.doi.org/10.3758/s13423-017-1309-5.

79. Aly M, Turk-Browne NB: **Attention promotes episodic encoding by stabilizing hippocampal representations**. *Proc Natl Acad Sci U S A* 2016, **113**:E420-E429 http://dx.doi.org/10.1073/pnas.1518931113.

80. Adam KCS, Vogel EK: **Reducing failures of working memory with performance feedback**. *Psychon Bull Rev* 2016, **23**:1520-1527 http://dx.doi.org/10.3758/s13423-016-1019-4.