The disentanglement of the neural and experiential complexity of self-generated thoughts: A users guide to combining experience sampling with neuroimaging data

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Abstract

Human cognition is not limited to the processing of events in the external environment, and the covert nature of certain aspects of the stream of consciousness (e.g. experiences such as mind-wandering) provides a methodological challenge. Although research has shown that we spend a substantial amount of time focused on thoughts and feelings that are intrinsically generated, evaluating such internal states, purely on psychological grounds can be restrictive. In this review of the different methods used to examine patterns of ongoing thought, we emphasise how the process of triangulation between neuroimaging techniques, with self-reported information, is important for the development of a more empirically grounded account of ongoing thought. Specifically, we show how imaging techniques have provided critical information regarding the presence of covert states and can help in the attempt to identify different aspects of experience.

Keywords: MRI; EEG; ERP; Connectivity; Mind-wandering; Self-generated thoughts

1 Why use neuroimaging methods to study ongoing thought?

Cognition is not always focused on the events taking place in the environment, we often spend large periods of time immersed in thoughts that are generated intrinsically. A common example of such a self-generated experiential state is the experience of mind-wandering where, instead of processing information from the external environment, one's attention is directed toward internal thoughts, feelings and personal reflections (Seli et al., 2018). Research suggests that mind-wandering takes up anywhere from a third to half of our mental life (Kane et al., 2007), has an impact on everyday life activities (Cowley, 2013; McVay et al., 2009) and has been observed across multiple cultures (Deng et al., 2012; Levinson et al., 2012; Smallwood et al., 2009; Song and Wang, 2012; Tusche et al., 2014).

By nature, therefore, ongoing thought is subject to a continuous evolution across time, and these changes can often occur in a covert manner (Smallwood, 2013). While techniques such as experience sampling (Csikszentmihalyi and Larson, 1987) make it possible to estimate participants' thoughts and feelings as they occur, providing an ‘online’ measure of experience, this data relies on subjective self-reports, rather than objective measurements. By comparison, although behavioural indices of ongoing thought may be less subjective because they provide measures of the observable consequences associated with performing dull, monotonous tasks, studies suggest that there is not a one to one mapping between slips of action and patterns of off-task thought (Konishi et al., 2017). The limitations of both subjective and behavioural indices, therefore, make it a challenge to establish a mature scientific account of ongoing thought.

This review considers the advantages that can be gained when patterns of ongoing thought are examined using the strategy of *triangulation* whereby self-reports, behavioural measures, and neurocognitive measures are used in concert (Smallwood and Schooler, 2015). We will argue that neuroimaging tools are important for understanding two aspects of ongoing thought. In particular, the tools of cognitive neuroscience (i) can provide insight into whether experience is focused externally or internally and (ii) will help determine the different forms that experiences can take with consideration of the underlying mechanisms. Before considering how neuroimaging can be combined with subjective measures of ongoing thought, this review will briefly consider the different methods of experience sampling, with a specific aim to consider their strengths and weaknesses in studies of neuroimaging (see Fig. 1., a flow chart describing the analytical decisions guiding the use of neuroimaging technics in the investigation of ongoing thought).

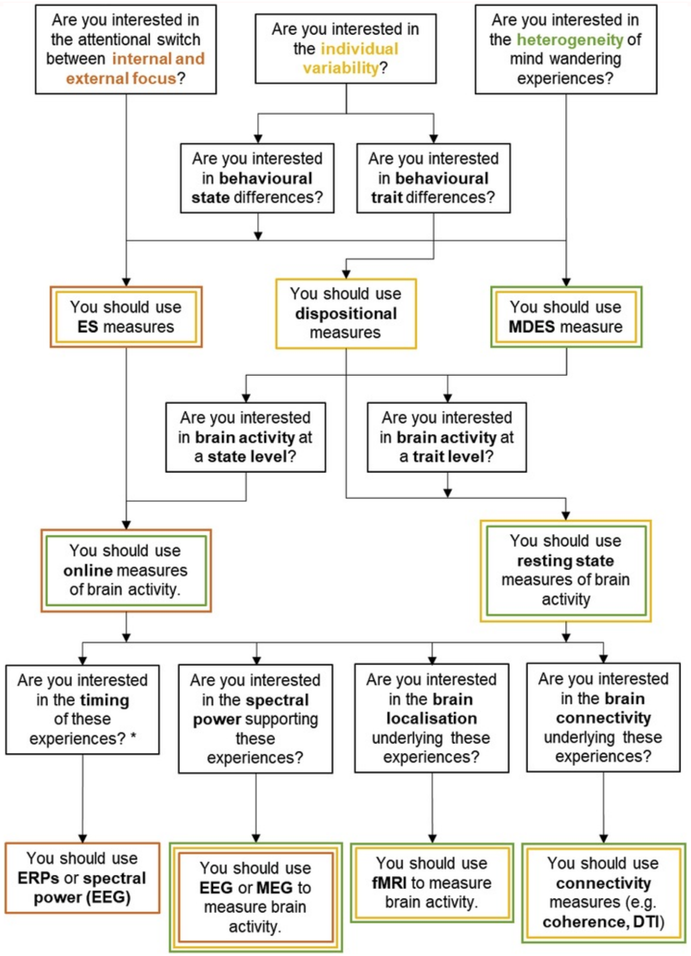

Fig. 1 Flow chart describing the analytical decisions guiding the use of neuroimaging technics in the investigation of ongoing thought. * This question can only be answered using online measure of brain activity. *Note*: ES = Experience Sampling, MDES = Multidimensional Experience Sampling.

alt-text: Fig. 1

2 Methodology of measuring ongoing thought

Although ongoing thought is a challenge to study, experience sampling remains the gold standard measure for identifying the explicit contents of consciousness (Smallwood and Schooler, 2015). There are a number of different methods of estimating patterns of ongoing thought and here we highlight the different self-report methods that can be combined with neuroimaging techniques.

2.1 Self-report methods

There are three basic methods of experience sampling that are used in studies of ongoing thought: online experience sampling, retrospective experience sampling, and assessment of disposition. Online experience sampling involves gathering self-reports regarding a participant's ongoing experience ‘in the moment’ while they are completing other activities. The *probe-caught method* requires participants to be intermittently interrupted, often while performing a task, and are asked to describe the content of their experience (Smallwood and Schooler, 2006). Within this area of research there are two main methods of analysis. One gains open reports from the participants which are then coded based on predefined characteristics, for example whether they are related to the task, or aspects of their content (Baird et al., 2011; Hulburt et al., 2006; Smallwood et al., 2003). Other approaches require that participants answer questions that probe specific aspects of experience such as its level of deliberation (Seli et al., 2017) or its level of awareness (Smallwood et al., 2007b). A second type of online experience sampling is the *self-caught method* where participants are asked to spontaneously report their mind-wandering episodes at the moments they are noticed (Smallwood and Schooler, 2006). In such paradigms, participants are asked to press a button when noticing that their mind has drifted away from the task at hand. Both types of online experience have the advantage of being able to determine the patterns of thought taking place at a specific moment in time.

Experience can also be sampled at the end of a task. In this approach, self-reported data is gathered retrospectively at the end of a task or a block of trials, rather than in the moment. Smallwood and Schooler (2015) refer to this as *retrospective sampling* as it involves gathering estimations of experiences immediately after the task has been completed. The advantage of this method is that it preserves the natural time course of ongoing thought, as participants do not need to be interrupted to report their experience. Retrospective, end of task estimations of mind-wandering may be gathered via single questions at the end of a task, via questionnaires (e.g. the Dundee Stress State Questionnaire, DSSQ; Matthews et al., 1999), using the New York Cognition Questionnaire (Gorgolewski et al., 2014; Wang et al., 2018a,b) or through open-ended questions. As retrospective measures do not interrupt the dynamics of cognition, their combination with online measures of neural function provides a promising way to understand the broader temporal dynamics of experience, using techniques that exploit temporal changes in neural signals such as functional connectivity (Biswal et al., 1996), hidden Markov modelling (Vidaurre et al., 2017) or sliding window analysis (Kucyi et al., 2017). However, a weakness of the retrospective approach is that this method relies on memory, making it impossible to relate self-reported data to a specific moment in time. Table 1 presents a summary of the different questionnaires that are available for use in both the online and retrospective domains.

Table 1 Most useful questionnaires to use in association with resting state fMRI scan, with a description of their purpose and aimed population.

alt-text: Table 1

Questionnaire	Description	Purpose	Population	Examples
Retrospective measures				
New York Cognition Questionnaire (Gorgolewski et al., 2014)	31-items and 2 subscales, the first containing questions about the content of thoughts (past, future, positive, negative, and social experiences), the second containing questions about the form that these thoughts take (words, images, and thought specificity).	Assess thoughts and feelings experienced during the performance of a particular task and at rest.	Any age in adulthood. Patients (e.g. generalised anxiety disorder) and healthy participants.	(Makovac et al., 2018; Sanders et al., 2017; Wang et al., 2018a,b)
Amsterdam Resting state questionnaire (Diaz et al., 2013)	50-items from which 5 factors can be extracted: Discontinuity of Mind, Theory of Mind, Self, Planning, Sleepiness, Comfort, and Somatic Awareness	Assess thoughts and feelings experienced during rest. Sensitive to brain disorder.	Patients (e.g. obsessive-compulsive personality disorder) and healthy participants of any age in adulthood.	(Coutinho et al., 2016; Diaz et al., 2014; Stoffers et al., 2015)
Resting state questionnaire (Delamillieure et al., 2010)	Semi-structured questionnaire of 62-items composing 5 types of mental activity: visual mental imagery, inner language (split into two subtypes: inner speech and auditory mental imagery), somatosensory awareness, inner musical experience, and mental manipulation of numbers.	Assess thoughts and feelings experienced during rest.	Healthy participants of any age in adulthood.	(Chou et al., 2017; Doucet et al., 2012; Hurlburt et al., 2015; Paban et al., 2018)
Probe and self-caught measures				
Multi-Dimensional Experience Sampling (e.g. Ruby et al., 2013a)	Multiple questions used in a probe caught context. The first question is referencing to task focus and the following 12 are targeting characteristics such as future, past, self, and detailed features of the experience.	Captures simultaneously different aspects of experience allowing their heterogeneity to be empirically evaluated in an online context.	Any age in adulthood. Patients and healthy participants.	(Golchert et al., 2017; Konishi et al., 2017; Medea et al., 2016; Smallwood et al., 2016; Turnbull et al., 2019)
Shape Expectations Task (O'Callaghan et al., 2015)	Task with minimal external stimulation and without constraints to perform on a cognitive task. Can be implemented by thought probes with free report of thought content. A scoring system is then used to evaluate thought frequency and content.	Investigate the frequency and content of mind wandering in the context of low cognitive demands.	Healthy participants of any age in adulthood. Particularly relevant for populations with reduced cognitive resources (e.g. older adults, dementia patients).	(Geffen et al., 2017; Irish, Goldberg, Alaeddin, O'Callaghan and Andrews-Hanna, 2018; O'Callaghan et al., 2017)

As originally suggested by Eric Klinger (Klinger and Cox, 1987) and Jerome Singer (for a review see McMillan et al., 2013; Singer, 1975), an emerging body of evidence has found that ongoing experience is heterogeneous with multiple distinct types of experience that may each have unique cognitive profiles (Smallwood and Andrews-Hanna, 2013). In this context, it has become important to assess multiple dimensions of experience at the same time (Golchert et al., 2017; Karapanagiotidis et al., 2017; Konishi et al., 2017; Medea et al., 2016; Ruby et al., 2013a,b; Smallwood et al., 2016; Wang et al., 2018a,b). This approach is often described as Multi-Dimensional Experience Sampling (MDES; Shrimpton et al., 2017; Smallwood et al., 2016) and allows the experimenter to simultaneously capture different aspects of experience allowing their heterogeneity to be empirically evaluated. Neuroimaging methods are particularly important in this regard because it remains unclear whether different types of experience can share underlying neural features (as would be expected if common cognitive processes are important in multiple different types of experience). ~~In this context~~Therefore, neuroimaging techniques ~~are important because they~~ raise the possibility of objectively identifying whether similar neural regions are involved in different states (e.g. through the analysis of spatial conjunction). For example, Smallwood et al. (2016) found that multiple different aspects of experience - thoughts related to different temporal periods, off-task thoughts, and thoughts with vivid detail were associated with stronger connectivity at rest between regions of the temporal lobe and the posterior cingulate cortex. This observation has important consequences for neurocognitive accounts of different types of experience emerge because they illustrate that multiple types of experience may depend on similar brain regions.

It is also possible to measure dispositional differences in patterns of ongoing thought using questionnaires that map traits linked to different types of experience. For example, the Imaginal Processes Inventory (IPI; Huba et al., 1982), the Mind-Wandering Questionnaire (MWQ; Mrazek et al., 2013), and the Mind-Wandering Deliberate and Spontaneous scale (Carriere et al., 2013; Seli et al., 2015a) are all individual difference measures which ask participants to assess the characteristics of their daydreams or mind-wandering experiences in the context of their daily functioning. Similar to end of task estimation measures, this method relies on retrospective judgements concerning previous mind-wandering experiences rather than online reporting. However, when these measures are used, participants have to think back over a longer period of time when reporting their experience and this presents greater risk of biases in reporting.

These different types of experience sampling enable researchers to investigate the role of individual differences on laboratory-based mind-wandering tasks and gather information regarding general patterns of ongoing thought in the real world, making them more ecologically valid. Interestingly, different characteristics can be found between experience sampling in the laboratory and in daily-life (Kane et al., 2017). While each approach has weaknesses, in combination, they offer the potential to refine our understanding of the nature of ongoing thought. For example, measures of typical mind-wandering styles have been successfully associated with experience sampling, giving insight about the association between temporal focus and self-related thoughts (Shrimpton et al., 2017), and the verification of differences in spontaneous and deliberate mind-wandering both through associations with ADHD (Seli et al., 2015b) and in the brain (Golchert et al., 2017).

2.2 Behavioural Methods

Building on evidence that certain forms of experience are linked to measures of performance on a task, research has also focused on the possibility that behavioural markers could provide additional insight into the processes underlying different aspects of experience. ~~Often this involves examining performance on tasks that encourage the onset of mind wandering in the first place~~Often this involves examining performance on tasks that encourage the onset of particular types of experience (e.g. mind wandering) in the first place because they are simple and non-demanding and one in which the occurrence of the experience is likely to have a consequence for performance. Examining the consequence of a particular covert state in this manner has a long history in psychology where direct measurement is not possible. For instance, when examining the cost of dual tasking on everyday memory, measures are not only made on the secondary task but also on the primary task (Huang and Mercer, 2001). Here, one can consider the ongoing activity of self-generated thoughts as a primary task, which will impact one's performance on the secondary task. As such, by measuring the secondary task, one gains information about the primary task, namely the self-generation of thoughts (Teasdale et al., 1995; Teasdale et al., 1993). One of the first examples of this procedure was a study by Teasdale et al. (1993) who showed that during a task of random number generation, the occurrence of off-task thoughts were linked to periods when the participant had begun to generate more predictable series of digits (Teasdale et al., 1995). Episodes of poorer performance on this secondary task, for example in terms of accuracy, false alarms, or reaction time variability are assumed to signal the occurrence of patterns of ongoing thought that are not related to efficient performance of the task. This technique has been applied to a wide range of different task paradigms and demonstrated that periods of off-task thought are linked to worse performance on tasks measuring encoding (Smallwood et al., 2003), reading (Smallwood et al., 2008), working memory (Kane et al., 2007), and intelligence (Mrazek et al., 2012).

A task that has frequently been used to both encourage and measure mind-wandering is the Sustained Attention Response Task (SART; Robertson et al., 1997). This requires participants to respond as quickly as possible to frequent and relevant stimuli (e.g., 'press the space bar when the letter X appears') whilst inhibiting their responses to infrequent stimuli (e.g. 'do nothing when the letter Y appears'). One advantage of this method is that researchers may use it to manipulate the prevalence of mind wandering by varying the demands of the task. For example, in an investigation into the effect of glucose on mind-wandering, Birnie et al. (2015) found that probed self-reports of mind-wandering were associated with false alarms on the SART (i.e., erroneously pressing the response key to the infrequent stimuli). Furthermore, this association was stronger on easier trials of the SART, supporting the inference that mind-wandering is more prevalent when the demands of the ongoing tasks are low. The use of the SART in the literature is extensive and has uncovered important mind-wandering consequences such as increased reaction times before errors and decreased reaction time after errors, which is particularly true in ageing (Jackson and Balota, 2012). Additionally, a variation of the original task extended the findings to the auditory modality (Seli et al., 2012). Notably, Seli et al. (2013) developed the metronome task, which involves responding synchronously (via button presses) with a continuous rhythmic presentation of tones, and demonstrated behavioural variability in the responses as a marker of mind wandering.

Although sustained attentional tasks such as the SART have been used extensively in the mind wandering literature, it has received recent criticism regarding its precision in measuring both sustained attention and the likelihood of mind wandering (Dillard et al., 2014). Problematically the SART does not include any control condition or baseline, therefore preventing researchers from a clear interpretation of the variation in mind-wandering rates (see the paradigm from Konishi et al., 2015). In view of this, a variant of the cognitive task used by Konishi et al. (2015) is increasingly being used to both encourage and measure mind wandering. In this n-back paradigm, participants alternate between blocks of trials in which they either make decisions about the location of shapes, which are currently available to the senses (0-back) or with respect to their location on a prior trial (1-back). Unlike the SART, the n-back task makes it possible to manipulate the demands of the task, with an increase in working memory load during the 1-back trials, which leads to a greater focus on task-relevant information. This task has been useful in understanding how the occurrence of off-task thought in the easier 0-back but not the 1-back task, is related to an increased capacity to delay gratification (Bernhardt et al., 2014; Smallwood et al., 2013b). More recently it has been used to document patterns of neural activity that support a range of different experiential states (e.g. Sormaz et al., 2018).

One specific area where the tools of neuroimaging could be valuable in moving forward our understanding of patterns of ongoing thought is by helping to identify the neural processes that are common to both errors in performance, and to patterns of off-task thinking. Studies have shown for example that both reading comprehension and the frequency of off-task thought are related to systematic variations in the connectivity of the Default Mode Network (Smallwood et al., 2013a). Such findings, provide a potential explanation for why off-task thought can interfere with our ability to read for comprehension (Smallwood et al., 2008). On the other hand, studies that have simultaneously assessed both performance and experience while neural activity has been recorded have revealed dissociations between the neural activity associated with patterns of off-task thinking form those linked to behaviour (Kucyi et al., 2016). Moving forward, the tools of neuroimaging may be helpful in assessing the underlying processes that help reveal the processes that describe the association between patterns in off-task thinking and performance, and this in turn will inform our understanding of why off-task thoughts can interfere with performance.

2.3 Interim summary

Both subjective and behavioural indicators of experience provide formal evidence of the nature of ongoing thought either at a specific moment of time or in a particular task or condition. However, these measures offer only a superficial description of the nature of experience, and in particular, in isolation, these measures will struggle to provide evidence on underlying causal mechanisms. Recent work has begun to overcome this limitation by combining self-reported data with measures of neuroimaging, an approach that has been useful in two different domains: i) the quantifying periods of internal focus and ii) the understanding of the heterogeneous nature of ongoing experience (see Fig. 1).

3 Quantifying internal focus

One area in which neuroimaging has helped move forward studies of ongoing thought is through the quantification of periods when the focus of ongoing thought shifts from the processing of external sensory input, known as perceptual decoupling (Schooler et al., 2011; Smallwood, 2013). These studies have largely used Event-Related Potentials (ERPs) generated from the Electroencephalogram (EEG). ERP has proven to be a particularly valuable tool for evaluating the level of perceptual engagement during different types of ongoing thought. Sensory information is processed relatively fast, within 150–200 ms, and described by evoked components known as the P1 and N1. While N1 has been found to be sensitive to auditory stimuli type and presentation predictability, P1 may reflect the “cost of attention” (Luck et al., 1990). Elsewhere, P1 and N1 have been used to indicate, respectively, the attentional filtering and categorization of perceptual information before integrating semantic knowledge (Klimesch, 2011, 2012), and the operation of a discrimination process when judgements about the stimuli are needed (Vogel and Luck, 2000). Interestingly, these components are found to be attenuated following reports of task-unrelated-thought (Baird et al., 2014; Kam et al., 2010). The reduction of the amplitude of ERPs that are linked to early sensory processing is suggestive of a reduction of brain-evoked response to sensory input (Baird et al., 2014). In particular, data such as these suggest that the processing of relatively basic perceptual input information is reduced during certain types of internal focus.

The study of a later component, the P3 (occurrence between 250 and 500 ms post-stimulus), is assumed to reflect the engagement of attentional processes and studies have shown that this is linked to a reduction in amplitude during periods of off-task thought compared to being task focused (Barron et al., 2011; Kam et al., 2012, 2010; Kam and Handy, 2013; Smallwood et al., 2007a). Given the well-documented role of the P3 in attentional processes, these data suggest that periods of off-task thought are linked to changes in attentionally mediated task sets. However, studies have shown that this process reflects a switch away from the task goals, rather than a failure to inhibit irrelevant information. Barron et al. (2011) used a 3-stimulus oddball paradigm to understand whether off-task thought was linked to lower processing of task events regardless of their relevance to the goal, or whether the attenuation was specific to task-relevant information. The 3-stimulus oddball task typically comprises the presentation of task-relevant infrequent targets (requiring a response) in a train of frequent stimuli that generates an ERP component called the P3b, while additional rare task-irrelevant stimuli are presented which generates a component known as the P3a. Barron and colleagues demonstrated a reduction of both the P3a and P3b, linked to off-task reports suggesting that the processing of all stimuli in the environment is reduced, rather than just those that are important to the task.

Alternative ways to quantify external focus have been provided by analysis of more dynamic aspects of the EEG signal. Braboszcz and Delorme (2011) demonstrated increased activity of lower frequencies such as theta (4–7 Hz) and delta (2–3.5 Hz), and a decrease of higher frequencies, namely alpha (9–11 Hz) and beta (15–30 Hz), during periods of mind-wandering as compared to breath focus (mindful condition). Delta power has been associated with poor cognitive ability (Harmony, 2013) and also linked to lower state of vigilances (Roth, 1961). These authors suggest that their findings highlight a reduction of alertness to the task during mind-wandering experiences. In a similar vein, Baird et al. (2014) observed reductions in spectral power during mind-wandering compared with task focus over frontal regions in the alpha and beta band. Enhanced alpha activity is mostly found during wakeful relaxation, and reflects inhibition of task-irrelevant cortical areas (Klimesch et al., 2007). In contrast, beta band activity is related to active concentration and maintenance of current cognitive states (Engel and Fries, 2010), together enabling the efficient treatment of external input (For frequency bands functional significance, see Britton et al., 2016). Braboszcz and Delorme (2011) outlined an additional layer of analyses by considering the impact of meta-cognitive processes. The moment where participants consciously realise their mind has been wandering is central as it allows the redirection of attention toward the task. Findings revealed that this process of refocus was related to an increase of the alpha peak frequency and a long-lasting increase in alpha power. Considering that peaks of alpha frequency are thought to represent a state of “cognitive preparedness” (Angelakis et al., 2004), and that alpha power has been linked to working memory (Jensen et al., 2002), the authors suggest that together the peak of alpha and its general increase in power may be markers of attention shifts from an internal focus on self-generated information, to external information relevant to the external task.

Together, these EEG and ERP findings provide a useful way to quantify whether experience is internally or externally focused. Off-task thought is linked to reductions in the cortical processing of the environment at a very early stage and both task-relevant and unrelated sensory information are processed in less detail. Additionally, the processing of an external input is less stable and this is accompanied by a decrease in the neural efficiency of task-related actions. Collectively, this suggests that when people are off-task their cortex is responding less to environmental input, a pattern that is described as perceptual decoupling (Smallwood, 2013). Although the relationship between evoked responses and patterns of experience are relatively well understood, the association between patterns of oscillatory activity and experience is less well understood. In Box 1 we present a set of ~~possible~~ hypotheses regarding potential relationships between different patterns of oscillatory activity and different aspects of experience.

Box 1 Suggestions for future work using frequency bands.

alt-text: Box 1

Frequency bands in EEG and MEG have been related to specific cognitive processes. They also vary across the sleep – wake continuum, with lower frequencies related to sleep or sleep like states and the higher frequency bands associated with high concentration and focus. Limited research has considered frequency bands in relation to mind-wandering experiences, particularly with regard to different types of experience. Here we suggest a number of hypotheses for future research investigating the relationship between self-generated thoughts and oscillations in neural activity.

The contribution of the theta band (4–7 Hz) has been evidenced during tasks involving working memory and episodic memory encoding and retrieval (Klimesch, 1999; Mitchell et al., 2008; Sauseng et al., 2005). Particularly, this frequency band has been linked on multiple occasion to activity in the hippocampus (for a review see Buzsáki, 2002). Since studies suggest that memory processes are important in self-generated thought (e.g. Poerio et al., 2017) it is possible that theta activity could reflect the role of memory representations in periods of self-generated thought.

The alpha band (8–12 Hz) is considered the dominant frequency band in adults and a striking increase in activity can be seen upon eyes closing. Enhanced alpha frequency band oscillation is suggested to reflect inhibition of task-irrelevant cortical areas (Klimesch et al., 2007). It is possible that high levels of alpha activity could reflect the process of perceptual decoupling that is thought to be important in internal states.

Lastly, higher frequency bands are good indicators of task-relevant treatment of information. Beta (13–29 Hz) activity, for example, is an indicator of concentration and is associated with focus and alertness, enabling the maintenance of a status quo (Engel and Fries, 2010). Less is known about the functionality of the gamma band (>30 Hz), yet, research seems to highlight its implication in higher order processing and the binding of higher cognitive functions (Başar-Eroglu et al., 1996). It is thus possible that gamma activity may help bind together patterns of self-generated thought.

4 Quantifying the processes underlying different types of experience

A second area in which neuroimaging research has the potential to propel our understanding of ongoing thought is through the ability to determine differences in types of ongoing thought, and these studies have often used fMRI. Contemporary accounts argue that the content of ongoing thought is heterogeneous in terms of both its content, and its relationship to functional outcomes (Smallwood and Andrews-Hanna, 2013). For example, there is a wide range of things that people think about when their mind wanders, reflecting variables such as temporal focus, affective state, and interest (Smallwood and Schooler, 2015). For ~~example~~instance, mind-wandering can sometimes focus on past or future events (Baird et al., 2011), may involve thoughts relevant to one's self or others (Baird et al., 2011; Ruby et al., 2013a,b), it may be positive or negative in valence (Poerio et al., 2013), and can either be intentional or unintentional in origin (Seli et al., 2016b). This wide variety of different patterns of thought requires the assessment of multiple experiential factors. In addition, evidence suggests that patterns of ongoing thought are also variable in terms of the associated functional outcomes. For example, while some studies have shown that periods of mind-wandering occurrence has a negative impact on mood (Killingsworth and Gilbert, 2010) and cognitive task performance, such as sustained attention, working memory capacity, and reading comprehension (Mrazek et al., 2012; Smallwood et al., 2008), others have revealed the positive effects of task unrelated thought, for example, enabling future planning (Baird et al., 2011; Medea et al., 2016), creativity (Baird et al., 2012), social problem solving (Ruby et al., 2013a), and fostering a more patient style of making decisions (Smallwood et al., 2013a,b).

As shown above, there are multiple patterns of experience that participants report in the off-task state, however, it remains to be seen whether these should be considered unique categories of experience or not. In this context, neuroimaging can help address this uncertainty since it could help determine whether different patterns of experience may depend on similar or different neural processes. In this way, combining self-reported information with modern neuroimaging techniques would provide a layer of objective data that can inform our understanding of the best way to categorise subjective states. For example, neuroimaging techniques provide covert measures of underlying cognitive processing, thus helping to determine whether variable mind-wandering frequency, content, and outcomes are associated with parallel physical differences in the brain. Moreover, advances in machine learning offer the potential to infer the heterogeneity of different experiential states directly from the combined decompositions of neural and self-reported data (Vatansever et al., 2017; Wang et al., 2018a,b). In one of these studies, Wang and colleagues used canonical correlation analysis to perform a conjoined decomposition of the reports that participants made at the end of a scanning session with the functional connectivity of the whole brain at rest. This identified a pattern of individual variation that correlated with both thoughts related to an individuals' current concerns as well as reduced connectivity within task-positive systems important for external attention and was linked to poor performance on measures of intelligence and control (Wang et al., 2018a,b). Interestingly these networks included both the ventral and dorsal attention networks, which are both thought to be important in the generation of stronger evoked response linked to attention (e.g. the P3).

A large proportion of previous fMRI research has focussed on the default mode network (DMN) which tends to show a pattern of deactivation in externally demanding tasks that depend upon the efficient processing of external information (for review see Raichle, 2015). While initial views of this network emphasised a role that was opposed to tasks (i.e. Fox et al., 2005), it is now recognised that this view is too simplistic. While the DMN is active during off-task thought (Allen et al., 2013; Christoff et al., 2009; Hasenkamp et al., 2012; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011), it is also active in many other situations involving autobiographical memory, semantic processing, planning of the personal future, imagination, theory of mind, and self-reflection (Andrews-Hanna, 2012; Spreng and Grady, 2009; Spreng et al., 2008; for a review of DMN functions see Andrews-Hanna, Smallwood and Spreng, 2014; Buckner et al., 2008). More recently, Sormaz and colleagues used experience sampling to show that the DMN plays an important role in the level of detail in representations of task-relevant information in working memory (Sormaz et al., 2018). Together these studies show that a simple account mapping the DMN to the off-task state is unwarranted because it is likely to be important for task relevant states as well.

Another way to understand neural processes linked to different patterns of ongoing thought, is through a specific comparison to brain activity of experiences that are produced spontaneously with those that are part of a task (Smallwood and Schooler, 2015). One assumption of contemporary component process accounts of the mind-wandering state is that the experience engages systems that can also be engaged as part of an external task. A recent study by Tusche et al. (2014) supports this assumption. They used multivariate pattern analysis (MVPA) to identify similarities between spontaneous and task-related examples of positive and negative thoughts. They found similar patterns of activation (i.e. medial orbitofrontal cortex; mOFC) for both the task-generated and task-free affective experiences, which suggests commonalities in the nature of thoughts regardless of the way they have been initiated. Ultimately, the use of MVPA enables researchers to draw parallels between task-induced and naturally occurring affective experiences and to test important features of contemporary accounts of how patterns of ongoing thought emerge. Another area in which we might expect to find overlap between the neural processes engaged during ongoing thought and those engaged in tasks may be in the domain of creativity.

There is a robust correlation between variation in types of off-task thought and more creative solutions to problems (Baird et al., 2012; Smeekens and Kane, 2016; Wang et al., 2018a,b). More generally, a key finding from the Christoff et al. (2009) study was the co-activation of both the default and executive networks. In general, the executive and default networks are thought to act in opposition to each other so that when the executive network becomes activated, the default network is deactivated or actively suppressed (Weissman et al., 2006). However, there are psychological phenomena including creativity, where co-activation of these systems has been observed. For example, co-activation of those networks occurs during creative thinking (Beaty et al., 2015; Beaty et al., 2018; Kounios et al., 2008, 2006), autobiographical planning (Spreng et al., 2010), during naturalistic film viewing (Golland et al., 2007) which is related to immersive simulative mental experiences (Mar and Oatley, 2008), and periods of decision making when information from memory can guide decision making (Konishi et al., 2015; Murphy et al., 2017). What is common about these examples is the requirement that goal relevant cognition must rely on information from memory, and it may be important in the future to understand the overlap between neural activity reflecting retrieval of information from memory with patterns observed during periods of ongoing thought, especially given evidence that more efficient memory processes are associated with the off-task state (Poerio et al., 2017).

5 Individual variation

A final area in which neuroimaging has advanced our understanding of ongoing thought is in the area of individual differences. These approaches depend on connectivity analyses that estimate the connections between different brain regions which can be derived from both the functional (i.e. the BOLD signal) and the structural domain (i.e. white matter connections, for a comprehensive review, see Rubinov and Sporns, 2010). These studies are useful in understanding the neural basis of different patterns of ongoing thought since they allow patterns of population variation in different aspects of ongoing thought to be embedded in the functional organisation of the cortex. Importantly, these studies use descriptions of the brain at rest to describe each individual's neural architecture, and so only require 5–15 min of brain activity to be recorded. While these studies cannot reveal the neural descriptions of the momentary changes that occur as the mind wanders, they do provide a cost-effective way to generate individual differences in spontaneous thought that have sufficient sample sizes to be generalizable to the underlying population, an issue that is increasingly important for both psychology and neuroscience (Yarkoni, 2009).

A growing body of individual difference studies have begun to use an individual difference approach to pinpoint the neural architecture underlying different patterns of ongoing thought, utilising both structural and functional descriptions of ongoing thought. Karapanagiotidis et al. (2017) assessed whether individual variability in the content of their thoughts related to markers of structural connectivity. Structural connectivity using DTI identified a temporo-limbic white matter region, highly connected to the right hippocampus, in people who spontaneously engaged in more mental time travel. Functional connectivity analyses revealed a temporal correlation of the right hippocampus with the dorsal anterior cingulated cortex, a core region of the DMN, which was modulated by inter-individual variation in mental time travel. Therefore, spontaneous thoughts experienced during mind wandering, especially those linked to mental time travel, seems to be underlined by the hippocampus and its integration to the DMN. This assumption has been highlighted by evidence that individuals with hippocampal amnesia are less likely to experience off-task episodes with rich experiential content (McCormick et al., 2018).

Other studies have looked at the relationship between the functional architecture of the mind and population variation in different types of ongoing thought. Smallwood et al. (2016) explored whether individual differences in the functional architecture of the cortex predicted the nature of spontaneous thoughts. Results illustrated that the functional connectivity of the temporal poles with ~~the~~ posterior cingulate~~d~~ cortex was predictive of both greater mental time travel involving social agents and unpleasant task-unrelated-thoughts. Elsewhere, the role of the temporal pole in mental time travel and social cognition have been reported (Pehrs et al., 2015; Pehrs et al., 2018). Smallwood et al. (2016) highlighted that connectivity from the hippocampus to the posterior cingulate cortex predicted greater specificity to thoughts, thus giving further insight into the key role that the hippocampus may play when connected to specific nodes of the DMN. It is possible that the role of the hippocampus is particularly important in the future planning that often takes place during spontaneous thought. Medea et al. (2016) demonstrated that our capacity to develop more concrete descriptions of both goals and aspects of our knowledge is supported by brain networks centred on the hippocampus. They found that greater coupling between the hippocampus and more dorsal medial frontal regions, including the pre-supplementary motor area, was a specific predictor of the generation of more concrete goals. Other authors have explored the relationship between ongoing thought and systems that are important in tasks. Work by Wang and colleagues (2018) for example, demonstrated that task negative aspects of ongoing thought may be linked to reduced patterns of connectivity with systems involved in external attention. In addition, Golchert et al. (2017) demonstrated that connectivity between the executive and default networks was greater for individuals who described having greater control over the off-task experience. A comparable pattern was observed by Mooneyham et al. (2016) who found that individuals reporting higher trait levels of mind-wandering in daily life showed more connectivity between executive and default systems, a pattern that may reflect ~~the fact that the majority of mind-wandering easy tasks~~the fact that the majority of mind-wandering reported during easy tasks (such as rest) is deliberate (Seli et al., 2016a). The combined use of functional and structural connectivity highlights further the heterogeneity of mind-wandering experiences, as specific characteristics are repetitively associated with variations in neural recruitments.

6 Future directions

Neuroimaging approaches have been critical in helping improve neurocognitive accounts of different patterns of ongoing thought. In particular, the triangulation of both measures of self-report with objective indices of information processing provided by neuroimaging in quantifying the nature of internal focus, as well as helping address the reality of different aspects of ongoing thought. In the future it seems likely that these measures will also be important in determining the dynamics that underpin ongoing experience, as well as refining our knowledge of the causal roles that different systems can play.

One important area of research is understanding the nature of neural dynamic during different aspects of experience (Kucyi, 2017). EEG phase differences are used to measure the directional flow of information between two EEG electrodes sites. Using mean phase coherence, Berkovich-Ohana et al. (2014) found that DMN deactivation during a task, compared to a resting baseline, was related to lower gamma and increased alpha mean phase coherence. Lower gamma band activity could reflect the decoupling of the control/executive system with the DMN, whereas the increase in alpha band activity could reflect the coupling of this system with task-activated network. Additionally, a recent study investigated the neuronal differences between thoughts triggered either internally or externally using a correlation coefficient measure, which is similar to coherence measures (Godwin et al., 2016). Findings revealed increased functional connectivity over parietal areas within the alpha band for internal compared to external thoughts. This was suggested to reflect a neural mechanism that enables the suppression of externally focused attention in favour of internally directed processes. It is possible that this method could be fruitfully employed in the examination of the processing of perceptual decoupling that it is thought to be important during periods of internally focused attention (Smallwood, 2013).

It is also possible to understand dynamical properties of neural signals using fMRI. A recent study demonstrated that states of mind-wandering elicited positive functional connectivity between regions of both the executive and default networks (Mooneyham et al., 2016). Here the use of dynamic functional connectivity enabled the identification of different states of functional connectivity across known networks. This measure is based on the principle that functional connectivity relationships between brain regions and networks are dynamically influenced by time, and reflects changes in cognitive states (Calhoun et al., 2014; Hutchison et al., 2013). This suggests that the relationship between different brain areas as they change over time may be an indicator of different cognitive states. Thus, dynamic functional connectivity measures may play an important role in future studies of periods of ongoing thought (for a review see Kucyi et al., 2017).

The majority of studies have looked at the neural basis of ongoing thought using EEG and ~~F~~fMRI and while these methods are important in describing the association between different states and patterns of neural activation, however, these data are correlational. In the future, it will be important to combine these methods with approaches such as Transcranial Magnetic Stimulation (tMS) and Transcranial Direct Current Stimulation (tDCS). A few studies (Axelrod et al., 2015; Axelrod et al., 2018; Boayue et al., 2019; Kajimura et al., 2016; Kajimura and Nomura, 2015) have explored the role that different large scale systems play in the maintenance and initiation of different patterns of thought. A related technique has explored the effects of lesions on patterns of ongoing thought. For example, lesions to the hippocampus reduce the episodic content of periods of mind-wandering (McCormick et al., 2018), while Bertossi and Ciaramelli (2016) demonstrated that lesions to the ventromedial prefrontal cortex reduce future thinking during the off-task state. These methods are important because they allow researchers to test causal accounts of the role of neural functions in periods of self-generated thought. Other studies have looked at the cognitive consequences of stimulation of aspects of the default mode network (Foster and Parvizi, 2017), and it would be useful to extend these types of methods to patterns of thought measured using experience sampling. As we gain a more conclusive account of the neural systems that support different patterns of ongoing thought, methods of non-invasive brain stimulation are likely to be increasingly important in fine-tuning mechanistic accounts of how covert states such as mind-wandering unfold.

Finally, it may be possible to make progress on understanding the processes that are important in periods of self-generated thought by testing formal models of how these processes emerge. The component process account (e.g. Smallwood and Schooler, 2015) argues that periods of off-task thought may rely on the combination of a number of different processes, such as episodic or semantic memory, executive control, and emotion. This approach has been successfully employed in studies of the default mode network (e.g. Axelrod et al., 2017) and in studies of ongoing experience (Poerio et al., 2017; Turnbull et al., 2019). One benefit of this approach is that the introspective evidence can be combined with objective tasks data (e.g. measures of memory retrieval). In addition, well-specified models could be tested formally (Axelrod and Teodorescu, 2015; Mittner et al., 2014).

7 Conclusion

In conclusion, the use of neuroimaging tools and converging methods has proven to be informative in the study of mind wandering. The use of ERP and EEG methodologies have helped demonstrate that during certain types of experience the perceptual processing is attenuated. In contrast, fMRI studies have provided evidence that different types of ongoing thought can emerge from the combination of different large-scale networks. Patterns of ongoing thought are a critical part of daily life with implications for the integrity of tasks such as driving, and has important implications for mental health. Accordingly, the combination of self-reported information with the detailed measures of neural function available hold the promise to shed critical light on aspects of human cognition.

Declarations of interest

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Highlights

- Converging methods should be further used to study self-generated thoughts.
- Combining MDES to neuroimaging enables the investigation of thought heterogeneity.
- ERP and EEG measures enable quantification of the switch toward an internal focus.
- Connectivity measures target individual differences in off-task thoughts.

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