Title

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Abstract

Much of our daily mental life is occupied by spontaneous thought processes. Evidence is accumulating that such spontaneous thought processes, which are often experienced as mind-wandering, share the same cognitive and neural resources that subserve goal-directed thought. While a distinction between mind-wandering with and without awareness has been made at a cognitive level, the mechanisms underlying this distinction at a neural level remain unknown. The present study employs a novel paradigm that was designed to examine this question by directly investigating instances of mind-wandering, using fMRI. A continuously engaging background task was employed, combined with a thought sampling approach that determined whether subjects were mind-wandering at a given moment of time, and whether they were aware of where their thought processes were focused. A clear distinction between spontaneous thought processes that occurred with and without awareness emerged. Temporal lobe structures were activated during mind-wandering in the absence of awareness, while prefrontal cortex was activated when subjects were aware of their own thoughts. These findings complement recent cognitive theories of spontaneous thought, by providing evidence for neural distinction between these two kinds of mind-wandering in addition to the previously proposed cognitive distinction. As well, the results suggest that an important aspect of human thought processes, which has been largely ignored thus far, may be the spontaneous generation of thoughts in the absence of awareness or explicit conscious goals. The implications for cognitive theories of human thought are discussed.

Introduction

Much of our daily mental life is occupied by spontaneous thought processes. These thoughts, also referred to as mind-wandering, are often unrelated to the task at hand and may occur with or without our awareness. Despite the prevalence of these types of thought processes in everyday life (Klinger & Cox, 1987), their cognitive mechanisms remain largely unknown. Instead, the vast majority of research on human thought processes has focused on goal-directed thinking and problem solving, equating these processes with executive functions and thinking in general.

Nonetheless, strong evidence is beginning to accumulate suggesting that spontaneously occurring thought processes share executive and cognitive mechanisms with goal-directed thought (Christoff, Ream & Gabrieli, 2004; Smallwood & Schooler, in press). Such evidence has been provided by a number of behavioral studies (Antrobus, 1968; Giambra, 1977,1979,1995; Klinger & Cox, 1987; Teasdale, Proctor, Lloyd, & Baddeley, 1993; Teasdale, Dritschel, Taylor, Proctor, Lloyd, Nimmo-Smith, et al., 1995; for review, see Christoff et al., 2004). Given these shared mechanisms, it is not surprising that the generation of spontaneous thought interferes with executive tasks. A prime example of this interference is the decreased degree of randomness in a random number generation task associated with periods of task-unrelated thoughts (Teasdale et al., 1995). A further line of evidence linking spontaneous thoughts with executive mechanisms is the parallel decline of spontaneous thoughts and executive resources with age (Giambra, 1989). This effect of decreasing spontaneous thought with increasing age has been reported across five different vigilance tasks (Giambra, 1989).

In addition, there is evidence at the neural level that spontaneous thought processes share executive mechanisms with goal-directed thought. Thus, functional magnetic resonance imaging (fMRI) studies investigating the spontaneous cognitions present during rest are consistent with conclusions drawn on the basis of behavioural studies. These studies have found consistent rest-related activations in brain structures that support higher order cognitive functions such as long-term memory and executive processes (Binder, Frost, Hammeke, Bellgowan, Rao & Cox, 1999; Stark & Squire, 2001). These findings suggest that conceptual processes such as semantic retrieval, representation, information manipulation (Binder et al., 1999) and long term memory processes (Stark & Squire,

2001), which typically occur during complex tasks, can also occur spontaneously, in the absence of task. The specific network of brain regions that are associated with spontaneous thought processes in the absence of tasks include the angular gyrus, posterior cingulate, rostrolateral and dorsolateral prefrontal cortex, ventral and medial temporal lobe (Binder et al., 1999; Christoff et al., 2004; Stark & Squire, 2001).

Direct empirical evidence for such overlapping neural mechanisms was provided in a recent study examining the network of brain regions involved in spontaneous thought processes occurring during rest (Christoff et al., 2004). In comparing rest to a simple arrows task, the areas showing activation, specifically the temporal lobe and rostrolateral prefrontal cortex, have been previously indicated in higher cognitive functions. While these results support the hypothesis that the executive systems of the prefrontal cortex play a role in spontaneous thought processes as suggested by the behavioural literature, they also implicate a primary role for long-term memory mechanisms involving the temporal lobe structures. While previous studies have highlighted the brain areas involved with spontaneous cognitions, they are limited in that they do not allow discrimination between spontaneous thought processes that occur with versus without awareness.

The present study aims to expand on the findings of Christoff et al (2004) by examining the cognitive mechanisms involved in spontaneous thought processes that occur with and without awareness. The Sustained Attention to Response Task (SART) which has been used previously to examine mind wandering and awareness behaviourally (Smallwood, Davies, Heim, Finnigan, Sudberry, O'Connor, et al., 2004) was utilized. This task is conducive to mind wandering as it is cognitively undemanding, but is continuously engaging. Based on previous research regarding the role of the temporal lobe and prefrontal cortex in thought processes, we expected that spontaneous thought processes occurring without awareness would be associated with temporal lobe recruitment, while prefrontal cortex recruitment would be observed for those thoughts occurring with awareness.

Methods

Participants

Ten right-handed University of British Columbia (UBC) students (mean age 24; age range 19 – 29 years; 9 female) gave their written consent to participate and received $20/hour as compensation. All participants had normal or corrected vision and were screened for MRI compatibility. Procedures were approved by the UBC Clinical Research Ethics Board and by the UBC High Field Magnetic Imaging Centre.

Experimental paradigm

Background task. The Sustained Attention to Response Task (SART) (Robertson, Manly, Andrade, Baddeley &

Yiend, 1997) (Fig. 1) was used. The SART is a continuous go-no-go task, which requires participants to respond to all non-targets (the numbers 0 – 9) quickly and accurately while inhibiting responses to targets (the number 3). It has been used extensively to study mind-wandering behaviourally (Robertson et al., 1997; Smallwood et al., 2004).
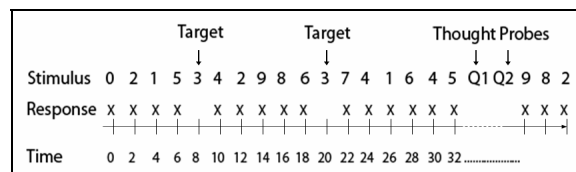

Figure 1: SART Paradigm

Mind-wandering measure. A thought sampling approach was used (Teasdale et al., 1995) to query participants about the focus of their attention during performance of the SART. Thought probes occurred pseudorandomly, at a rate of approximately one per minute. Each thought probe consisted of two consecutively displayed questions. The two questions were as follows:

Q1: Where was your attention focused just before the probe?

Q2: How aware were you of where your attention was?

Behavioural Procedure

Participants completed 3 practice task sessions on a laptop prior to entering the scanner room. Once positioned in the scanner, they were given practice adjusting the thought probe scale; they then completed 5 sessions of the SART, each approximately 13 minutes in duration. Each session consisted of 329 trials and included 16 thought probes, 16 targets and 297 non-targets, resulting in 5% target frequency. The order of events (targets and thought probes) was pseudo-counterbalanced so that a variable distance between events (5 – 15 trials) was uniformly distributed within each session. Three events appeared 5 trials apart, 3 events appeared 6 trials apart, and so on up to a distance of 15 trials apart.

The number stimuli and thought probes were back-projected onto a screen mounted at the end of the scanner bore. A mirror attached to the head coil enabled participants to view the presented stimuli. Participants responded to the number stimuli by pressing a response box button using their right index finger.

The thought probes appeared in a pseudo-random order, temporarily suspending SART performance. Participants answered each question within the thought probe by using an adjustable 7-point scale. Participants adjusted the scale by pressing the left index finger button to move the cursor towards the right and the left middle finger button to move it towards the left. The direction of the scale was counterbalanced between participants, such that "on task" and "aware" were on the right for 6 of the participants and "off task" and "unaware" were on the right for the other 4

participants. Once the cursor was in the desired position on the scale, participants pressed the left thumb key to register their response. Participants then continued with the SART task until the next thought probe appeared.

fMRI Data Acquisition

Data acquisition was performed using a Philips Gyroscan Intera 3 Tesla MRI scanner. Five functional runs, each consisting of 800 dynamics, were acquired for each participant using 1 sec TR; 24 x 13.2 X 24 cm rectangular FOV; acquisition matrix: 80 x 78 voxels; inplane resolution: 3 mm; 19 axial-oblique slices (AC/PC); 6 mm slice thickness; 1mm skip. An inplane (2-D) anatomical image was obtained prior to the functional runs.

fMRI Data Analysis

All fMRI data preprocessing and analysis was performed using SPM2 (Statistical Parametric Mapping; Wellcome department of Cognitive Neurology, London, UK). Prior to analysis, all images were preprocessed. Slice-timing correction to equate for the different sampling times of the slices consisted of interpolating the voxel time series using sinc interpolation and resampling with the middle slice as a reference point. Next, motion correction was accomplished by realignment of the T2*-weighted volumes using the first slice in the time series. The structural T1-weighted volumes were normalized to the MNI template using affine spatial transformation, by first deriving the transformation parameters derived from normalizing each subject's anatomical image to the MNI template and second, applying these transformation parameters to the subject's EPI image. In order to account for any residual between-subject variation and allow application of Gaussian random field theory to provide for corrected statistical inference, the T2*-weighted volumes were then smoothed using a Gaussian kernel with 8 mm full-width at half-maximum (FWHM) (Friston, Worsley, Frackowiak, Mazziotta, & Evans, 1994).

Modeling of events and periods prior to events. Statistical results were assessed using a voxel-based approach, by constructing regressor functions based on event-types and estimating regression coefficients to estimate the regionally specific effects. The hemodynamic response function (HRF) was used to model events and periods prior to events (a single HRF or a set of 5 HRFs, respectively). Single events that were modeled included targets (occurrences of the number "3") and thought probes. In addition, the period of 10 seconds (5 non-target responses) prior to targets and probes was modeled in separate regressors.

Using parametric modulation to construct contrasts. The regressors were modulated parametrically in order to construct specific contrasts of interest. Thus, a parametric modulation according to accuracy of response to targets resulted in new regressors that effectively compared incorrect versus correct responses to targets. A similar modulation was applied to the regressors modeling the period prior to targets. Parametric modulation was particularly effective in contrasting the periods prior to thought probes. Two such parametrically modulated regressors were formed: one, based on responses to the first question during the probe, and another one, based on responses to the second question during the probe. In this way, an effective contrast between periods of mind-wandering versus periods of being on task was constructed, as well as periods of mind-wandering with versus without awareness. Here we focus on the results of the latter contrast, examining the differences between mind-wandering with and without awareness.

The contrast images obtained at the individual level of analysis were entered into a group level analysis, using one-sample t-test, thus, effecting a random-effect model across subjects. The threshold for significance was set at P<0.001 (uncorrected) for all group comparisons, except for the aware vs. unaware comparisons, in which case it was set at P<0.005.

Results

Behavioural

Results regarding accuracy are presented in Table 1. Average response time for non-targets was 389.35 ms with a standard deviation of 69.42 ms.

Table 1: Accuracy on the SART task (targets and non-targets).

Stimulus Type	Mean Accuracy (%)	StDev (across subject)	Range (Min-Max) (%)
Target	59.18	0.1586	32.94-88.24
Non-target	98.27	0.0271	91.37-99.93

The thought sampling procedure did not increase the likelihood that subjects would be more on-task or aware of their thoughts. Rather, throughout the experiment, subjects became more likely to report "off task" and "unaware" experiences. Figure 2 shows this trend across sessions.

fMRI

The first comparison of interest examined the effects of errors during target responses. This comparison aimed to replicate previous findings concerning error-related processing. When incorrect targets were compared to correct targets, we observed prominent activations in the anterior cingulate cortex (Fig. 3 & Table 2). In addition, activation in posterior cingulate cortex was observed. These results replicate previous findings of error-related processing (Carter et al., 1999) and its relation to anterior cingulate recruitment, thus, demonstrating the validity of the experimental manipulation employed here and its consistency with prior results.
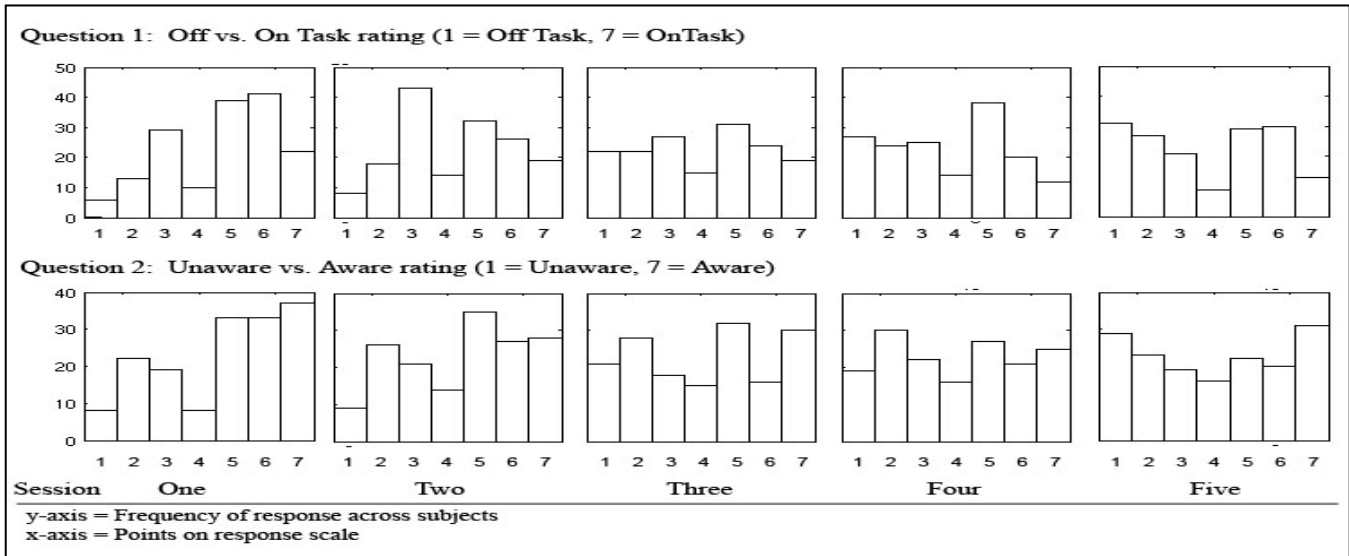
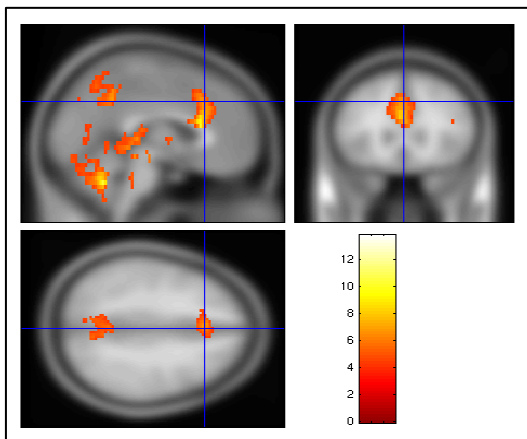Figure 2: Distribution of Probe Responses Across Sessions

Figure 3: Incorrect versus correct response to targets

Table 2: Activation areas for
incorrect versus correct response to targets

Activation Areas	BA	Z-Score	Voxels
Anterior Cingulate	24	4.63	441
	32	3.94	
Posterior Cingulate	31	4.08	479
Precuneus	7	3.53	
R Cerebellum		5.17	3300
L Cerebellum		4.63	

Note: BA = Brodmann area, L/R = Left/Right hemisphere

Of interest to our investigation of spontaneous thought, however, was the question of what happens in terms of neural processes *just prior to errors*. The behavioral literature using the SART task (Robertson et al., 1997;

Smallwood et al., 2004)) has demonstrated that people are much more likely to be mind-wandering just prior to an error. The contrast of periods prior to incorrect targets versus periods prior to correct targets yielded robust activations in lateral prefrontal and temporal regions (Fig 4 and Table 3).
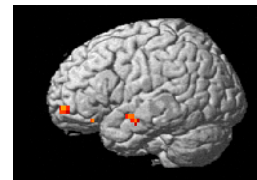

Figure 4: Period prior to target -
Incorrect versus correct response

Table 3: Activation areas for period prior to target -
Incorrect versus correct response

Activation Areas	BA	Z-Score	Voxels
L Anterior Prefrontal Cortex	10	3.58	35
L Ventrolateral Prefrontal Cortex	47	3.43	9
L Temporal Cortex	21	3.19	37
R Temporal Cortex	21	3.75	164
Precuneus	18	3.57	186
		3.16	

Note: BA = Brodmann area, L/R = Left/Right hemisphere

Finally, a distinction was observed between neural recruitment when subjects were aware of their mind-wandering versus when they were unaware. (Fig 5a and Table 4). Thus, the contrast between periods prior to a probe on which subjects were aware of where their attention was, compared to periods prior to probes where subjects were unaware, resulted in activation of the dorsolateral prefrontal cortex. On the other hand, the contrast of unaware versus aware periods prior to a probe resulted in activation in the anterior temporal and lateral mid-temporal regions (Fig 5b and Table 4).
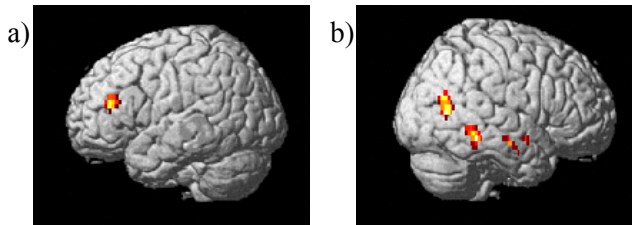

Figure 5: Period prior to thought probe
(a) aware versus unaware (b) unaware versus aware

Table 4: Activation areas for awareness contrasts

Condition	Activation Areas	BA	Z-score	Voxels
Aware > Unaware	L Dorsolateral Prefrontal Cortex	46	3.07	56
	R Visual Cortex	18/19	2.67	36
Unaware > Aware	R Anterior Temporal	38	2.93	40
	R Mid-Temporal	21	2.78	87
		22	2.68	
		21	2.56	
		39	2.92	72
		39	2.88	
		21	2.95	48
		21	2.84	
		21	2.81	

Note: BA = Brodmann area, L/R = Left/Right hemisphere

Discussion

The present findings provide further support for the hypothesis that the prefrontal and temporal cortices play differential roles in spontaneous thought (Christoff et al., 2004). The observed pattern of activation suggests a dissociation between conscious and unconscious mind-wandering at the neural level – a dissociation that parallels a previously proposed distinction at the cognitive level (Schooler, 2002). Activation in the lateral prefrontal cortex characterized thoughts that occurred with the subjects' awareness while activation in the lateral temporal cortex was associated with thoughts that occurred without the subjects' awareness. The observed activation of the temporal cortex for thoughts lacking awareness provide direct empirical evidence that long-term memory processes play a key role in the generation of spontaneous thought processes, consistent with previous theoretical ideas (Binder et al., 1999; Christoff et al., 2004). That this thought flow occurs without awareness underscores the unsuitability of rest as a baseline for fMRI studies (Binder et al., 1999; Christoff et al., 2004; Stark & Squire, 2001). Even though the participants themselves may believe that they are at rest or conversely that they are focused on the task at hand, it may be that they are cognitively very active with their attention focused elsewhere. Thus, if rest is used as a baseline for tasks that also activate these areas, misleading, non-significant results may be obtained.

Finally, the distinct difference between the observed mind-wandering activations and activations usually observed during "default" state processes (Raichle et al., 2001) clearly indicate that mind-wandering is not part of default mechanisms, but rather part of an executive system (see Teadsdale et al., 1995 for a similar argument based on behavioral findings).

In this paper, we have presented a method that can successfully be used for directly investigating the neural basis of spontaneous thought processes. This method can also be used to investigate the crucial distinction between mind-wandering with and without awareness. Consistent with the literature on executive function and long-term memory mechanisms, our results indicate separate components of the experience of mind-wandering, and suggest a separation between the *spontaneous generation* of spontaneous thoughts, on the one hand, and the *conscious experience* of these thoughts, on the other. This distinction has been outlined at the behavioral level by Schooler (2002) in terms of thought processes that can be referred to as "tuning out" (mind-wandering with awareness) and "zoning out" (mind-wandering without awareness). Here we present results suggesting that this distinction holds validity at the neural level as well. Thought processes that occur without our awareness appear to be associated with temporal lobes structures, while awareness elicits prefrontal recruitment.

In conclusion, spontaneous mental cognitions are not only ubiquitous, but also crucially important in understanding the full scope of thought phenomena. Although these types of cognitions have been relatively neglected in the past, methods for their scientific investigation are now beginning to appear. The evidence for overlap between such spontaneous thought mechanisms and mechanisms of goal-directed thought is overwhelming and present at both the behavioral and neural level. It is now incumbent upon researchers interested in thought processes to further elucidate the flip side of thought – the spontaneously

occurring cognitions that may occur without apparent purpose or relation to the task at hand, which, despite their underprivileged status in current research, may turn out to hold the key to a fuller understanding of the infinite complexities of human cognition.

Acknowledgements

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