

## SPECIAL SECTION

# NEURAL BASIS OF SPONTANEOUS THOUGHT PROCESSES

Kalina Christoff<sup>1</sup>, Justin M. Ream<sup>2</sup>, and John D. E. Gabrieli<sup>2</sup>

(<sup>1</sup>MRC Cognition and Brain Sciences Unit, Cambridge, UK, now at Department of Psychology, University of British Columbia, <sup>2</sup>Department of Psychology, Stanford University, USA)

### ABSTRACT

Studies examining thought processes have focused upon the deliberate, goal-directed mental processes occurring during complex cognitive tasks. Spontaneously occurring thought processes have, on the other hand, received much less attention. Such spontaneous thought processes occur frequently when no task is present or when task demands are low. Although their existence has been recognised, their study has been difficult due to lack of direct behavioural measures. Nevertheless, a number of behavioural methods based on subjects' verbal reports have been developed. Findings derived using such behavioural methods suggest that spontaneous thought processes share common cognitive mechanisms with purposeful, task-related thought processes. Furthermore, evidence from neuroimaging observations is accumulating suggesting similar conclusions about the neural basis of spontaneous thought processes. These neuroimaging findings demonstrate an overlap in the pattern of activation between various cognitive tasks and rest, with a number of higher cortical regions activated in common, including visual areas, medial temporal lobe, and lateral cortical association areas. Many of these observations have, however, been based upon comparisons between rest and tasks posing relatively high cognitive demands. In contrast, here we report an fMRI study in which rest was compared to a simple left/right response task of minimal cognitive demands. Rest was associated with greater activation in temporopolar cortex, parahippocampus, rostrolateral prefrontal cortex, parietal and visual cortical areas. Activation of temporal lobe structures was particularly extensive and robust, suggesting that long-term memory processes may form the core of spontaneous thought. By considering such long-term memory processes as an essential part of thought mechanisms, it may be possible to gain better understanding into spontaneous thought phenomena that have remained unaccounted for until now.

Key words: thinking, reasoning, spontaneous thought, stimulus-independent thought, higher cognition, neuroimaging, fMRI

### INTRODUCTION

The study of higher cognitive function has focused almost exclusively upon mental processes occurring during complex, demanding cognitive tasks. The flow of inner mental events, however, continues even when no tasks are present, forming a "stream of thought" in William James' (1890) classical phrase. Such inner, spontaneous thought processes have been difficult to observe and characterise using traditional experimental methods. Nevertheless, several lines of research from the behavioural literature and a number of functional neuroimaging observations provide relevant implications regarding their cognitive and neural basis. Here, we summarise behavioural and neuroimaging evidence indicating that spontaneous, task-unrelated cognitive processes share common cognitive and neural mechanisms with purposeful, task-related thought processes. This evidence, including a review of the relevant literature and findings from a new functional magnetic resonance imaging (fMRI) study, suggests that spontaneous thought is based upon higher order cognitive processes and brain regions, amongst which long-term memory processes supported by temporal lobe structures may play a particularly prominent role.

### SPONTANEOUS THOUGHT AS A HIGHER COGNITIVE FUNCTION: EVIDENCE FROM BEHAVIOURAL RESEARCH

A long-established tradition of behavioural research has aimed at studying spontaneous thought processes. Such processes have been referred to as "daydreaming" (Singer, 1966; Giambra, 1979), "mind-wandering" (Antrobus et al., 1970), "stimulus-independent" (Antrobus, 1968; Teasdale et al., 1993) or "task-unrelated" thought (Giambra, 1989). Despite apparent differences in terminology, however, the target of research across studies has been the same: thought processes that occur spontaneously and bear no relation to the task at hand.

Several methods for studying spontaneous thought have been developed and used in the literature. Despite their inevitable reliance on subjective verbal reports (Singer, 1974), these behavioural techniques have proven invaluable in several respects. First, they have demonstrated that it is possible to study spontaneous thought processes, albeit indirectly, and that it is important to do so, given the large part of mental life they occupy (Klinger and Cox, 1987). More importantly, these behavioural techniques have provided information regarding the cognitive mechanisms underlying spontaneous thought.

### *Behavioural Methods for Studying Spontaneous Thought*

At the broadest level of description, there are two possible ways to investigate spontaneous thought processes. On the one hand, this can be done using *questionnaires* based on retrospective (Giambra, 1977, 1979) or immediate (Klinger and Cox, 1987) reports, in which subjects are asked questions about the presence, frequency, or contents of their daydreams. Such questionnaires are usually quite detailed, cover multiple aspects of inner mental life, and provide a wealth of data that can be subjected to a factor analysis to reveal intra- and inter-individual differences.

Although questionnaires can be useful for descriptive purposes, they limit investigators to conclusions at the observational level, providing little information about possible mechanisms. In contrast, the second main type of method for investigating spontaneous thought processes employs a more controlled, laboratory-based approach, using *dual-task interference paradigms* to examine how spontaneous thought interacts with task-related processes. Subjects are presented with some primary task, for instance, tone-detection or random number generation. Simultaneously with this, they are asked to monitor the occurrence of task-unrelated thoughts and to either press a button when one occurs (Giambra, 1989) or to report the number of such thoughts during certain interval of time (Antrobus, 1968; Giambra, 1995).

Continuous self-monitoring of spontaneous thoughts as an explicit requirement, however, has many disadvantages. It presents additional attentional and mnemonic demands that may alter performance of the primary task. Furthermore, cueing subjects to monitor spontaneous thoughts can decrease the frequency with which such thoughts occur (Filler and Giambra, 1973). In an attempt to avoid these disadvantages, Teasdale and colleagues developed an *implicit dual task interference paradigm* (Teasdale et al., 1993, 1995). In this paradigm, subjects are required to perform a single primary task. The generation of spontaneous task-unrelated thoughts is treated as a secondary, implicit task, for experimental purposes only, but is never mentioned as such to subjects. Spontaneous thoughts are monitored and recorded by the experimenter, using a *thought-sampling* approach in which subjects are probed, at unpredictable intervals, to report their thought content at that instant. This procedure remains the most advanced experimental method for studying spontaneous thought to date.

### *Spontaneous Thought and Executive Resources*

Research conducted using dual-task interference paradigms has provided a number of important findings relating to the cognitive mechanisms of spontaneous thought. First, it has convincingly rejected the possibility that spontaneously occurring thoughts are a by-product of task-related thought

processes. If spontaneous thoughts were indeed such a by-product, they should be expected to occur only during tasks, and to *decrease* with decreasing task demands. Quite on the contrary, however, spontaneous thoughts consistently *increase* with decreasing task demands (Antrobus, 1968; Filler and Giambra, 1973; Teasdale et al., 1993).

Perhaps most striking, however, is the conclusion from this literature that *the generation of spontaneous thought depends on central executive processes*. In support of this conclusion, Teasdale and colleagues have repeatedly demonstrated that tasks interfere with the production of spontaneous thoughts to the extent that they make continuous demands upon central executive resources (Teasdale et al., 1993, 1995). For instance, Teasdale et al. (1995, Experiment 4) used a random-number generation task, in which the degree of produced randomness can be used as an indicator of the extent to which limited central resources of control and coordination are being utilised (Baddeley, 1986). They found that the degree of randomness was consistently lower during intervals in which task-unrelated thoughts were reported, indicating that random number generation and spontaneous thought production compete for the same, limited executive control and coordination resources. Thus, when more executive resources are allocated to production of spontaneous thoughts, fewer are available to control the generation of random numbers and, consequently, randomness decreases.

A second line of evidence linking executive function and spontaneous thought comes from examining age-related differences. Giambra (1989) studied people between 17 and 92 years of age and recorded the frequency with which they reported task-unrelated thoughts during a number of vigilance tasks. During each vigilance task, a target stimulus occurred at long and irregular intervals (e.g., once every 5 minutes), and subjects had to respond to its occurrence. In addition, they pressed a different button every time they had a thought unrelated to the vigilance task. Across five different experiments, Giambra found a consistent and substantial *decrease* in the number of spontaneous thoughts with increasing age – a reduction that parallels the overall decline in executive functioning observed with increasing age (e.g., Salthouse et al., 1998).

In sum, behavioural studies have indicated that spontaneous, task-unrelated thought processes are closely linked to the same cognitive mechanisms that underlie deliberate, task-related thought processes. Next we turn to evidence from neuroimaging suggesting similar conclusions in terms of neural mechanisms.

### *Activation in Higher Cortical Regions in the Absence of Demanding Tasks: Evidence from Neuroimaging*

The absence of task in the context of neuroimaging is usually referred to as “rest” and

consists of blocks during which subjects are typically asked to simply remain lying still in the scanner and “do nothing”. Such rest conditions were originally intended to provide a baseline against which target conditions can be assessed. As Seneca remarked, however, in 62 A.D., long before the advent of neuroimaging, “The fact that the body is lying down is no reason for supposing that the mind is at peace. Rest is sometimes far from restful.”\* If rest is marked by spontaneous thought processes relying on the same cognitive mechanisms as task-related thought, then an overlap in the pattern of brain activation during rest and cognitive tasks should be expected.

#### *Regions Activated Commonly by Cognitive Tasks and Rest*

Indeed, such an overlap has been observed ever since the beginning of neural explorations of higher cognition. Ingvar (1975) was the first to report a “striking similarity” between the relative distribution of blood flow in the “problem solving mode” on the one hand, and in the “resting mode”, on the other hand. He observed that the relative increase in blood flow over frontal regions associated with a performance of a reasoning test (the Raven’s Matrices) was matched, and even surpassed, by frontal increases in the absence of a task. Ingvar termed this resting pattern “hyperfrontal”, and attributed it to the fact that “thought processes in resting consciousness are constantly active” (Ingvar, 1979).

In the time since these early observations, brain imaging techniques have undergone a refinement in spatial and temporal sensitivity. Despite the lessons from the early neuroimaging findings, however, the use of a resting baseline for the study of higher cognitive processes has remained a common practice, frequently justified by the argument that mental processes during rest are likely to be unsystematic and unorganised, so that any corresponding neural activation would be nonlocalised and negligible. On several occasions, however, researchers have presented evidence to the contrary, demonstrating that particular brain regions are systematically activated during rest.

*Absence of task-related activation when a resting baseline is used.* One line of evidence suggesting that particular regions are consistently recruited during rest comes from observations of the *absence* of task-related activation in particular brain regions when a resting baseline is used, indicating that these regions are activated not only during the task, but also during rest. For instance, Kosslyn et al. (1995) observed visual cortex activation during a visual imagery task, but only when it was compared to a listening baseline

condition; when a resting baseline was used, imagery activation was obscured, due to the presence of rest-related activation in visual cortex. A similar pattern of findings was observed for medial temporal lobe structures (Stark and Squire, 2001). In this study, brain structures such as the hippocampus and parahippocampal gyrus were activated not only during task-related memory encoding and retrieval, but also during periods of rest (in comparison to several alternative non-resting baseline conditions). The authors argued that “periods of rest are associated with significant cognitive activity”, including incidental encoding and retrieval processes that would account for the observed rest-related activation.

In addition, findings of absence of activation in another brain region, the rostralateral prefrontal cortex (RLPFC), have also been linked to the use of resting baselines (Christoff and Gabrieli, 2000). This prefrontal region is consistently activated during higher order cognitive tasks, such as problem solving (e.g., Baker et al., 1996; Christoff et al., 2001) and complex memory retrieval (for a review, see Christoff and Gabrieli, 2000). Buckner et al. (1996), however, used such a complex memory retrieval task involving cued recall of paired associates, and observed no RLPFC activation when a resting baseline was used; when a non-resting word repetition baseline was used, however, RLPFC activation was apparent. Similarly, Ragland et al. (1998) observed no RLPFC activation when a problem solving task, the Wisconsin Card Sorting Test, was compared to rest – although such activation has been consistently reported for this task in comparison to non-resting baselines (Berman et al., 1995; Goldberg et al., 1998; Nagahama et al., 1996). Thus, the RLPFC appears to be another brain region consistently recruited during rest – a recruitment that is likely due to evaluative processes directed towards subjects’ own internal cognitive states during the resting period (Christoff and Gabrieli, 2000; Christoff et al., 2003).

*Overlapping network of regions activated during rest and higher cognitive tasks.* Instead of focusing on the absence of activation in particular brain regions, some researchers have argued, similarly to Ingvar (1975; 1979), that the overall pattern of brain activation during rest resembles remarkably the pattern of activation associated with particular higher cognitive functions. Thus, Andreasen et al. (1995) used an episodic memory task requiring the recall of a specific event from one’s past experience, and a rest condition (or “random episodic silent thinking”, as they described rest, using an intentionally ironic acronym). Compared to a semantic memory condition consisting of recalling words that start with a specific letter, both the episodic and the rest condition produced activation in higher cortical regions, including prefrontal and parietal

\* Letters from a Stoic, Penguin Press, p. 111



association cortices. Andreasen et al. argued that rest is likely to be associated with “random episodic memory” processes, or a type of free-association, uncensored recollection of past experiences. Indeed, in debriefing interviews with subjects after the study, mental activity during rest was described as “quite vigorous” and consisting of a mixture of freely wandering past recollections, future plans, and other personal thoughts and experiences that appeared to be loosely linked.

A related set of findings was reported by Binder et al. (1999), who observed largely overlapping set of polymodal cortical regions activated both by a semantic retrieval task and by rest. The semantic task required subjects to listen to the names of animals (e.g., squirrel), and to respond when a named animal is found in the United States and is used by people (e.g., cow). Compared to a perceptual baseline (a tones task during which subjects listened to a sequence of low and high tones and had to respond when it included two high tones), both the semantic and rest condition produced activation in regions similar to those reported by Andreasen et al. (1995) – prefrontal and parietal association cortices, medial temporal lobe, and cingulate cortices. Binder et al. argued that the observed rest-related pattern of activation reflected conceptual processes occurring during the conscious resting state: processes involving semantic knowledge retrieval, representation in awareness, and manipulation of represented knowledge.

This summary of findings shows that a number of higher cortical regions, including visual areas, medial temporal lobe, and lateral association cortical areas, are consistently recruited during rest as well as during a variety of higher cognitive tasks. Furthermore, this recruitment has been associated with specific higher cognitive functions, such as visual imagery, memory retrieval, conceptual processing and problem solving – processes that seem to occur both in the presence and in the absence of cognitive tasks.

#### REGIONS ACTIVE DURING REST BUT DEACTIVATED DURING COGNITIVE TASKS

A different set of brain regions, most often identified along the medial prefrontal and parietal surface, are also systematically active during rest but are, in contrast, *deactivated* during cognitive tasks (Shulman et al., 1997; Raichle, 1998; Mazoyer et al., 2001). Such regions have been associated with a “default mode” of brain function (Raichle et al., 2001) – i.e., mental processes that occur during rest, but are *suspended* during cognitive tasks. For instance, one such default mode process is the general, unfocused monitoring of information from external sensory and internal somatic states – a process that would be suspended during a demanding cognitive task (Raichle, 1998).

While intrinsically interesting, such default state processes seem different from the spontaneous thought processes discussed here, both in terms of their neural basis and in terms of their relation to higher cognitive functions. Thus, brain regions identified as “default state” areas have been localised most often along the medial surface (Shulman et al., 1997; Gusnard et al., 2001; Raichle et al., 2001; Greicius et al., 2003; see Gusnard and Raichle, 2001 for a review). Furthermore, some of these regions, such as the rostromedial prefrontal (Lane et al., 1997) and posterior cingulate cortices (Maddock, 1999), while consistently deactivated during cognitive tasks, are known to be *activated* during emotionally relevant tasks (see also Drevets and Raichle, 1998; Simpson et al., 2001b; Simpson et al., 2001a). This suggests that at least some “default state” regions may be activated in common by emotional tasks and rest. In contrast, the network of regions activated in common between cognitive tasks and rest includes more lateral cortical regions and medial temporal lobe structures, as reviewed above. We limit our discussion to this latter set of regions and to spontaneous cognitive processes.

#### *Rest as a Condition of Interest*

Discussions of neural recruitment associated with cognitive processes during rest have concentrated either on a particular brain region (Kosslyn et al., 1995; Christoff and Gabrieli, 2000; Stark and Squire, 2001), or on a network of activations overlapping between rest and a particular cognitive function, such as episodic (Andreasen et al., 1995) or semantic (Binder et al., 1999) retrieval. Furthermore, although the importance of studying the spontaneously occurring cognitive processes during rest has been emphasised repeatedly, virtually all discussion of these processes has been based on comparisons between rest, on the one hand, and some task posing relatively high cognitive demands, on the other hand.

If rest is to be treated as a condition of interest, however, it is necessary to examine the whole-brain pattern of activation resulting from a comparison between rest and a baseline task that poses only minimal cognitive demands and is thus as closely matched to rest as possible. In the next section, we report an fMRI study in which rest was explicitly treated as a condition of interest, and was compared to a baseline task requiring only minimal cognitive demands, in order to assess the resulting whole-brain pattern of activation.

#### REST COMPARED TO A TASK OF MINIMAL COGNITIVE DEMANDS: AN FMRI STUDY

##### *Materials and Methods*

**Subjects.** Twelve right-handed volunteers from the Stanford community (eight female) took part in the experiment. Subjects were 18 to 25 years old

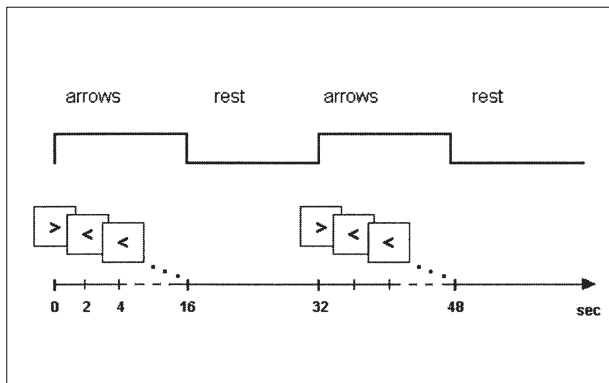


Fig. 1 – Behavioural paradigm. Rest was compared to a closely matched, continuously engaging task of minimal cognitive demands (arrows).

(mean age 20) and were native speakers of English. All subjects gave informed, written consent to participate in the study, which was approved by the Institutional Review Board at Stanford University.

**Task and procedure.** Subjects alternated between performing an arrows task and resting (Figure 1). Blocks were 16 s long and there were 8 blocks of each condition. During the arrows task, an arrow appeared on the screen every 2 s, pointing randomly to right or left. Subjects responded with their right hand, pressing one of two buttons on a hand-held button-box (right button for right arrow and left button for left arrow). They were instructed to respond as quickly as possible after each arrow's onset, and were told responses would be considered incorrect if they occurred later than 500 ms after the arrow onset.

Prior to scanning, subjects were given a brief practice session on the task. During scanning, subjects first performed a different cognitive task (results from which have been reported elsewhere), during which the arrows task was used as a baseline task, so that by the time the functional data reported here were acquired, performance on the arrows task was fully automatised.

**Functional acquisition.** The fMRI procedure followed a standard protocol. Imaging was performed using a 3T fMRI GE scanner. Functional images covering the whole brain were obtained (TR = 1 s; FOV = 24 × 24 cm; 64 × 64 voxels; spiral sequence; 17 contiguous slices, each 7 mm thick). A total of 256 functional volumes were acquired for each subject over 4 minutes and 16 seconds. Four subsequently discarded volumes (a total of 4 s) were acquired at the beginning of each session to allow for T1 stabilisation. Anatomical images were also obtained (using a T1-weighted spin echo sequence) in the same location as the functional images. Head movement was minimised using a bite-bar.

**Data analysis.** Preprocessing and statistical analysis were performed using SPM99. Preprocessing included correction for slice-timing

differences, motion correction, spatial normalisation into MNI space (using nonlinear transformations derived from normalising the segmented grey matter from the anatomical images to a grey matter image of the MNI template), and spatial smoothing (using 8 mm FWHM isotropic Gaussian kernel). An anatomically defined whole brain mask was created and explicitly specified prior to statistical analysis to ensure that statistics are performed in all brain regions, including those where signal may be low due to susceptibility artefacts. Data were scaled to the session-specific grand mean and were high-pass filtered using an upper cut-off period of 70 s. Condition effects at each voxel were estimated according to the general linear model, using a single regressor of interest modelling the arrows task (boxcar convolved with the canonical HRF). Regionally specific effects were estimated by positively or negatively weighting the parameter estimate for this regressor in linear contrasts. A random effects model was used at the group level.

## RESULTS

**Task performance.** Behavioural performance indicated that subjects followed closely the arrows task instructions. Mean accuracy was 98% ( $SE = 0.52\%$ ; range across subjects: 94 to 100%), and all responses occurred within 500 ms after the arrow's onset with a mean response time of 353 ms ( $SE = 15.92$  ms; range across subjects: 270 ms to 452 ms).

**Neuroimaging results.** Comparing rest versus arrows yielded activations in multiple regions (Table I, Figure 2). Regions of strong activation in right temporopolar cortex and left parahippocampal gyrus were observed, surviving a threshold of  $P < 0.05$  corrected for multiple comparisons throughout the brain. After relaxing activation threshold to  $P < 0.001$  uncorrected, the temporopolar and parahippocampal activations were found to extend bilaterally. At this threshold level, several additional regions of activation were observed, including left rostralateral prefrontal cortex, primary and extrastriate visual areas, left insula, and right inferior parietal cortex.

Comparing the arrows task versus rest yielded a single cluster of activation in the left primary motor cortex (Table I, figure 2). Activation in this cluster was significant at  $P < 0.05$  corrected for multiple comparisons within a priori defined region of interest comprising the left motor cortex (BA4).

## DISCUSSION

A network of regions related to spontaneous cognitive processes was identified, by treating rest as a condition of interest and comparing it to a

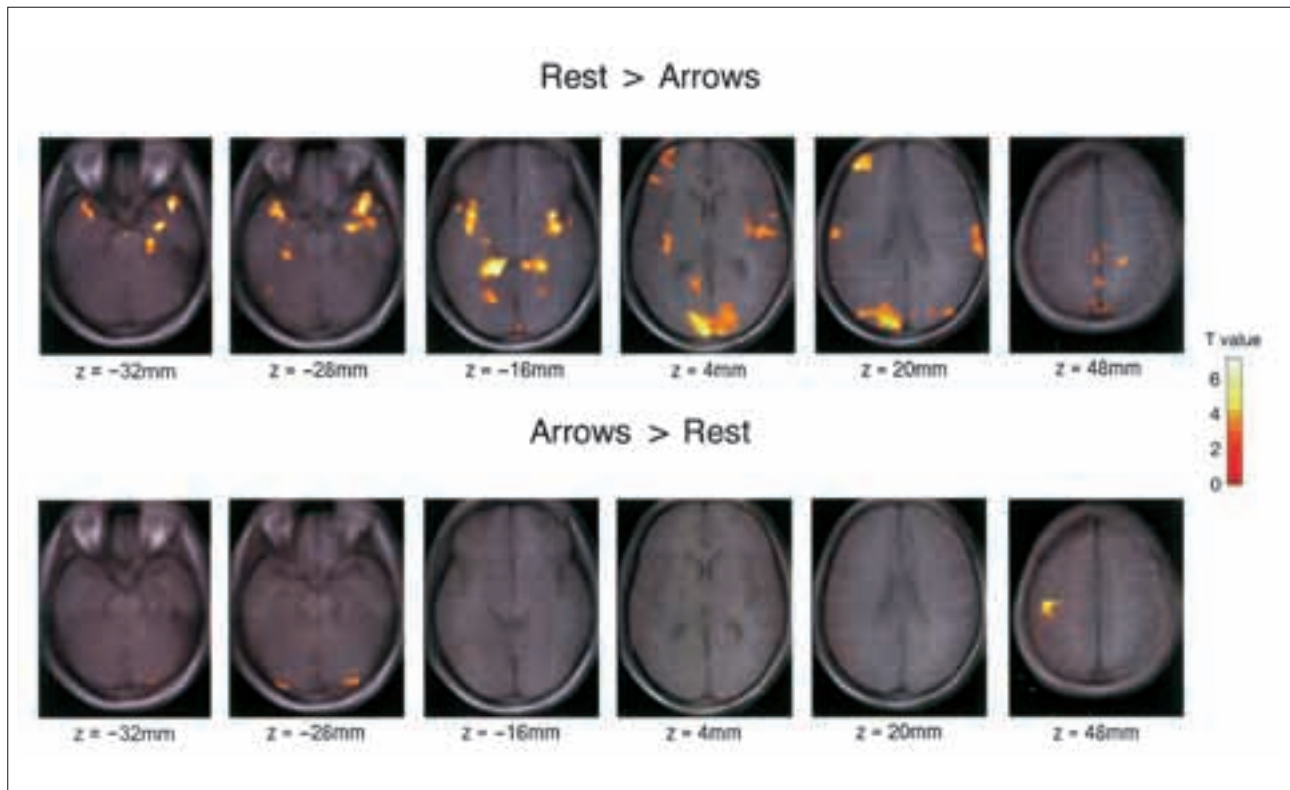


Fig. 2 – Activation results. Whole-brain pattern of activation resulting from random-effects group analysis (12 subjects). Activation maps are displayed on axial slices derived from the group-averaged anatomical image. Results are thresholded at  $P < 0.005$ , with an extent threshold of 10 voxels.

TABLE I  
Maxima of regions showing significant signal changes

Region of activation	L/R	BA	No. of voxels	Talairach coordinates			Z value	P value
				x	y	z		
<b>Rest vs. Arrows</b>								
<i>Temporal lobes</i>								
Superior Temporal Gyrus	R	38	169	40	12	-28	5.07	< 0.05*
Superior Temporal Gyrus	L	38	102	-38	8	-20	3.84	< 0.001
Parahippocampal Gyrus	L	-	171	-14	-44	-16	4.99	< 0.05*
Parahippocampal Gyrus	R	-	57	12	-40	-12	3.80	< 0.001
Hippocampal region	R	-	27	24	-18	-36	3.86	< 0.001
<i>Prefrontal cortex</i>								
Middle Frontal Gyrus	L	10/46	72	-40	50	20	3.59	< 0.001
<i>Posterior cortices</i>								
Inferior parietal lobe	R	40	104	72	-24	28	4.18	< 0.001
Posterior Insula	L	-	10	-38	-26	8	3.69	< 0.001
Precuneus	R	7	38	24	-34	52	4.00	< 0.001
Precuneus	L	31	28	-16	-60	12	3.86	< 0.001
Cuneus	L	17	260	-4	-98	4	3.71	< 0.001
Middle Occipital Gyrus	L	19	-	-40	-88	16	3.67	< 0.001
	M	18	-	-6	-92	16	3.62	< 0.001
Cuneus	L	19	22	-10	-68	32	3.45	< 0.001
Cuneus	R	18	16	12	-98	8	3.39	< 0.001
<b>Arrows vs. Rest</b>								
Precentral Gyrus	L	4	63	-44	-18	48	3.70	< 0.05†

\*P value corrected for entire brain volume; †P value corrected for volume of interest (left primary motor cortex, BA4); the remaining P values are uncorrected. Abbreviations: L, Left; R, Right; BA, Brodmann area.

continuously engaging task of minimal cognitive demands. The most robust activation was localised in temporal lobe structures, including lateral anterior and medial temporal regions. Activations

were also observed in anterior lateral prefrontal cortex and visual cortical areas. Thus, neural recruitment during rest was statistically robust and consistently localised to specific brain regions.

Furthermore, the strength of observed activations was comparable to that seen during many highly demanding cognitive tasks.

The observed activations were localised to brain regions that have been implicated repeatedly in a variety of higher cognitive functions – as well as rest (Andreasen et al., 1995; Binder et al., 1999). However, unlike previous related studies, no cognitive task was present in either condition of the present comparison. Therefore, the observed pattern could not have been influenced by relative difference in the employment of particular task-related cognitive processes. Furthermore, cognitive demands posed by the two conditions in the present comparison were kept at a minimum. Thus, the activation pattern was also unlikely to be influenced by variations in cognitive demands. The lack of modulation in medial prefrontal cortex – a region frequently activated with reduction in cognitive demands (Shulman et al., 1997; Raichle, 1998; Mazoyer et al., 2001) – was, therefore, likely due to the lack of modulation of cognitive demands in the present comparison.

The specific brain regions previously implicated in spontaneous cognitive processes during rest – medial temporal lobe, visual cortex, and rostralateral prefrontal cortex – were all observed as prominent part of the activation pattern. This is consistent with previous arguments (Kosslyn et al., 1995; Christoff and Gabrieli, 2000; Stark and Squire, 2001) for the presence of long-term memory, visual imagery and introspective evaluative processes in the absence of tasks. The results from the present study, however, reveal differences in the relative contribution of these regions to the overall pattern of brain activation – and suggest differences in the corresponding contribution of various cognitive functions to spontaneous thought flow.

Most importantly, the observed strong dominance of temporal lobe recruitment suggests that *long-term memory processes may form the core of spontaneous thought flow*. This observation is important on several accounts. First, it is unpredicted by the behavioural literature. Behavioural research, as reviewed in the introduction, has emphasised the executive aspects of thought flow – or the conscious, controlled mental processes responsible for producing connected sequences of thoughts. While executive mechanisms do appear to contribute to the generation of spontaneous thought flow, as evidenced by the observed prefrontal cortex activation, this contribution seems secondary compared to that of long-term memory mechanisms. Such long-term memory processes may not be accessible to subjects' awareness and may not, therefore, be possible to observe through behavioural techniques based on subjective verbal reports. The pattern of brain activation, on the other hand, does not discriminate between

processes that are accessible to awareness and those that are not – which underscores the importance of using neuroimaging methods for the study of spontaneous thought flow.

Second, by pointing to long-term memory mechanisms as an essential part of thought flow, it forces us to reconsider current definitions of thought processes – and higher cognitive functions in general. The prevalent current approach to studying thought processes equates them with conscious, controlled, executive processes, and defines them almost exclusively in terms of frontal lobe functions. In this approach, any contributions from long-term memory processes and temporal lobe structures would be considered only secondary – supplementing the process of thinking rather than determining its flow. In contrast, we propose that long-term memory processes, such as spontaneous retrieval, may play an important role in the generation of thought flow – particularly in the absence of deliberate, task-related cognitive processes. By considering long-term memory processes as part of thought mechanisms, it may be possible to address aspects of thought flow that have remained unaccounted for until now – such as its tendency to “drift”, or to change its course spontaneously (James, 1890). Furthermore, it may allow us to better understand a variety of spontaneous thought phenomena, such as the rare but characteristic “leaps of thought”, leading to an insight into the solution of a problem (Maier, 1931), or the ironic mental processes (Wegner, 1994) leading to the intrusion of certain thoughts into consciousness, despite our efforts to prevent them. Such spontaneous thought phenomena are likely to remain beyond our scope of study if human thinking is defined solely in terms of conscious, controlled, executive processes.

In Piaget's (1929) theory, thought development passes through a stage at which children acquire the concept of “object permanence” – or the notion that objects in the environment continue to exist even when the child is not observing them directly. Incorporating this knowledge into children's thinking advances their conceptual development to a next level. In a similar way, we may have to recognise the idea of “thought permanence” – or the notion that thought continues to exist even when we are not observing it directly. Incorporating this knowledge into our experimental paradigms and theoretical notions could well advance our study of thought flow and its mechanisms to a next level.

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