Science AAAS

www.sciencemag.org/cgi/content/full/315/5810/393/DC1

Supporting Online Material for

Wandering Minds: The Default Network and Stimulus-Independent Thought

Malia F. Mason,* Michael I. Norton, John D. Van Horn, Daniel M. Wegner, Scott T. Grafton, C. Neil Macrae

*To whom correspondence should be addressed. E-mail: malia@nmr.mgh.harvard.edu

Published 19 January 2007, *Science* **315**, 393 (2007)
DOI: 10.1126/science.1131295

This PDF file includes

Supporting Online Material

Materials and Methods

Participants

Nineteen participants (12 female; 7 male) completed the experiment in exchange for course credit. All participants were right-handed, native English speakers with no history of neurological problems. All gave informed consent according to the procedures approved by the Committee for the Protection of Human Subjects at Dartmouth College.

Design and Stimulus Materials

The first phase involved training participants on both a verbal and a visuospatial working memory task. The verbal working memory task involved remembering and manipulating 4 four-letter sequences (e.g., 'R H V X'). A verbal working memory trial consisted of the following sequence of events (see Fig. S1): A fixation cross appeared in the center of the screen for 200 ms. The fixation cross was erased and replaced by a 4-letter string (e.g., 'R H V X') which remained on the screen for a duration of 1000 ms. Immediately after the 4-letter string was erased, an arrow indicating whether the string should be referenced in the forward (if it was displayed pointing to the right) or backward direction (if was displayed pointing to the left) appeared. The participant was then prompted by the appearance of one of the four letters contained in the string (e.g., 'H') to which the participant was to indicate, via a key press, the position at which the letter appeared in the string (i.e., first, second, third or last). Once the computer registered a response, a new letter was presented. After participants were prompted for the position of all four letters in the sequence, a new arrow would appear indicating a change in the referencing direction.

The visuospatial task involved remembering and manipulating 4 finger-tapping patterns. A visuospatial working memory trial consisted of the following sequence of events (see Fig. S2). A fixation cross appeared in the center of the screen for 200 ms and was replaced by a picture of four boxes that changed color, one by one, indicating the target key-press sequence. The boxes were then erased and replaced by an arrow indicating whether the key-press sequence should be performed in the forward (if the arrow pointed to the right) or backward direction (if the arrow pointed to the left). Once the computer registered a response, a new arrow appeared indicating a new reference direction. To ensure that participants spent equivalent time performing the 'practiced' and the 'novel' working memory sequences, all trials were self-paced.

Procedure

Sequence Training (Days 1, 2 & 3)

On three consecutive days, participants reported to the laboratory for 30 minutes of training with the sequences. As an incentive to perform well, participants were informed that the individual whose performance showed the greatest improvement across the course of the four training days would be paid an additional $75.

Thought-sampling (Day 4)

Upon arrival on the fourth day of training, participants were directed to the testing room and informed that they again would be practicing the learned sequences in blocks but that, at random intervals, they would be interrupted and asked to indicate whether they were having an "irrelevant thought." Consistent with previous studies of this nature (*see 1, 2*), the term "irrelevant thought" was defined to participants as "thoughts that do not facilitate performance and are not immediate reactions to perceptual information gleaned over the course of a trial." To be certain they understood the definition of 'task irrelevant', participants completed a short test that involved them classifying example thoughts. Participants were then informed of one final change. In addition to performing blocks of the working memory task on the eight learned sequences (four letter strings, four motor patterns), they would also be performing the task on sequences that they had not practiced previously.

The participant was then administered three 7-minute runs of interleaved rest (i.e.,'+') and task blocks (i.e., verbal and visuospatial working memory tasks). Data from one participant was not included in the analysis because of a computer malfunction.

Functional MRI (Day 5)

On the fifth and final day of the experiment, participants were scanned (fMRI) while performing both working memory tasks on the practiced sequences, on novel sequences and while passively observing a centrally-presented fixation cross. The experiment consisted of 5 EPI scans, each lasting 6 minutes and 50 seconds. Each of the blocks (fixation, practiced sequences, novel sequences) within a single scan lasted between 20 and 40 seconds in duration.

Images were acquired using a 1.5 Tesla whole body scanner with a standard head coil. Visual stimuli were generated with Presentation software. Stimuli were displayed to participants on a screen positioned at the head end of the bore. Participants viewed the screen through a mirror. Cushions were used to minimize head movement.

T1- weighted anatomical images were collected using a high resolution 3-D sequence (SPGR; 128 sagittal slices, TR = 7 ms, TE = 3 ms, prep time = 315 ms, flip angle = 15°, FOV = 24 cm, slice thickness = 1.2 mm, matrix = 256 x 192). Functional images were collected in runs using a gradient echo EPI sequence (each volume comprised 25 slices; 4.5 mm thick, 1 mm skip; TR = 2500 ms, TE = 35 ms, FOV = 24 cm, 64 x 64 matrix; 90° flip angle).

Image Analysis

Functional MRI data were analyzed using SPM99. For each functional run, data were preprocessed to remove sources of noise and artifact. Functional data were corrected for differences in acquisition time between slices for each whole-brain volume, realigned within and across runs to correct for head movement, and coregistered with each participant's anatomical data. Functional data were then transformed into a standard anatomical space (3 mm isotropic voxels) based on the ICBM 152 brain template (MNI), which approximates Talairach and Tournoux's atlas space. Normalized data were then spatially smoothed using a Gaussian kernel (6 mm FWHM).

For each participant, a general linear model specifying task effects (modeled with a function for the hemodynamic response), runs (modeled as constants), and scanner drift (modeled with linear trends) was used to compute parameter estimates (β) and *t*-contrast images for each comparison at each voxel. These individual contrast images were then submitted to a second-level, random-effects analysis to obtain mean *t*-images. As expected, regions of the default network exhibited greater BOLD activity during baseline periods than during the task blocks (i.e., ‘baseline > all tasks’; thresholded at $p = .001$, uncorrected; k = 10 mm^3; see Table S1).

The resulting default network contrast was subsequently converted to a binary image and used as an ‘inclusive’ mask in subsequent analyses (at a more lenient threshold of $p < .05$, k = 10). In effect, this made it possible to identify differences in cortical activity during ‘practiced’ blocks relative to ‘novel’ blocks that occurred *within* the default network. This analysis is critical since, as our thought-sampling results suggest, regions involved in mind-wandering should fulfill two criteria: they should exhibit the greatest activity during baseline periods (i.e., emerge from the ‘baseline > all tasks’ contrast) and exhibit greater activity during ‘practiced’ blocks relative to ‘novel’ blocks. Regions within the default network that attenuated less during high-incidence SIT periods -- that emerged from the ‘practiced > novel’, inclusively masked with ‘baseline > all tasks’ -- are reported in Table S2.

Correlational Analyses. Participants were contacted two weeks after completing the functional imaging portion of the study and asked to fill out a short questionnaire in exchange for monetary compensation. Sixteen of the 19 individuals who participated in the fMRI portion of the investigation completed the 12-item *daydream frequency* scale of the Imaginal Process Inventory (*3*; e.g., “*On a long bus, train, or airplane ride I lose myself in thought*”). To determine whether changes in default network BOLD activity during practiced relative to novel blocks was related to individuals’ propensity to mind-wander we conducted voxel-wise correlations using participants’ standardized score on the *daydream frequency* scale and their ‘practiced > novel’ contrast images (thresholded at r(*14*) > .50, $p < .05$). See Table S3 for a list of the r-values and extent sizes associated with the clusters that emerged from this analysis.

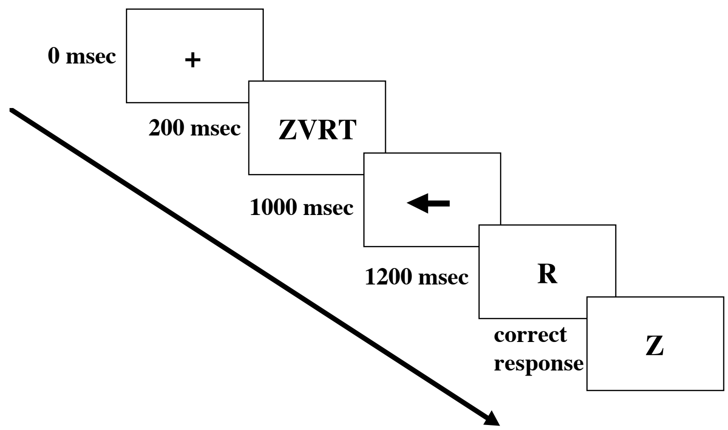
Supporting Text

Differences observed outside the default network. Consistent with previous investigations which have demonstrated that increases in working memory demand are associated with stronger and more extensive activity in the ventrolateral PFC (BAs 44/45/47), the dorsolateral PFC (BAs 9/46), and the superior parietal lobule (BA 7), the present study found significantly greater activity in bilateral aspects of the middle and superior frontal gyri (BAs 6/8/9), in the left inferior frontal gyrus (BA 44), and bilateral aspects of the superior parietal lobule (BA 7) during the ‘novel’ blocks relative to the ‘practiced’ blocks.

As is clear from the thought sampling results (see Phase 2), participants reported the greatest incidence of SIT during the baseline blocks. Accordingly, the analyses conducted in the present investigation were restricted to regions that exhibited the strongest BOLD signal during the baseline blocks. There are regions outside the default network which exhibit significantly greater activity during the ‘practiced’ blocks relative to the more demanding ‘novel’ blocks, including: bilateral aspects of the thalamus, the left precentral sulcus (BA 6), Broca’s area (BA 44), the lingual gyri bilaterally (BA 17), and a region that extended across the right fusiform and the parahippocampal gyrus (BA 19). Given that these regions fail to exhibit statistically significant recruitment during the periods in which SIT was most prevalent (i.e., the baseline blocks), we suspect that the differences in BOLD signal observed in these regions are related to the primary tasks (i.e., the verbal and visuospatial working memory tasks) rather than to episodes of mind-wandering. For example, because the trials were self-paced, participants completed a greater number of trials during the ‘practiced’ blocks, relative to the ‘novel’ blocks. One would therefore expect to find greater recruitment of areas that are associated with button presses or sub-vocalization when participants performed the ‘practiced’ blocks.

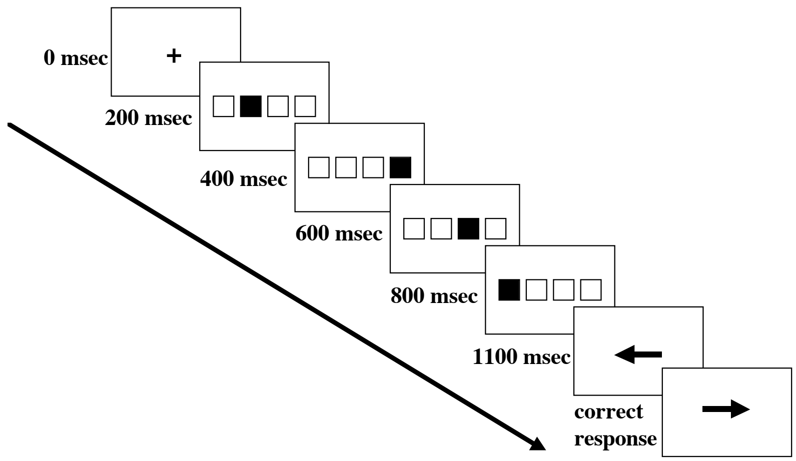
Supporting Figures

Figure S1.



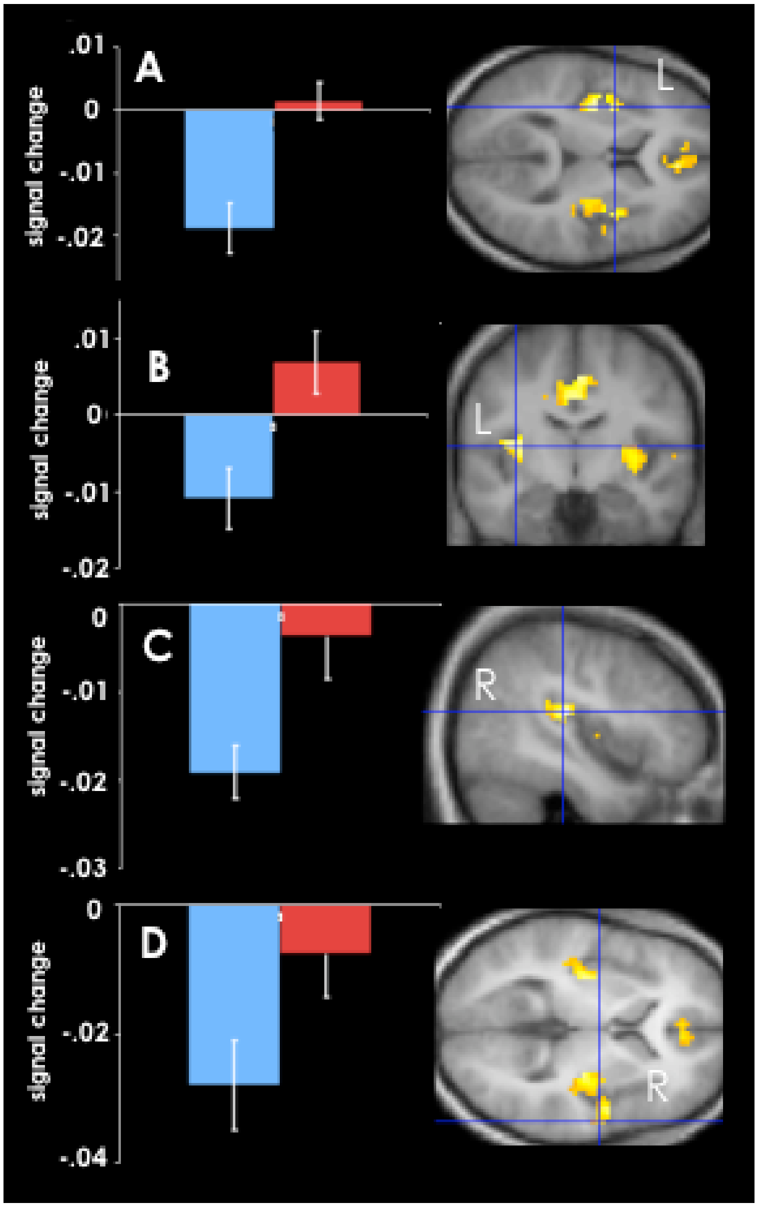
Timeline for verbal working memory trials.

Figure S2.



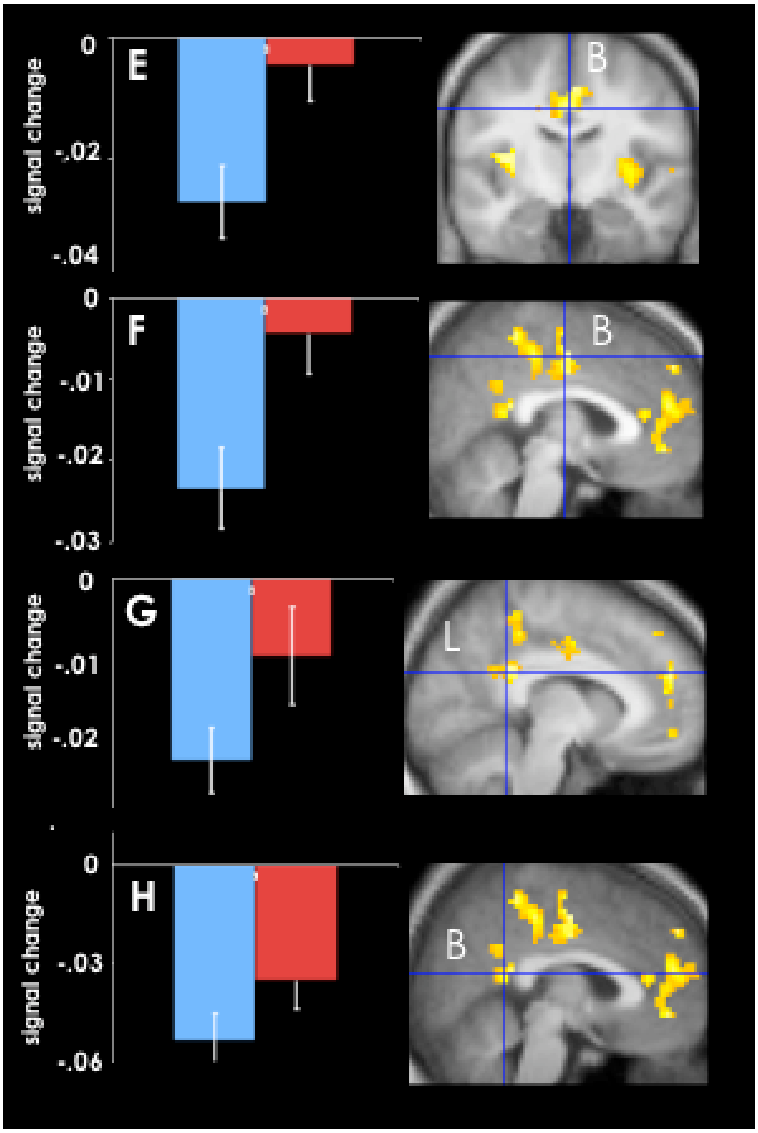
Timeline for visuospatial working memory trials.

Figure S3



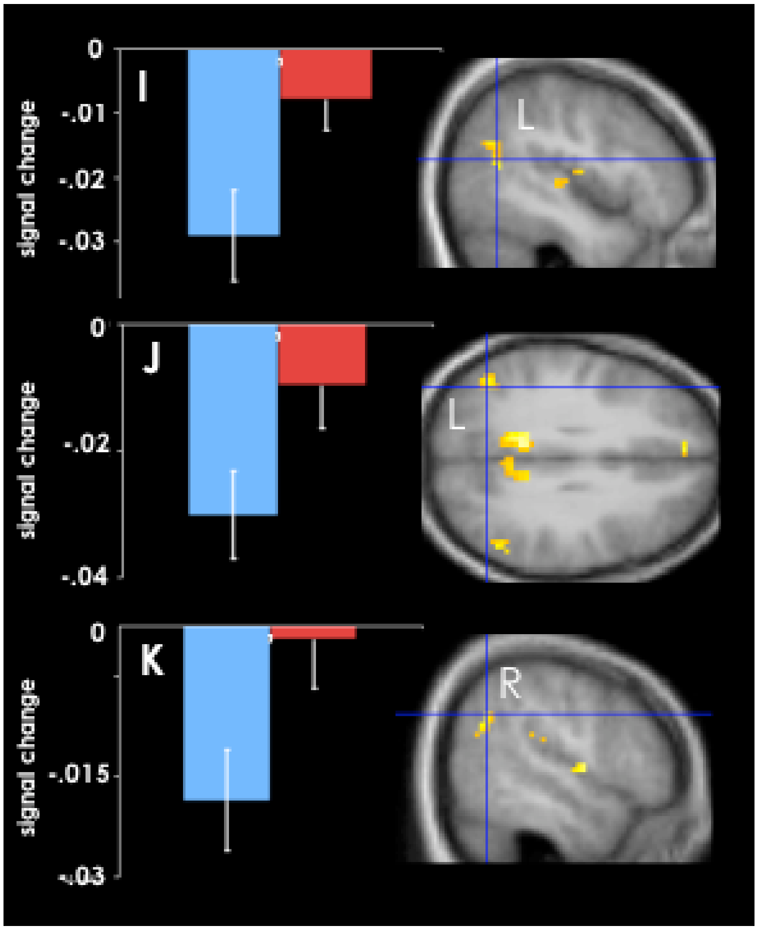
Regions of the insula that exhibited greater activity during the 'practiced' blocks (red) relative to the 'novel' blocks (blue). A = right insula (45, -24, 18); B = left insula (-42, 0, 9); C = right insula/claustrum (36, -3, 9); D = left insula/claustrum (-36, -9, 9); R = right; L = left. Mean activity was computed for each participant by averaging the signal in regions within 10 mm of the peak, from 4 TRs to 10 TRs after the onset of the blocks. Depicted in the graph are the average signal changes in these regions by task across all participants.

Figure S4.



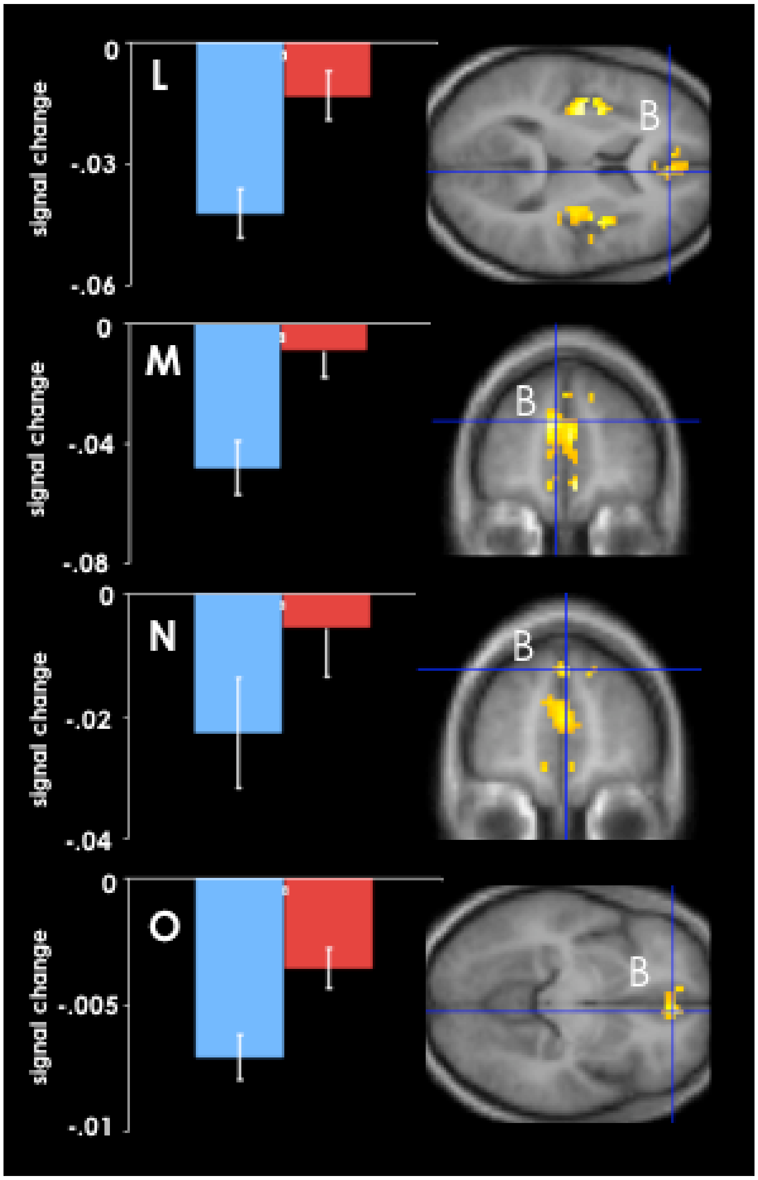
Posterior cingulate regions that exhibited greater activity during the 'practiced' blocks (red) relative to the 'novel' blocks (blue). E = bilateral cingulate (0, -9, 39); F = bilateral cingulate (3, -6, 47); G = left posterior cingulate (-9, -42, 27); H = bilateral posterior cingulate (3, -45, 18); L = left; B = bilateral. Mean activity was computed for each participant by averaging the signal in regions within 10 mm of the peak, from 4 TRs to 10 TRs after the onset of the blocks. Depicted in the graph are the average signal changes in these regions by task across all participants.

Figure S5.



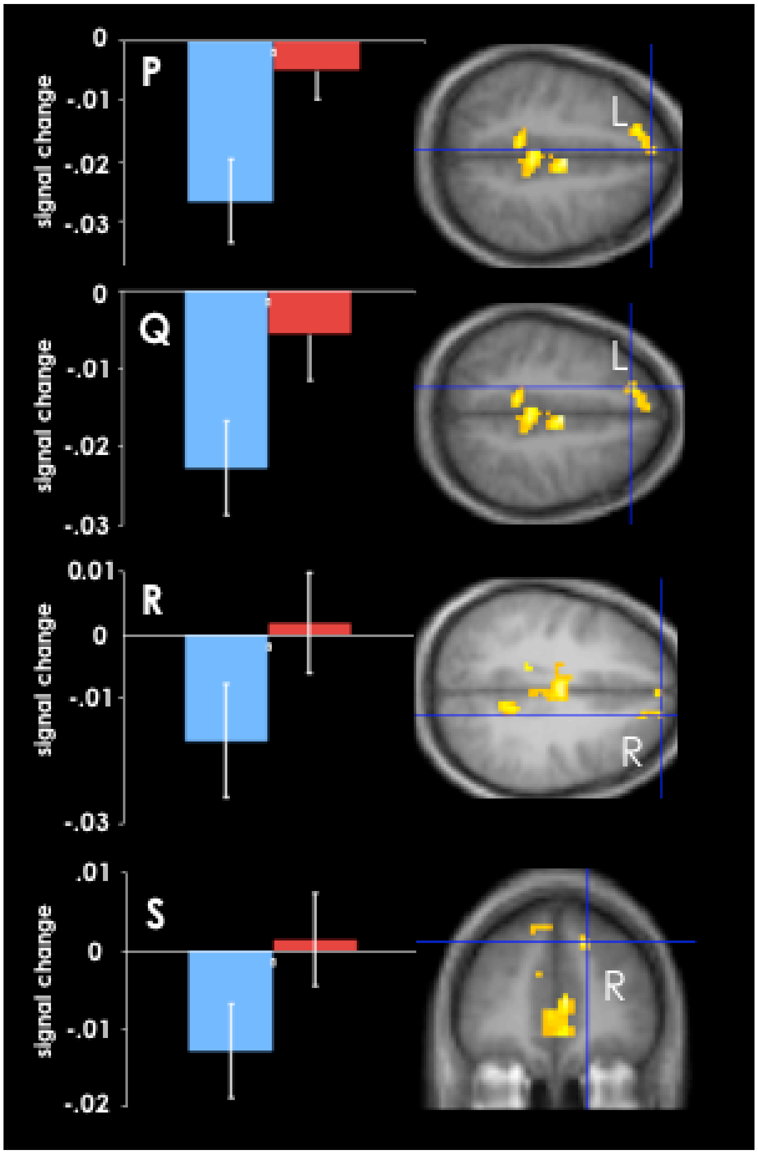
Lateral parietal regions that exhibited greater activity during the 'practiced' blocks (red) relative to the 'novel' blocks (blue). I = left temporal-parietal junction (-45, -57, 17); J = left angular gyrus (-48, -66, 30); K = right supramarginal/angular gyrus (53, -54, 36); L = left; R = right. Mean activity was computed for each participant by averaging the signal in regions within 10 mm of the peak, from 4 TRs to 10 TRs after the onset of the blocks. Depicted in the graph are the average signal changes in these regions by task across all participants.

Figure S6.



Medial frontal and anterior cingulate regions that exhibited greater activity during the 'practiced' blocks (red) relative to the 'novel' blocks (blue). L = bilateral anterior cingulate (6, 48, 9); M= bilateral superior frontal (-48, -66, 30); N =bilateral medial frontal (3, 57, 42); O = bilateral medial frontal (6, 51, -9); B= bilateral. Mean activity was computed for each participant by averaging the signal in regions within 10 mm of the peak, from 4 TRs to 10 TRs after the onset of the blocks. Depicted in the graph are the average signal changes in these regions by task across all participants.

Figure S7.



Superior frontal regions that exhibited greater activity during the 'practiced' blocks (red) relative to the 'novel' blocks (blue). P = left superior frontal (-3, 51, 51); Q= left superior frontal (-17, 42, 48); R =right superior frontal (15, 60, 39); s = right superior frontal (5, 48, 42); B= bilateral; R = right. Mean activity was computed for each participant by averaging the signal in regions within 10 mm of the peak, from 4 TRs to 10 TRs after the onset of the blocks. Depicted in the graph are the average signal changes in these regions by task across all participants.

Supporting Tables

Table S1. Regions that exhibited greater activity during baseline relative to the working memory tasks. Coordinates are reported in Talairach space. The displayed *t*-values are associated with the area's peak hemodynamic response during baseline ('+') relative to working memory (novel and practiced) blocks. All coordinates emerged with at a threshold of $p < .001$, k = 10.

Anatomical Location	BA	coordinates			*t*-value
		x	Y	z	
Frontal					
R. medial frontal gyrus	10	6	62	11	7.18
L. medial frontal gyrus	10	0	62	16	7.40
L. superior frontal gyrus	8	-12	49	45	7.05
R. superior frontal gyrus	8	12	49	47	6.12
R. superior frontal gyrus	8	21	40	45	4.82
L. superior frontal gyrus	8	-38	20	48	4.93
Limbic					
L. posterior cingulated	31	-9	-39	35	7.53
R. anterior cingulated	24	6	-15	39	7.25
R. amygdale		24	-7	-20	7.07
R. anterior cingulated	32	6	41	4	6.73
Parietal					
L. parahippocampal gyrus	35	-18	-36	-13	4.30
L. angular gyrus	39	-45	-68	37	8.46
L. precuneus	31	-9	-51	30	8.22
Sub-lobar					
R. insula	13	42	-11	3	8.55
R. insula	13	45	-28	18	5.43
L. insula	13	-42	-18	-2	8.04
Temporal					
L. middle temporal gyrus	39	-45	-63	31	9.56
L. superior temporal gyrus	22	-45	-6	-7	5.13
R. superior temporal gyrus	39	50	-57	33	6.72
L. fusiform	37	-30	-39	-13	5.11

Table S2. Regions within the default network that attenuated less during high-incidence SIT periods (i.e., ‘practiced > novel’, inclusively masked with ‘baseline > all tasks’). Coordinates are reported in Talairach space. The displayed *t*-values are associated with the area’s peak hemodynamic response during ‘practiced’ (high-SIT incidence) blocks relative to ‘novel’ (low-SIT incidence) blocks, when masked inclusively with the contrast (‘rest > tasks’, $p < .05$; k = 10). All coordinates emerged with at a threshold of $p < .001$, k = 10; ‘*’ denotes regions that exhibit only marginally significant ‘cluster-level’ effects.

Anatomical Location	BA	coordinates			*t*-value
		x	y	z	
Frontal					
R. medial frontal	10	6	51	-9	6.10
R. medial frontal*	9	3	57	42	5.62
R. medial frontal	6	3	-9	51	5.95
L. medial frontal	8	-3	51	51	4.19
L. superior frontal	9	-6	54	27	6.08
L. superior frontal	8	-18	39	51	4.89
R. superior frontal	8	15	48	42	5.58
R. superior frontal	9	15	60	39	4.29
R. precentral	6	21	-24	72	4.59
Limbic					
R. anterior cingulate	10	6	48	9	5.59
L. posterior cingulate	29	-6	-45	18	6.08
L. posterior cingulate	31	-9	-42	27	5.98
R. posterior cingulate	30	3	-45	18	5.52
B. cingulate	24	0	-9	39	5.76
Parietal					
R. inferior parietal	40	54	-57	36	4.99
L. angular gyrus	39	-48	-66	30	4.92
R. precuneus	7	6	-41	60	5.55
Sub-Lobar					
R. insula	13	45	-24	18	7.08
L. insula	13	-42	0	9	4.85
R. putamen		30	-15	3	5.78
R. claustrum*		36	-3	9	4.79
L. claustrum*		-36	-9	9	6.06
Temporal					
R. superior temporal	22	60	-6	3	4.52
L. middle temporal	19	-45	-60	15	4.90
L. superior temporal	41	-42	-27	3	4.12

Table S3. Regions within the default network that correlated with *daydream* propensity. Table depicts each cluster's mean r value, each cluster's peak r value, and the number of voxels (k) within the clusters that are significant at various r thresholds [$r(14) = .50$, $p < .05$; $r(14) = .57$, $p < .02$; $r(14) = .62$, $p < .01$].

			cluster extent (k)		
Anatomical Location	mean (r)	peak (r)	r = .50	r = .57	r = .62
B. medial prefrontal cortex (BA10)	.54	.63	25	4	1
R. insula	.65	.72	13	7	5
L. insula	.60	.76	10	6	6
B. cingulate/postcentral gyrus (BA31/6)	.58	.76	72	23	16
B. precuenus/ posterior cingulate (BA7/31)	.56	.69	73	33	23
R. superior frontal gyrus (BA8)	.58	.74	17	9	4

Supporting References

1. J. Smallwood, J. W. Schooler, *Psyc. Bull.*, **132**, 946 (2006).
2. J. D. Teasdale, B. H. Dritschel, M. J. Taylor et al., *Mem.Cognit.,* **23**, 551 (1995).
3. J. L. Singer, J. S. Antrobus in *The Function and Nature of Imagery,* P. Sheehan, Ed. (Academic Press, New York, 1972), pp. 175-202.