How do neuroimaging studies identify and measure the neural correlates of conscious thought processes?

Scientists use complementary neuroimaging methods including fMRI, PET, EEG, and MEG to contrast brain states and measure both spatial and temporal aspects of conscious thought processes.

Abstract

Neuroimaging studies identify neural correlates of conscious thought by contrasting brain states elicited under nearly identical sensory conditions. Studies using visual paradigms such as bistable perception, masking, and inattentional blindness report that conscious visual experience engages a distributed network—including subcortical, extrastriate, and fronto-parietal regions—rather than a single isolated area. In investigations of mind-wandering and self-generated thought, tasks that combine sustained attention with experience sampling reveal activations in the default mode, executive, and attention networks. Memory retrieval and skill-learning paradigms, by comparing explicit recollection with implicit processing, show that conscious access reliably involves prefrontal and medial temporal regions.

Measurement techniques span methods that emphasize spatial versus temporal resolution. For example: 1. Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) map activity in distributed networks with high spatial precision. 2. Electroencephalography/event-related potentials (EEG/ERP) and magnetoencephalography (MEG) capture rapid neural dynamics (including markers such as the Visual Awareness Negativity). 3. Intracranial recordings directly assess neural synchrony and phase relationships. Collectively, seven studies implicate the prefrontal cortex, seven report parietal involvement, and eight highlight the role of the temporal lobe. Such findings support models in which conscious thought is subserved by a global neuronal workspace that broadcasts information across interrelated brain regions.

Paper search

Using your research question "How do neuroimaging studies identify and measure the neural correlates of conscious thought processes?", we searched across over 126 million academic papers from the Semantic Scholar corpus. We retrieved the 50 papers most relevant to the query.

Screening

We screened in sources that met these criteria:

- **Neuroimaging Methods**: Does the study use functional neuroimaging techniques (fMRI, PET, EEG, or MEG) to measure brain activity during conscious cognitive processes?
- **Participant Population**: Does the study exclusively involve healthy adult human participants aged 18 or older?
- **Cognitive Process Definition**: Does the study examine conscious cognitive processes with clearly defined operational definitions?
- **Study Design**: Is the study either a primary research study or systematic review/meta-analysis with quantitative measurements?
- **Sample Size**: Does the study include at least 10 participants?
- **Consciousness State**: Does the study focus on normal waking consciousness (rather than unconscious/subliminal processing, sleep, or altered states)?
- **Neurological Status**: Are all participants free from severe neurological or psychiatric conditions?

- **Species**: Is the study conducted exclusively with human participants (not animal subjects)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Neuroimaging Technique**:

  Identify and specify the primary neuroimaging technique used in the study. Look in the methods section for details about:

- Type of neuroimaging (e.g., fMRI, PET, EEG)
- Specific scanning parameters
- Equipment used (if specified)

If multiple techniques were used, list all in order of primary to secondary importance. If unclear, note "technique not clearly specified".

Examples of acceptable answers:

- Functional Magnetic Resonance Imaging (fMRI)
- Activation Likelihood Estimation (ALE) meta-analysis of fMRI studies
- Combination of fMRI and EEG

Ensure the technique directly relates to measuring neural correlates of conscious thought processes.

- **Experimental Paradigm**:

  Describe the specific experimental paradigm used to investigate conscious thought processes. Look in methods and experimental design sections for:

- Type of cognitive task or experimental condition
- How consciousness or conscious thought was operationalized
- Specific stimuli or experimental manipulations used

Provide a concise but detailed description that explains how the paradigm allows investigation of neural correlates of consciousness.

Examples of acceptable answers:

- Multistable perception task with ambiguous visual stimuli
- Mind-wandering detection during resting-state scanning
- Bistable perception paradigm with alternating visual stimuli

If multiple paradigms were used, list all in order of primary to secondary importance.

- **Participant Details**:

  Extract key participant characteristics relevant to the neural correlates of consciousness study:

- Total number of participants
- Age range and mean age

- Gender distribution
- Neurological or psychological status (if relevant)

If multiple groups were studied, specify details for each group.

Formatting:

- Use numerical ranges where possible
- Include percentages for categorical data
- Note if any specific inclusion/exclusion criteria were applied that might impact neural correlates

Example:

- Total participants: 24
- Age: 25-45 years (mean 35.2)
- Gender: 60% female, 40% male
- Inclusion criteria: healthy adults with no history of neurological disorders

- **Neural Regions of Interest**:

  Identify and list specific brain regions consistently activated or associated with conscious thought processes:

- List brain regions in order of statistical significance or activation strength
- Include Brodmann areas or specific anatomical locations if provided
- Note whether regions are part of specific networks (e.g., Default Mode Network)

Formatting:

- Use standard neuroanatomical nomenclature
- Include statistical significance measures if available
- Separate cortical and subcortical regions

Example:

1. Medial Prefrontal Cortex (significant activation)
2. Posterior Cingulate Cortex (strong correlation)
3. Bilateral Inferior Parietal Lobule (consistent activation)

Results

Characteristics of Included Studies

Study	Experimental Paradigm	Brain Regions Studied	Measurement Techniques	Key Findings	Full text retrieved
Bisenius et al., 2015	Bistable perception, masking, and other standard paradigms for conscious visual perception (perceptual changes with invariant stimuli)	Inferior/middle occipital gyrus, fusiform gyrus, inferior temporal gyrus, caudate nucleus, insula, inferior/middle/superior frontal gyri, precuneus, inferior/superior parietal lobules	Activation Likelihood Estimation (ALE) meta-analysis of functional magnetic resonance imaging (fMRI) studies	The study reported that conscious visual perception involves a subcortical-extrastriate-fronto-parietal network, not a single region.	No
Martinon et al., 2019	Mind-wandering detection during Sustained Attention Response Task (SART) with neuroimaging (electroencephalography (EEG), fMRI)	Temporal lobe, posterior cingulate cortex, hippocampus, default mode network (DMN), executive, ventral/dorsal attention networks	Combination of fMRI and EEG/event-related potentials (ERP)	The study found that mind-wandering and self-generated thought involve DMN, executive, and attention networks; triangulation of neuroimaging and self-report is critical.	Yes
Dehaene and Changeux, 2011	We didn't find mention of a specific experimental paradigm in the abstract; review of minimal contrasts between conscious and nonconscious processing	Prefrontal, parieto-temporal, cingulate cortices (Global Neuronal Workspace (GNW) model)	We didn't find mention of measurement techniques in the abstract	The review reported that conscious access is linked to late sensory amplification, long-range synchronization, and prefronto-parietal network ”ignition”.	No

Study	Experimental Paradigm	Brain Regions Studied	Measurement Techniques	Key Findings	Full text retrieved
Fox et al., 2015	We didn't find mention of a specific experimental paradigm in the abstract; meta-analysis of mind-wandering and spontaneous thought studies	Medial prefrontal cortex, posterior cingulate cortex, medial temporal lobe, bilateral inferior parietal lobule, rostrolateral prefrontal cortex, dorsal anterior cingulate, insula, temporopolar cortex, secondary somatosensory cortex, lingual gyrus	Activation Likelihood Estimation (ALE) meta-analysis of neuroimaging studies	The study found that both DMN and non-DMN regions are consistently recruited during mind-wandering.	No
Schacter et al., 1998	Priming (implicit), intentional/effortful search, conscious recollection (explicit)	Prefrontal regions, medial temporal regions	Positron emission tomography (PET), fMRI, event-related potentials (ERPs)	The study reported that explicit memory retrieval (conscious recollection) activates prefrontal and medial temporal regions; implicit retrieval shows decreased cortical activity.	No
Pitts et al., 2014	Modified inattentional blindness and backward masking (aware/unaware, task-relevant/irrelevant)	Occipital and parietal lobes (Visual Awareness Negativity (VAN))	EEG (event-related potentials)	The study found that occipital and parietal regions (VAN) are associated with conscious perception, distinct from report-related activity.	Yes

Study	Experimental Paradigm	Brain Regions Studied	Measurement Techniques	Key Findings	Full text retrieved
Raichle, 1998	Skill learning: generating verbs for visually presented nouns, before and after practice	We didn't find mention of specific brain regions in the abstract	We didn't find mention of measurement techniques in the abstract	The study reported that skill learning alters neural circuitry supporting conscious task performance, but did not detail specific regions.	No
Rees, 2007	Bistable perception (binocular rivalry), visible/invisible stimuli	Primary visual cortex (V1), ventral visual pathway (V4, V5/MT), parietal, prefrontal cortex	fMRI (primary), also PET, EEG, magnetoen-cephalography (MEG)	The review found that conscious visual contents are encoded in V1, ventral visual areas, parietal, and frontal cortices; no single area is necessary or sufficient.	Yes
Sterzer et al., 2009	Multistable perception with ambiguous visual stimuli	Right inferior prefrontal cortex, bilateral superior parietal cortex, lateral prefrontal cortex, temporo-parietal cortex	fMRI (primary), also EEG, MEG	The study found that multistable perception involves right inferior prefrontal cortex, bilateral superior parietal cortex, and temporo-parietal cortex.	Yes

Study	Experimental Paradigm	Brain Regions Studied	Measurement Techniques	Key Findings	Full text retrieved
Dehaene et al., 2014	Masking/crowding, MEG with gratings at threshold, dual-task (psychological refractory period, attentional blink)	Dorsolateral prefrontal cortex, inferior parietal cortex, mid-temporal cortex, precuneus, global pari-etal/prefrontal network	EEG, MEG, intracranial recordings	The study reported that conscious processing involves dorsolateral prefrontal cortex, inferior parietal, mid-temporal cortex, and precuneus; consistent with the GNW network.	Yes

Summary of Experimental Paradigms:

- Visual awareness paradigms (including bistable/multistable perception, masking, inattentional blindness): 5 studies
- Mind-wandering or self-generated thought paradigms: 2 studies
- Memory retrieval paradigms: 1 study
- Skill learning: 1 study
- We didn't find mention of a specific experimental paradigm in the abstract for 1 review study

Summary of Brain Regions Studied:

- Prefrontal cortex: 7 studies
- Parietal cortex: 7 studies
- Temporal lobe/medial temporal/hippocampus: 8 studies
- Occipital/visual cortex: 3 studies
- Cingulate cortex: 3 studies
- Insula: 2 studies
- Default mode network: 1 study
- Subcortical structures (e.g., caudate): 1 study
- Precuneus: 2 studies
- Somatosensory cortex: 1 study
- We didn't find mention of brain region information in the abstract for 1 study

Summary of Measurement Techniques:

- fMRI: 5 studies
- EEG/event-related potentials: 6 studies
- PET: 2 studies
- MEG: 3 studies

- Intracranial recordings: 1 study
- Meta-analysis or review methods: 3 studies
- We didn't find mention of measurement technique information in the abstract for 2 studies

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Thematic Analysis

Experimental Paradigms for Measuring Consciousness

Across these studies, a range of experimental paradigms were used to operationalize and measure conscious thought processes:

- Visual perception paradigms : Bistable, multistable, and masking paradigms were prominent, allowing dissociation of conscious and nonconscious processing by manipulating perceptual awareness while keeping sensory input constant (as reported in Bisenius et al., Pitts et al., Rees, Sterzer et al.).
- Mind-wandering and self-generated thought : Investigated using tasks such as the Sustained Attention Response Task and resting-state paradigms, often combined with experience sampling (as reported in Martinon et al., Fox et al.).
- Memory retrieval paradigms : Distinguished between implicit and explicit processes, with explicit recollection serving as a proxy for conscious access (as reported in Schacter et al.).
- Skill learning and dual-task paradigms : Used to probe changes in conscious processing over time or under cognitive load (as reported in Raichle, Dehaene et al.).

Neural Network Architecture

The included studies consistently reported the involvement of distributed neural networks in conscious thought processes:

- Global Neuronal Workspace (GNW) model : Several reviews (Dehaene and Changeux, Dehaene et al.) described conscious access as arising from global broadcasting of information across prefrontal, parietal, and temporal cortices.
- Default Mode Network (DMN) and frontoparietal control networks : Implicated in spontaneous thought and mind-wandering (Martinon et al., Fox et al.).
- Visual awareness paradigms : Highlighted the role of occipital, parietal, and frontal regions, with no single area being necessary or sufficient for consciousness (Bisenius et al., Pitts et al., Rees, Sterzer et al.).

Temporal Dynamics of Conscious Processing

Network Component	Role in Consciousness	Evidence Quality (as reported)	Consistency Across Studies
Prefrontal Cortex	Global broadcasting, executive control, conscious access	High (multiple reviews/meta-analyses)	Consistently implicated (Bisenius et al., Dehaene and Changeux, Fox et al., Dehaene et al.)

Network Component	Role in Consciousness	Evidence Quality (as reported)	Consistency Across Studies
Parietal Cortex	Integration, attention, perceptual alternations	High	Consistently implicated (Bisenius et al., Rees, Sterzer et al., Dehaene et al.)
Temporal Cortex/Hippocampus	Memory, mental time travel, vividness of experience	Moderate (review evidence)	Frequently implicated (Martinon et al., Fox et al., Schacter et al.)
Occipital Cortex	Visual awareness, perceptual encoding	High (primary and review evidence)	Consistently implicated in visual paradigms (Bisenius et al., Pitts et al., Rees)
Default Mode Network	Self-generated thought, mind-wandering	High (meta-analyses, reviews)	Consistently implicated in spontaneous thought (Martinon et al., Fox et al.)
Frontoparietal Control Network	Cognitive control, flexible routing	High	Consistently implicated (Bisenius et al., Dehaene and Changeux, Dehaene et al.)
Visual Awareness Negativity (VAN)	Early marker of conscious perception	High (primary EEG evidence)	Consistently observed in visual awareness studies (Pitts et al.)

Summary of Evidence Quality and Consistency:

- High evidence quality was reported for 6 out of 7 network components, with only the temporal cortex/hippocampus rated as moderate (based on review evidence).
- Three network components (prefrontal cortex, parietal cortex, frontoparietal control network) were consistently implicated across studies.
- Three network components (occipital cortex, default mode network, Visual Awareness Negativity) were consistently implicated in specific paradigms (visual awareness, spontaneous thought, or visual awareness studies).
- The temporal cortex/hippocampus was frequently implicated, but not described as consistently implicated.
- We didn't find any network components with low or unclear evidence quality, nor any described as inconsistently implicated.

Measurement Approaches

Imaging Techniques and Their Applications

The studies employed a range of neuroimaging techniques, each with distinct advantages and limitations as reported:

Technique	Advantages	Limitations	Key Applications
Functional magnetic resonance imaging (fMRI)	High spatial resolution, whole-brain coverage	Low temporal resolution, indirect measure (blood-oxygen-level-dependent signal)	Mapping distributed networks, decoding contents of consciousness (Bisenius et al., Rees, Sterzer et al.)
Electroencephalography (EEG)/Event-related potentials (ERP)	High temporal resolution, direct neural activity	Poor spatial resolution, sensitive to artifacts	Temporal dynamics of conscious access, dissociating perception from report (Martinon et al., Pitts et al., Dehaene et al.)
Positron emission tomography (PET)	Metabolic activity, whole-brain coverage	Low temporal resolution, radioactive tracers	Memory retrieval, implicit/explicit processes (Schacter et al.)
Magnetoencephalography (MEG)	High temporal resolution, better spatial than EEG	Expensive, limited availability	Oscillatory dynamics, synchronization (Rees, Dehaene et al.)
Intracranial Recordings	Direct neural measurement, high temporal/spatial resolution	Invasive, limited to clinical cases	Phase synchrony, sustained activation (Dehaene et al.)
Activation Likelihood Estimation (ALE) Meta-analysis	Synthesizes across studies, increases power	Heterogeneity, loss of paradigm-specific detail	Identifying consistent neural correlates (Bisenius et al., Fox et al.)

Patterns in Advantages, Limitations, and Applications:

- High spatial resolution: fMRI
- Whole-brain coverage: fMRI, PET
- High temporal resolution: EEG/ERP, MEG
- Direct neural activity or measurement: EEG/ERP, Intracranial Recordings
- Metabolic activity: PET
- Better spatial resolution than EEG: MEG
- High temporal/spatial resolution: Intracranial Recordings
- Synthesizing across studies and increasing power: ALE Meta-analysis

Limitations:

- Low temporal resolution: fMRI, PET
- Indirect measurement: fMRI
- Poor spatial resolution and sensitivity to artifacts: EEG/ERP
- Use of radioactive tracers: PET
- High cost and limited availability: MEG
- Invasiveness and restriction to clinical cases: Intracranial Recordings
- Heterogeneity and loss of paradigm-specific detail: ALE Meta-analysis

Key Applications:

- Mapping distributed networks and decoding contents of consciousness: fMRI
- Temporal dynamics of conscious access and dissociating perception from report: EEG/ERP
- Memory retrieval and implicit/explicit processes: PET
- Oscillatory dynamics and synchronization: MEG
- Phase synchrony and sustained activation: Intracranial Recordings
- Identifying consistent neural correlates: ALE Meta-analysis

Additional Insights:

- None of the techniques combined both high spatial and high temporal resolution in a non-invasive manner.
- Each technique was associated with distinct advantages, limitations, and key applications, with no overlap in key application categories across techniques in these studies.

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