Unlocking Spontaneous Cognition in the Age of Data Science

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Standfirst
Spontaneous brain activity is experimentally unconstrained. Embracing this freedom unlocks rich opportunities beyond task-based and naturalistic paradigms, the traditional Herculean Pillars of constrained cognition. Emerging data-driven approaches can extract cognitively meaningful and translationally relevant insights from spontaneous brain activity: across profoundly altered states, across the human lifespan, and across species.

Beyond constrained cognition

Cognitive neuroscience traditionally relies on tasks and pre-defined stimuli to link controlled sequences of cognitive operations to concomitant brain activity. However, the more tightly controlled the task, the more un-natural it becomes. Hence the inception of 'naturalistic' paradigms such as movie-watching and narratives, to study cognition (stimulus processing, attention, memory; one's internal monologue and subjective experience) under more ecologically valid stimuli[1].

Task-based and naturalistic paradigms are both forms of 'constrained cognition': both study brain responses to externally imposed inputs of the experimenter's choice. Yet, ~30-50% of human waking cognition is task-unrelated[2], and profound cognition can occur without any observable behavioural manifestation. As iconified by Rodin's *Thinker* statue, "sometimes I just sit and think". To understand task-unrelated, internally-driven cognition, we must study spontaneous brain activity ('resting-state'): what the brain does, when not driven to respond to externally-imposed demands[2].

The traditional refrain against the study of spontaneous brain activity is that it is experimentally unconstrained. However, worthwhile aspiration for experimental constraint should not rigidify into 'experimenter' constraint. Cognitive neuroscience should not shy away from the challenge of understanding spontaneous activity, just because its unconstrained nature resists traditional experimental paradigms. Although behaviour can make cognition manifest, it is not the only way. The mantra that spontaneous brain activity is unsuitable to illuminate specific cognitive

processes is increasingly outdated, thanks to advances in data-driven science. Here we focus on cases where the unfeasibility of external constraints highlights the unique contribution of spontaneous brain activity.

Spontaneous and constrained cognition: inextricably intertwined

Neuroscientists should be wary of overestimating experimental insight into experimenter-directed cognition. The awake brain is never truly at rest, nor completely monopolised by any task. Imposing a task cannot guarantee that it will be performed exactly as intended: individuals may adopt idiosyncratic strategies, become disengaged or frustrated. The label 'naturalistic' should also not mislead us: movies are curated cultural artifacts, with variable effectiveness based on film-maker skill and viewer cultural, demographic, and personal characteristics.

Proponents of constrained cognition argue that spontaneous brain activity is just the same as task-oriented activity, but with individuals performing different, unknown tasks. Not so: they occupy non-overlapping trajectories of neural activity[3]. Moreover, across scales and species task performance depends on pre-stimulus spontaneous activity[4], and differences in spontaneous dynamics reflect phenotype, behaviour, and mental health[2]. Thus, even behaviour-oriented researchers cannot afford to neglect spontaneous brain activity. Rather than jostling for either to take center-stage, the field should embrace spontaneous and constrained cognition as complementary avenues.

Reversing the direction of control

Though unconstrained, it would be mistaken to conclude that spontaneous brain activity is not 'constrainable'. Controlled task-based and naturalistic paradigms manipulate cognition to identify statistical relationships with brain activity. Pharmacology and brain stimulation – and chemo/optogenetics in other species –provide an alternative: directly intervening on the brain, to examine the resulting effects on cognition, with or without externally imposed stimuli or tasks.

Acute pharmacology provides a mechanistic link via brain activity from the drug's receptor targets, to the resulting alterations in cognition. For example, the psychedelic DMT[5] replicates the time-locked neural and emotional responses across individuals seen in naturalistic paradigms. A psychoactive DMT dose induces changes in spontaneous brain activity and concomitant hallucinatory subjective experiences, which are consistent in content and time-course across individuals[5] . Thus, acute pharmacology can reverse the direction of experimental control: directly acting on the brain to induce predictable changes, and observing the resulting changes in cognition. Hence, experimental control can co-exist with spontaneous cognition, overcoming the dichotomy of traditional constrained paradigms.

Data-driven decoding of spontaneous brain activity

Complementing creative approaches for achieving control over brain activity without sacrificing spontaneity, advances in machine learning and computational methodologies are establishing a growing capability to harness spontaneous brain activity by recovering its cognitive contents. Creative methods are deployed to “decode” cognitive operations (such as memory or attention) from the flow of spontaneous brain activity[6]. One approach[7] uses machine learning systems trained on large neuroimaging meta-analytic corpora (such as NeuroSynth, NeuroQuery, or BrainMap). Data-driven inferences about the cognitive meaning of spontaneous brain activation are then grounded in what cognitive operations give rise to topographically similar brain maps in the literature (Fig.1). Another approach is to learn from participants’ own task- or movie-constrained brain activity to identify patterns of brain activity indicative of specific cognitive operations. Deploying them in other datasets (whether constrained or spontaneous) enables data-driven 'reverse inference' from brain activity to cognition (Fig.1). Applications include detecting confounds like attention drops during experimenter-directed constrained cognition[1]. These approaches are validated against both objective and subjective ground truth: movie annotations, task data retrospective reports and experience-sampling[2,6,8]. Combining brain decoding with direct brain interventions is especially promising, allowing validation of decoded contents against the interventions’ effects. For example, brain-decoding success drops when cognition (both externally- and internally-driven) is abolished by general anaesthesia[7], providing valuable negative control. Though current brain-decoding is largely limited to data-informed ‘best guesses’ among a fixed menu, the state-of-the-art is rapidly evolving, fuelled by AI advances (such as the TRIBE v2 foundation model for fMRI: https://ai.meta.com/blog/tribe-v2-brain-predictive-foundation-model/) trained on ever-larger neuroimaging datasets (for example, the recently released LAION visual fMRI: https://laion-fmri.hebartlab.com/).

Crucially, these approaches can be deployed retrospectively on previously-acquired neuroimaging data. The re-use value of resting-state datasets from functional MRI and other imaging modalities (near-infrared spectroscopy, electro/magnetoencephalography) is therefore appreciating over time, as methodological improvements allow neuroscientists to extract more cognitive insights latent in their resting-state data. If a ceiling exists on the cognitive insights extractable from spontaneous brain activity, we are yet to reach it: there has never been a better time to be excited about resting-state neuroimaging.

Gained in translation: How spontaneous brain activity expands translational and clinical applications

Spontaneous brain activity extends cognitive investigation to human populations where behavioural compliance or processing a narrative is challenging or impossible. It also holds great translational potential, enabling comparison across non-human organisms, and revealing fundamental shared principles of neural function.

Key examples include patients with disorders of consciousness (DOC) characterised by chronic behavioural unresponsiveness. Advanced dementia resembles DOC, with severely reduced behavioural responsiveness and compromised object and language recognition. At the other end of the human lifespan, task performance and narrative comprehension are also challenging in newborns – let alone *in utero*. Yet there is pressing scientific and clinical need to identify signatures of residual or emerging cognition in these populations. Bypassing the need for stimulus comprehension and response execution, spontaneous brain activity provides a unique window into the neural architecture of cognition coming online and fading:

whether through meta-analytic "cognitive matching"[7], or comparing patients' spontaneous brain activity with the patterns induced by known perturbations like anaesthesia.

Although movie-watching can also provide a comparable condition between species[1], its suitability may be limited to comparing similar functions in similar species (such as vision in primates). In cross-species comparisons, a video clip viewed by a nocturnal laboratory mouse whose main sensory modalities are ultrasonic frequencies and olfaction hardly shares ecological validity with a human's experience. By contrast, spontaneous cognition appears ecologically valid across species[4]. In zebrafish, representations of internal states can be decoded and translated from spontaneous brain activity across individuals[9]. More broadly, there are remarkable similarities in the intrinsic spatiotemporal organisation of spontaneous fMRI brain activity in awake humans, macaques, and mice[10]. This correspondence empowers neuroscientists to adopt targeted avenues of manipulating spontaneous brain activity in animals, and translate findings to the human brain, where self-reports and decoding methods enable inferences about concomitant cognition. This translational value positions spontaneous brain activity as a unique bridge between mechanistic neuroscience and clinical need, which cannot be replaced by externally constrained tasks or movies.

Outlook: Cognition out of the cage

With converging advances in AI, data science, and large-scale neuroimaging providing the key to unlock its cognitive content, spontaneous brain activity provides a bridge to extend cognitive investigation to other species, and to populations who cannot engage with task demands. Thus, the unconstrained nature of spontaneous brain activity has transformed from a limitation to an opportunity. 'If you love something, set it free': the adage sometimes also applies to studying cognition.

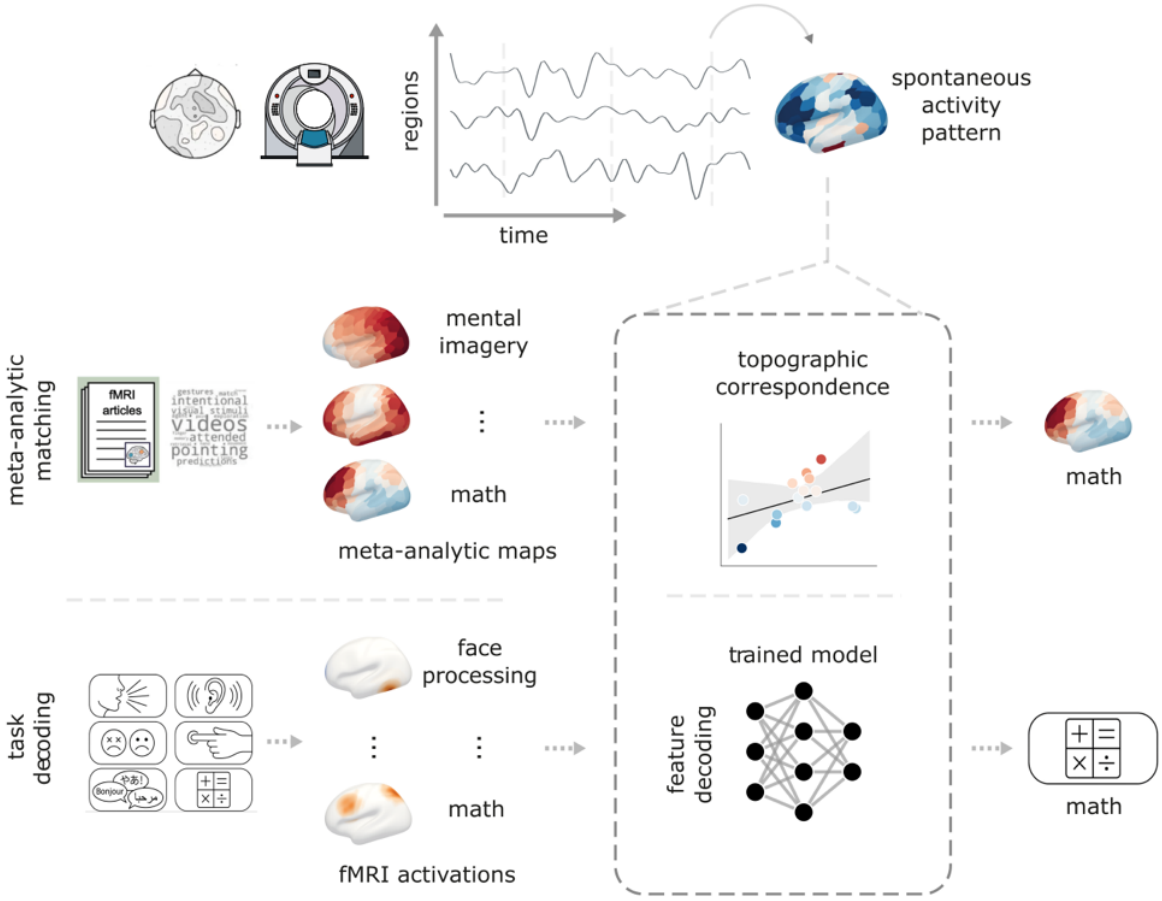


Figure 1 | Data-driven decoding of cognition from spontaneous brain activity Schematic illustration of methods for extracting data-driven insights into cognition from spontaneous brain activity (e.g., resting-state functional MRI). Each fMRI volume in a scan can be compared against a library of brain maps reflecting canonical cognitive operations for example obtained through meta-analytic aggregation of the neuroimaging literature. Alternatively, functional MRI data acquired during a variety of tasks or stimuli can be aggregated using machine-learning methods (e.g., support vector machines, deep neural networks). The resulting feature-based representation of brain activity can then be used to decode an unseen fMRI volume as a combination of features derived from the machine learning model. An implementation of meta-analytic 'cognitive matching' is made available at https://github.com/netneuro-lab/luppi-cognitive-matching.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

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