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Naturalistic imaging

Published in:
NeuroImage

DOI:
10.1016/j.neuroimage.2021.118776

Published: 15/02/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Finn, E. S., Glerean, E., Hasson, U., & Vanderwal, T. (2022). Naturalistic imaging: The use of ecologically valid conditions to study brain function. *NeuroImage*, *247*, Article 118776.
https://doi.org/10.1016/j.neuroimage.2021.118776

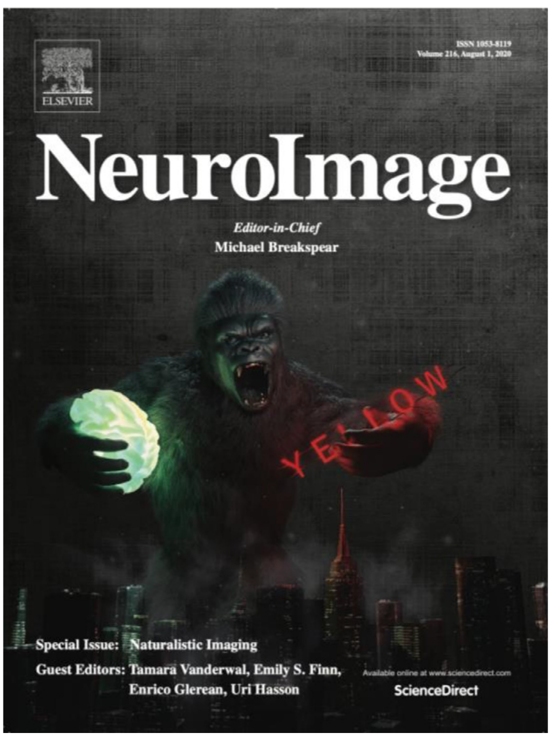
NeuroImage 247 (2022) 118776

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Naturalistic imaging: The use of ecologically valid conditions to study brain function



The cover (by artist Tobias S. Hoffmann) for this special issue on Naturalistic imaging was created with vintage movie posters in mind. It depicts a King Kong-like figure taking a city by storm, the remnants of the beloved Stroop task dangling from one hand, the promise of a glowing brain in the other. From our vantage point as guest editors, this issue has captured a tipping point for naturalistic imaging in the field. The sheer number of submissions received (more than 100) suggests that naturalistic imaging has become more than just a subfield in and of itself, and many articles are from groups that previously worked exclusively with resting state and/or conventional task conditions. In other words, these studies reflect the widespread use of naturalistic conditions as an acquisition state. The goal of the issue was to represent the breadth of research being done that is using naturalistic conditions, and to capture both theoretical and practical implications of the pivot towards these types of conditions in neuroimaging. Due to the size of the issue (fifty articles) and the long period over which the articles came to press, we have structured our editorial summary as a curated Table of Contents to point readers to papers by theme (of note, some articles are listed in more than one category). We also include a more visual table of contents, where the issue is presented as a network of articles based on a similarity analysis of article abstracts.

Framing the issue: Some of the first reports of significant differences in evoked responses between naturalistic viewing and conventional tasks came from vision research, and to provide a conceptual framework for this issue, we suggest starting with the excellent review article by Leopold and Park that traces work in the visual brain over the past 40 years, and outlines questions and challenges for the future (Leopold and Park, 2020). Nastase et al. carry these themes and ideas forward, and throw down the gauntlet in their commentary titled “Keep it real” (Nastase et al., al.,2020). The authors argue that naturalistic conditions should be the primary starting point for all efforts to study brain function in cognitive neuroscience.

Studying the visual brain in its natural rhythm

Keep it real: rethinking the primacy of experimental control in cognitive neuroscience

Social Cognition: The stories and movies that humans create are almost always profoundly and fundamentally social. As such, they provide powerful stimuli for studying complex aspects of social processing. For a review, see Redcay and Moraczewski, who categorize prior work as “within-brain” or “between-brain” (Redcay and Moraczewski, 2020). In an empirical study using emotional Hollywood movies, Jimenez et al. manipulated the intentional control of empathy (Borja Jimenez et al., 2020). Participants were instructed to actively empathize with the characters or to simply watch in a detached manner. The authors found distinct signatures of both inter-subject correlations and functional connectivity depending on the intentionally adopted perspective. Finally, in another empirical study, Hyon et al. show that beyond univariate response magnitude, socially close individuals show similar fine-grained response patterns to engaging, documentary-style video clips, especially in regions associated with high-level processing (Hyon et al., 2020).

Social cognition in context: A naturalistic imaging approach

Changes in brain activity following the voluntary control of empathy

Social network proximity predicts similar trajectories of psychological states: Evidence from multi-voxel spatiotemporal dynamics

Unique naturalistic conditions: Naturalistic conditions can be many things—any condition in which complex, dynamic information is being processed in ways that are more ecologically valid than highly con-

https://doi.org/10.1016/j.neuroimage.2021.118776.

Available online 2 December 2021.

trolled, conventional scientific tasks. Some of the papers in this issue introduce readers to unique forms and versions of naturalistic conditions, including folding origami inside the magnet (Kostorz et al., 2020), viewing 360-degree panoramic video (Kim et al., 2020), initial tests using virtual reality with MEG (Roberts et al., 2019), and combining movies with tactile stimulation (Espenhahn et al., 2020). This is an exciting area within naturalistic imaging that we expect to expand significantly in the near future, perhaps comprising its own special issue in the years ahead. Finally, though horror movies have been used before to study fear responses, Hudson and colleagues used two full-length horror movies (selected according to *Rotten Tomatoes* ratings) in some unique ways, including modeling jump-scares and using dynamic, continuous fear-ratings to model sustained fear responses for both task-based and functional connectivity analyses (Hudson et al., 2020).

Synchronization between instructor and observer when learning a complex bimanual skill

A naturalistic viewing paradigm using 360° panoramic video clips and real-time field-of-view changes with eye-gaze tracking

Towards OPM-MEG in a virtual reality environment

The effect of movie-watching on electroencephalographic responses to tactile stimulation

Dissociable neural systems for unconditioned acute and sustained fear

Vision: Beyond basics. Naturalistic paradigms have continued to yield novel insights into what is arguably the brain's best characterized system, vision. Puckett et al. introduce a novel method to show that cortical responses are differentially tuned to the subtle spatial structures characteristic of natural images (Puckett et al., 2020). Haxby and colleagues review evidence that, in contrast to still images, movies evoke widespread representations of agents' actions in not only classical visual regions, but also across a surprising expanse of the brain (Haxby et al., 2020). Other empirical articles use movie watching to tackle questions about the neural correlates of dynamic smooth pursuit (in contrast to saccades, their simpler counterparts) (Agtzidis et al., 2020), and how selective attention warps voxelwise responses to competing categories during naturalistic visual search (Shahdloo et al., 2020).

Manipulating the structure of natural scenes using wavelets to study the functional architecture of perceptual hierarchies in the brain

Naturalistic stimuli reveal a dominant role for agentic action in visual representation

Following Forrest Gump: Smooth pursuit related brain activation during free movie viewing

Biased competition in semantic representation during natural visual search

Dynamics. The study of the dynamics of brain function, particularly under naturalistic conditions, is rapidly revealing new insights into the importance of the temporal domain. Here we point readers to a commentary by Simony and Chang who provide a succinct treatment of the promise and challenges of studying both neural and physiological dynamics during naturalistic conditions (Simony and Chang, 2019). Li and colleagues look at dynamics of functional connectivity to quantify the greater stability of higher-order associative brain regions such as the default mode network, versus more dynamic unimodal regions such as primary visual and somatomotor cortices (Li et al., 2020). In a fitting use of the increased temporal resolution of MEG, Nunes and colleagues examine temporal responses to specific types of stimuli (e.g., faces, hands, words and non-words) as time-locked events embedded within naturalistic stimuli (Nunes et al., 2020).

Analysis of stimulus-induced brain dynamics during naturalistic paradigms

Stability of dynamic functional architecture differs between brain networks and states

Neuromagnetic activation and oscillatory dynamics of stimulus-locked processing during naturalistic viewing

Intersubject interest. A clear thread running through many papers in the issue, and the naturalistic imaging world more generally, is that time-locked naturalistic stimuli allow investigators to leverage powerful inter-subject techniques such as inter-subject correlation and inter-subject functional connectivity. While the core ideas behind this family of approaches have been around for a long time, some work in this issue refines and extends these techniques to better parse activity into components that are synchronized at the population level (Di and Biswal, 2020; Nastase et al., 2020b; Chen and Farivar, 2020b), as well as those that are more strongly synchronized in pairs or groups of participants who are also more similar in certain trait- or state-level behavioral measures (Finn et al., 2020; Chen et al., 2020b2020a). Additional work examines how affective responses to movie trailers can be decoded across subjects (Chan et al., 2020), and how inter-subject approaches might provide an index of engagement that could inform real-world messaging campaigns, e.g., for public health (Imhof et al., 2020). Finally, we highlight work by Jiahui et al., whose paper on functional hyperalignment demonstrates an emerging method in which an intersubject approach is used to identify an individual subject's idiosyncratic functional topography (Jiahui et al., 2020).

Idiosynchrony: From shared responses to individual differences during naturalistic neuroimaging

Intersubject representational similarity analysis reveals individual variations in affective experience when watching erotic movies

Intersubject consistent dynamic connectivity during natural vision revealed by functional MRI

Decoding dynamic affective responses to naturalistic videos with shared neural patterns

Leveraging shared connectivity to aggregate heterogeneous datasets into a common response space

Untangling the relatedness among correlations, part III: Inter-subject correlation analysis through Bayesian multilevel modeling for naturalistic scanning

Natural scene representations in the gamma band are prototypical across subjects

Strong health messages increase audience brain coupling

Predicting individual face-selective topography using naturalistic stimuli

Clinical Populations. Naturalistic conditions provide a way to study neural responses in individuals with psychiatric and neurological disorders. To begin this section, three psychiatrists (Eickhoff et al., 2020) provide a brief commentary, outlining potential roads ahead for the clinical application of movie fMRI. Relevant articles use movies to study intersubject correlations in adults with ADHD while they watch a movie with auditory distractors embedded within the soundtrack (Salmi et al., 2019), or to study the role of the default network during narrative comprehension in a patient with hippocampal amnesia (Zuo et al., 2020). Other studies look at depressive symptoms (Gruskin et al., 2020), first-episode schizophrenia (Yang et al., 2020), autism spectrum disorder (Bolton et al., 2020) and dyslexia (Thiede et al., 2020).

Towards clinical applications of movie fMRI

Relationships between depressive symptoms and brain responses during emotional movie viewing emerge in adolescence

Individualized psychiatric imaging based on inter-subject neural synchronization in movie watching

Temporal integration of narrative information in a hippocampal amnesic patient

ADHD desynchronizes brain activity during watching a distracted multi-talker conversation

Neural responses in autism during movie watching: Inter-individual response variability co-varies with symptomatology

Atypical MEG inter-subject correlation during listening to continuous natural speech in dyslexia

Development. Naturalistic conditions have started to become mainstream in developmental studies ahead of adult work, thanks in part to the fact that movie-watching can reduce head motion in younger children. The papers in this section cover a wide developmental range from infancy (Hakuno et al., 2020; Jessen et al., 2019) to young childhood

(2–5 years) (Benischek et al., 2020) to middle childhood (6–12 years) (Moraczewski et al., 2020) to populations spanning ranges from middle childhood to late adolescence/early adulthood (Sanchez-Alonso et al., 2021; Vanderwal et al., 2021; Gruskin et al., 2020). Of note, these three articles use data from the Healthy Brain Network database, the first large-scale child and youth database to include movie-watching as a scanning condition.

The balance of rigor and reality in developmental neuroscience

Interactive live fNIRS reveals engagement of the temporoparietal junction in response to social contingency in infants

Quantifying the individual auditory and visual brain response in 7-month-old infants watching a brief cartoon movie

Pre-reading language abilities and the brain's functional reading network in young children

Cortical temporal hierarchy is immature in middle childhood

Functional connectivity patterns predict naturalistic viewing versus rest across development

Stability and similarity of the pediatric connectome as developmental measures

Relationships between depressive symptoms and brain responses during emotional movie viewing emerge in adolescence

Music. Music must be studied naturalistically as it cannot be broken down into discrete components such as individual notes without becoming a different entity. Four articles here use music-listening conditions to ask questions about how the brain processes and perceives music. Toiviainen et al. used state-of-the-art music-information-retrieval algorithms to estimate beat saliency (Toiviainen et al., 2020). By using psychophysiological interaction (PPI) analysis of fMRI data, the authors show how different brain regions contribute to beat perception and beat inference (mostly localized in motor cortices) than to beat maintenance (basal ganglia, thalamus, cerebellum and auditory cortices). Brauchli et al. showed that individuals with absolute pitch had *decreased* FC between hubs of the default network relative to musicians without absolute pitch (Brauchli et al., 2020). Sachs and colleagues used continuous self-report ratings of sadness and enjoyment during music listening and found that such ratings were predictive of moment-to-moment network synchronization with differential patterns (Sachs et al., 2020). Finally, Kaneshiro et al. also used self-report ratings of music enjoyment, but this time in an EEG study of intersubject similarity during natural and scrambled or manipulated music. Participants reported greater enjoyment and demonstrated greater intersubject correlations when music was intact in a way that is perhaps similar to our responses to intact narratives in stories (Kaneshiro et al., 2020).

Natural music evokes correlated EEG responses reflecting temporal structure and beat

The chronnectome of musical beat

Dynamic intersubject neural synchronization reflects affective responses to sad music

Diminished large-scale functional brain networks in absolute pitch during the perception of naturalistic music and audiobooks

Language. Not unlike music, language is another human faculty that changes character as it is broken down into its constituent parts (i.e., sentences, words, syllables, phonemes), and thus is perhaps best understood from a holistic perspective. One article empirically tests this proposal, finding that core language regions have temporal receptive windows that are equally sensitive to intact stories or stories scrambled at the paragraph or sentence level, but less sensitive to word scrambles or reversed audio (Blank and Fedorenko., 2020). These results indicate that these regions integrate information over a common timescale. Several other articles exploit naturalistic paradigms to investigate various high-level linguistic phenomena, such as how embodied processes during reading increase with language proficiency (Birba et al., 2020); how word sentiment can be decoded from EEG signatures during reading (Pfeiffer et al., 2020); how word sequence predictability has a brain signature via MEG (Koskinen et al., 2020); and how spatial demonstratives (e.g., "this one") recruit visuospatial networks in service of linguistic comprehension (Rocca et al., 2020), speaking to the integrated nature of language processing.

Motor-system dynamics during naturalistic reading of action narratives in first and second language

Neural dynamics of sentiment processing during naturalistic sentence reading

Language beyond the language system: Dorsal visuospatial pathways support processing of demonstratives and spatial language during naturalistic fast fMRI

Brain activity reflects the predictability of word sequences in listened continuous speech

No evidence for differences among language regions in their temporal receptive windows

Future Directions. We asked researchers to consider how naturalistic conditions might be applied within their own areas of expertise, and what advantages and challenges they might anticipate as naturalistic conditions are adopted in their own research area. The resulting suite of brief commentaries provides fodder for the naturalistically inclined across a broad array of topics: open science practices for naturalistic imaging studies as well as the legal and copyright considerations for the stimuli themselves (DuPre et al., 2019); resolving and interpreting stimulus-driven signal during naturalistic stimulation (Simony and Chang, 2019); and a call to combine lab-controlled tasks with exploratory naturalistic paradigms in studying development (Cantlon, 2020). Here we also include aforementioned commentaries from Eickhoff, Milham & Vanderwal and Nastase et al. (Eickhoff et al., 2020; Nastase et al., 2020a).

Nature abhors a paywall: How open science can realize the potential of naturalistic stimuli

Analysis of stimulus-induced brain dynamics during naturalistic paradigms

The balance of rigor and reality in developmental neuroscience

Towards clinical applications of movie fMRI

Keep it real: rethinking the primacy of experimental control in cognitive neuroscience

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