The neural basis of abstract representations in humans and non-human primates

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Abstract

The ability to recognize and manipulate abstract representations appears to be a fundamental aspect of human cognition, present since the origins of our species and transcending cultural barriers. In contrast, this capacity is very limited in non-human primates and artificial neural networks. To explore this distinction, we presented visual stimuli depicting the same concepts (e.g., faces or objects) at varying levels of abstractions (e.g., photos, drawings, words) to both humans and monkeys while recording neural activity using 7T fMRI and MEG in humans, and intracranial recordings in monkeys. Our findings reveal that while monkeys demonstrated a limited capacity for generalization – restricted mostly to faces – humans display a robust ability to abstract across all levels of abstraction, underscoring a fundamental specificity in conceptual processing.

Keywords: Abstraction, 7T fMRI, MEG, Utah-arrays, Neural Networks, cross-species

Introduction

Homo sapiens has been creating abstract and figurative representations for over 73k years (Henshilwood et al., 2018), suggesting that recognizing and manipulating abstract visual form is a core human trait. Studies supports this, showing that the ability to understand abstract representations, like drawings, is universal and emerges early in life (Kennedy & Ross, 1975; Smith, 2003, 2009; Smith & Jones, 2011). In contrast, non-human primates (Close & Call, 2015; Diamond et al., 2016) and neural networks (Jo & Bengio, 2017) struggle to recognize drawings, even after intensive training.

To explore this human singularity, we conducted neuro-imaging studies in both humans and non-human primates. Stimuli representing the same concept (e.g., a house or a face) at varying levels of abstraction (e.g., photos, words) were presented to both populations, with neural activity recorded through intracranial recordings in monkeys (N=2), and 7T fMRI (N=20) and MEG (N=13) in humans. We found that monkeys exhibited proto-abilities to generalize from photos to more abstract representations (excluding words) for faces only, while humans demonstrate this capacity across all conditions and abstraction levels, including words.

Methods

Stimuli. Six semantic categories of images were presented to participants: *faces*, *bodies*, *animals*, *flora*, *objects* and *spaces* (figure 1). Each category includes 4 color photos, 4 detailed drawings, 4 minimalist cartoons and 4 words. In total, 96 images were presented to participants: 6 semantic categories x 4 renderings x 4 exemplars.

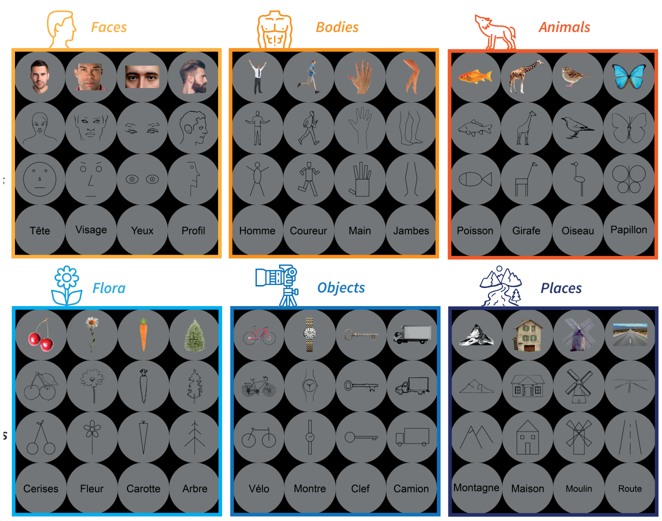

Figure 1: 96 stimuli presented to participants.

Monkey Intracranial Recordings. Two macaque monkeys were implemented with 16 Utah arrays (64 channels each) across V1, V4 and IT while the monkey performed a fixation task. Each stimulus was presented to each monkey 150 times, during 200ms each (200ms ISI).

Humans' fMRI Recordings. 20 adult participants underwent 7T fMRI with a slow event-related paradigm, with six blocks in which each image was presented for 200ms (ISI ~ 5.8s). A localizer with black-and-white photos was also used, consisting of seven blocks: six for each semantic category and one for words.

Humans' MEG Recordings. 13 other adult participants performed the MEG task (expected 30) with a similar paradigm: 4 blocks in which each image was presented 6 times during 200ms each (ISI: 800ms).

Results

Monkeys. To assess monkey's generalization abilities, we trained a decoder to classify neural activity recorded while they viewed color photos of six semantic categories (chance level = 1/6). We then tested whether this same decoder could distinguish neural responses to the same categories presented in more abstract renderings. When trained on IT neurons, the decoder successfully generalized from photos to drawings and to a lesser extent cartoons, but not to words (figure 2). Importantly, this ability was largely driven by face generalization, and that generalization for other conditions was mostly absent.

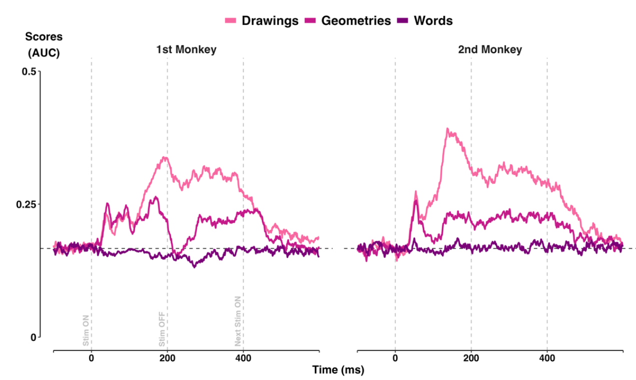

Figure 2: Decoding scores obtained in two monkeys, for a decoder trained on photos and tested on three other more abstract renderings.

fMRI Humans. To measure human abstraction abilities and explore whether the human brain exhibits semantic organization, we performed a principal component analysis on voxel responses from a single participant to the 96 stimuli (focusing only on voxels activated during the main runs). The first principal component separated the stimuli into two broad semantic domains – *animate* (faces, bodies, animals) and *inanimate* (objects, flora, places) – regardless of the stimuli's level of abstraction (figure 3). Ongoing analysis aim to 1) identify the brain regions driving this effect and whether a gradual semantic organization emerges along the visual processing hierarchy, and 2) replicate these results at the group level.

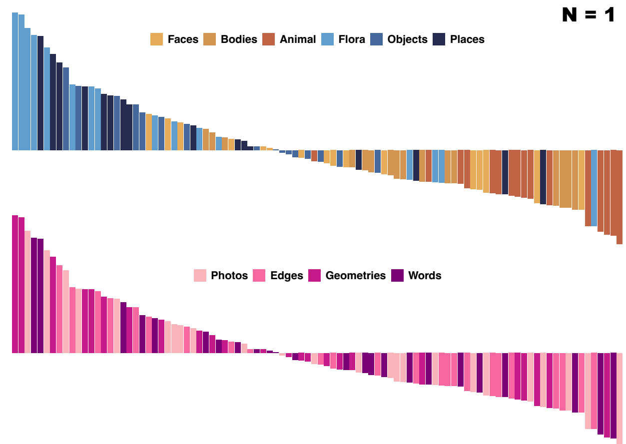

Figure 3: First PCA component in one human subject separate animate vs. inanimate stimuli.

Discussion

Our preliminary findings reveal a continuum in visual concept abstraction between humans and non-human primates. While monkeys show early forms of abstraction – limited to faces – humans are able to abstract animate and inanimate concepts. Indeed, in the human brain, neural responses reflect semantic identity more than visual similarity, pointing to a deep structuring around meaning. These results echo recent findings on semantic categorization in humans (Bezsudnova et al., 2024; Singer et al., 2023) but goes further by: (1) introducing a novel symbolic format between words and drawings, (2) directly comparing humans and monkeys; and (3) using ultra-high-field fMRI (7T). These results offer new insight into how meaning is represented in the brain—and how abstraction may have phylogenetically evolved.

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