

Functional Imaging of the Human Brain: A Window into the Organization of the Human Mind

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My course on The Human Brain is online at MIT's Open Course Ware:
<https://ocw.mit.edu/courses/brain-and-cognitive-sciences/9-13-the-human-brain-spring-2019/>

Some of My Collaborators:

Dobs

Murty

Kosakowski

Martinez

Fedorenko

Lafer-Sousa

McDermott N.

Haignere

Saxe

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Functional Organization of the Cortex Circa 1990

Faces

Attention

Language

that was it
but then fMRI came along

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Functional Organization of the Cortex 2022

Places

Faces

Color

Grasping
~Intuitive Physics

Other minds
Reaching

Words
letters

Music
3P Social Pitch

Bodies
Speech Language

Motion **Shape**

Dozens of cortical regions with known functions.
Each of these regions is present in every normal person.
Highly schematic – what does this actually mean?

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Faces

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Vis. Words

Scenes **Faces**

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Vis. Words Aud. Speech

Language

Bodies

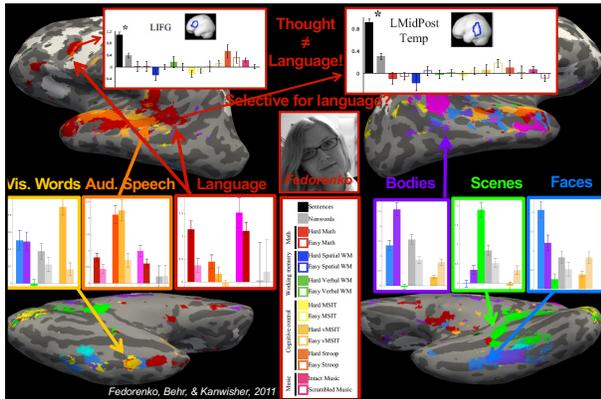
Scenes **Faces**

Selective for language?

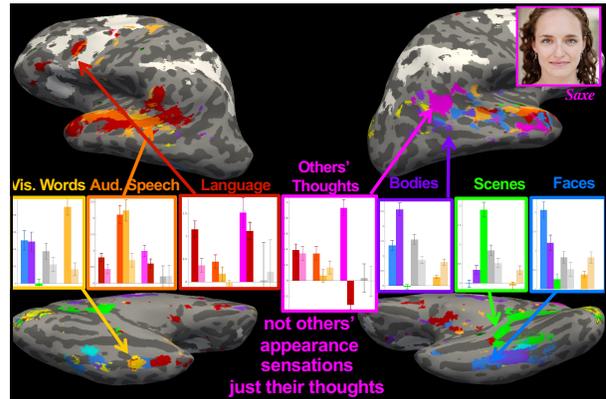
Fedorenko

Only for perception?
Or also for abstract cognition?

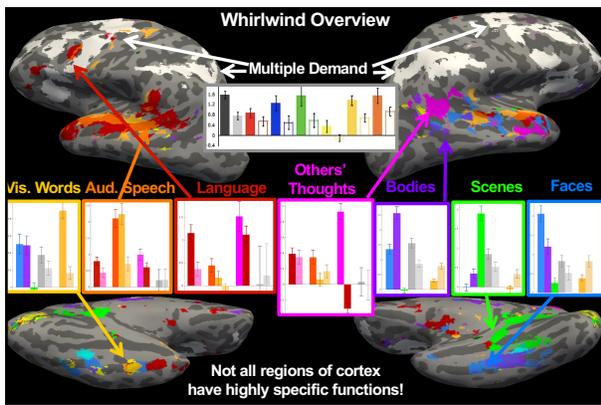
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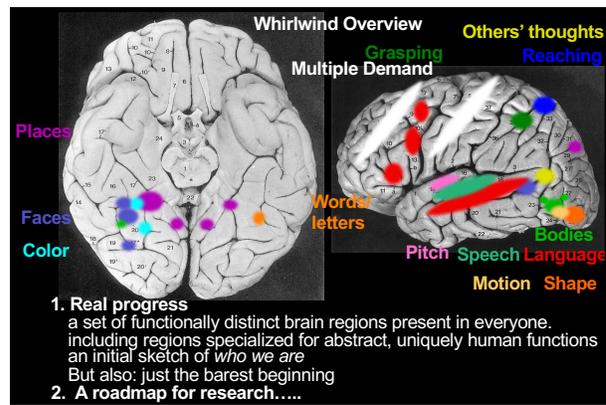
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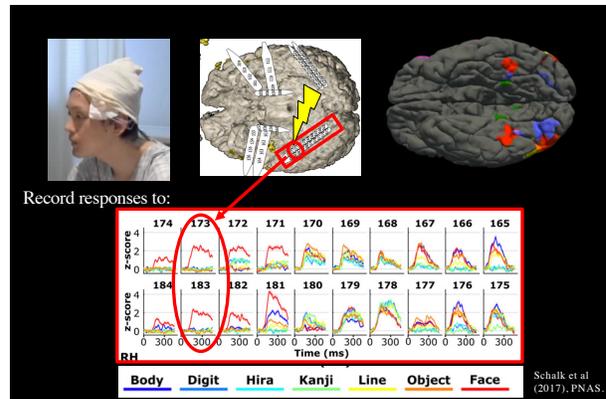
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Vast Landscape of Unanswered Questions

- Causal role of these regions?
Causality is of the essence in science. But functional MRI cannot tell you.

A phone call a few years ago...

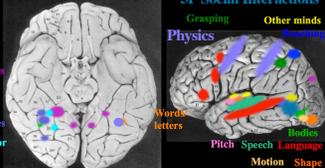
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A Roadmap for Research

- What is the causal role of these regions in cognition/behavior?
 - A strikingly specific causal role of face-selective regions in face perception only and color-prefering regions in color perception only ("I see rainbows")
- What other specializations?
 - Perception of 3P soc. interactions
 - Reasoning about physical world

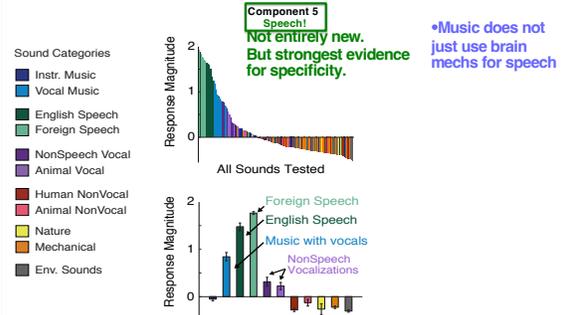


Auditory Cortex...
Here we used a different method.
Instead of testing a specific hypothesis,
we just scanned people while they listened to 165 everyday sounds,
then did some math (~ICA) to discover the inherent structure in the data,
and found...

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Six "Components" of Cortical Response to Sounds

Really?



Sound Categories

- Instr. Music
- Vocal Music
- English Speech
- Foreign Speech
- NonSpeech Vocal
- Animal Vocal
- Human NonVocal
- Animal NonVocal
- Nature
- Mechanical
- Env. Sounds

Response Magnitude

All Sounds Tested

Sound Categories

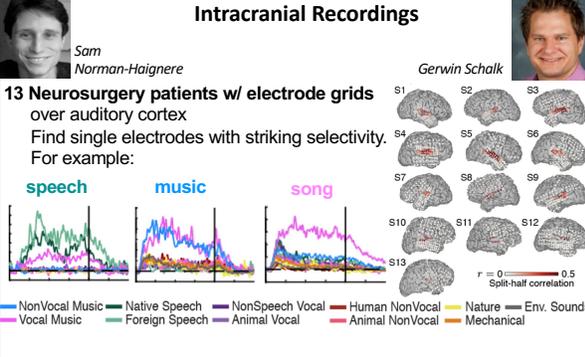
Norman-Haignere, Kanwisher & McDermott, *Neuron*, 2015

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Intracranial Recordings

Sam Norman-Haignere
Gerwin Schalk

13 Neurosurgery patients w/ electrode grids over auditory cortex
Find single electrodes with striking selectivity.
For example:



speech music song

Legend:

- NonVocal Music
- Vocal Music
- Native Speech
- Foreign Speech
- NonSpeech Vocal
- Animal Vocal
- Human NonVocal
- Animal NonVocal
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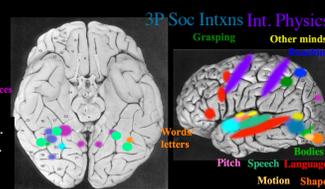
Norman-Haignere, et al, *Current Biology*, 2022

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A Roadmap for Research

- What is the causal role of these regions in cognition/behavior?
 - A strikingly specific causal role of face-selective regions in face perception only and color-prefering regions in color perception only
- What other specializations?
 - Perceiving social interactions
 - Intuitive physics
 - Visual food perception???
 - Music!
- How does all this organization get wired up in development?
 - Many studies: very slow development of face area, through adolescence
 - & One study finds that monkeys who never see faces do not develop face areas.

So, looks like face area takes years to arise and requires visual experience.



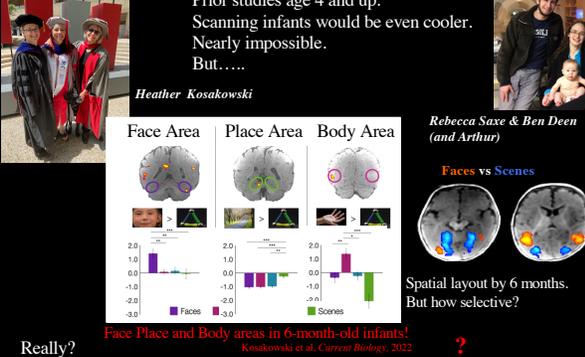
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Prior studies age 4 and up.
Scanning infants would be even cooler.
Nearly impossible.
But.....

Heather Kosakowski

Rebecca Saxe & Ben Deen (and Arthur)

Faces vs Scenes



Spatial layout by 6 months.
But how selective?

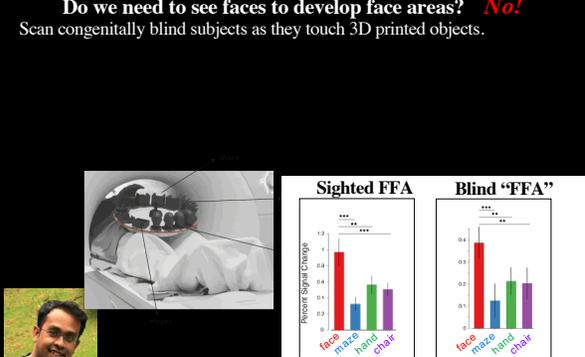
Face Place and Body areas in 6-month-old infants!
Kosakowski et al, *Current Biology*, 2022

Really?
So, looks like face area takes years to arise and requires visual experience.

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Do we need to see faces to develop face areas? No!

Scan congenitally blind subjects as they touch 3D printed objects.



Sighted FFA

Blind "FFA"

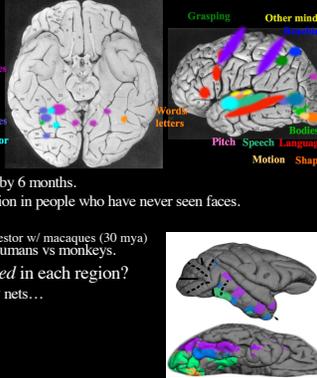
Neural Signal Change

Murty et al, *PNAS*, 2020

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A Roadmap for Research

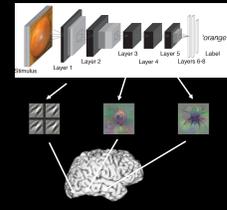
- Causal role?
 - Specific causal role of face-selective regions in face perc and color-prefering regions in color perception.
- What other specializations?
 - Music
- Developmental origins?
 - Face, place, and body areas present by 6 months.
 - Face selectivity arises in same location in people who have never seen faces.
- Evolutionary origins?
 - Vision inherited from our common ancestor w/ macaques (30 mya)
 - But hearing is used differently by humans vs monkeys.
- What's *represented* and *computed* in each region?
 - Astonishing recent success of conv nets...



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Convolutional Neural Networks

- Work pretty well!
 - first plausible models of how vision *might* work in the brain.
 - Match the brain to a surprising degree.

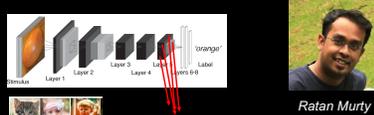



Ratan Murty

Can we build CNN-based models of the FFA, PPA, & EBA?

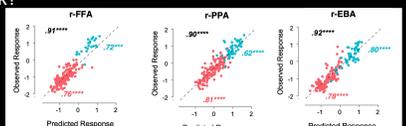
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- Measure response of FFA, PPA, and EBA to 185 complex natural images.
- Collect "responses" of the network to the same images.
- Build CNN-based encoding models.



Ratan Murty

$\sum a_i w_i$



So....

Can we build CNN-based models of the FFA, PPA, & EBA? **Yes!**

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What We Can Do with these Models

- We now have the first image-computable models with high predictivity for the FFA, PPA, and EBA. = hypotheses about the computations conducted in these regions.
- Can use the model to conduct high throughput tests not possible in people.
 - strongest test yet of category specificity: screen the entire ML data base for top images for each region
 - use GANs to generate "best" images



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What We Can Do with these Models

- We now have the first image-computable models with high predictivity for the FFA, PPA, and EBA. = hypotheses about the computations conducted in these regions.
- Can use the model to conduct high throughput tests not possible in people.
 - strongest test yet of category specificity
- Because model works on new subjects and images, test it on all published results that localize these regions and publish their stimuli and responses.
 - all 12/12 FFA papers replicated
 - So our models explain all those effects: curvature, animacy, sensitivity to real-world size, "holistic processing", etc

But CNNs can also be used in a different way to ask a different kind of question

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Why does the Brain have Category-Selective Regions in the First Place?



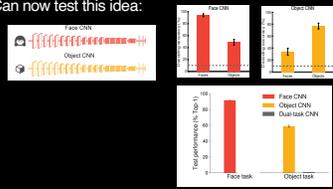
Katharina Dobs



Julio Martinez

Old Hypothesis: Face specific regions required because face recognition entails distinct computations/features from object recognition.

Can now test this idea:



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Why does the Brain have Category-Selective Regions in the First Place?

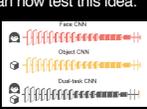


Katharina Dobs

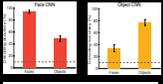


Julio Martinez

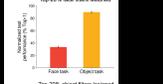
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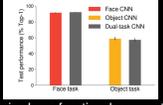
Face CNN
Object CNN
Dual-task CNN



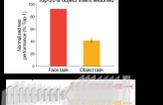
Top-10% face fibers accuracy



Top-20% object fibers accuracy



Top-10% face fibers accuracy



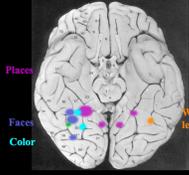
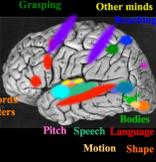
Top-20% object fibers accuracy

- Suggests why human brains have functional segregation
- Shows domain-specific org can in principle arise without innate domain-specific priors
- Raises lots of questions of when & how & for what functions, ongoing work

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Thank You!

- Causal role?
 Specific causal role of face-selective regions in face perc and color-perceiving regions in color perception.
- What other specializations?
 3P Social Interaction
 Intuitive Physics
 Music
- Developmental origins?
 Obviously a major role for experience (VWFA, Arcaro, common sense).
 But substantial innate constraints, perhaps implemented as long-range connectivity.
- Evolutionary origins?
 Vision inherited from our common ancestor w/ macaques (30 mya)
 But hearing is used differently by humans vs monkeys.
- What's *represented* and *computed* in each region?
 Deep nets have provided a promising new way to tackle this question.
 And to answer *why* questions about mind and brain.

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