Introduction

Background:

- **Three main principles of how visual cortex processing visual stimuli:**
  - Different visual information are preserved and segregated in different visual information streams.
  - To differentiate different visual signals, the same brain region processes different visual signals differently.
  - Different brain pathways process the same type of visual information in a hierarchical manner — areas more upstream in the processing stream process more general features of visual stimuli (*e.g. direction)* while areas more downstream in the processing stream encodes more detailed information (*e.g. textures*).
- **Principal component analysis (PCA)** – the process of computing principal components (PCs) to reduce the dimensionality of the dataset.
  - The first eigenvector of the dataset is the high dimensional axis where all data points have minimal average projections on – it represent the most general information representation of the dataset.
  - The later extracted eigenvectors have a greater average projection of the data on the vector – they capture more detailed representations of the dataset.
- **Kay dataset:** a fMRI dataset published in 2008 on Nature (Kay et al. 2008)
  - In the study human subjects was asked to lie in an fMRI scanner and was presented with 1750 grayscale nature images of different kinds. Meanwhile, their brain activity was recorded by fMRI, from which voxel activities of 7 vision-related areas are extracted (V1, V2, V3, V3A, V3B, V4)

Introduction

Why study visual system:

- Understand the process of visual inputs – the ways of different types of visual stimuli are represented along the central visual pathway and turned into useful information
- The studies of visual pathway also facilitate understanding of higher cognitive functions, such as spatial navigation, multi-sensory integration, memories, etc., where visual information is an essential input.
- Knowledge of visual pathway can be applied to both medical and translational applications and day-to-day life technology
    - **Medical** – treat diseases such as retinal damage and cortical blindness
    - **Day-to-day life technologies** – some inventions are built upon the understanding of how visual pathway function (*VR industry*); some inventions was designed based on mimicking the way visual pathway process visual stimuli (*autonomous car*).

Hypothesis (purpose):

Different brain regions process different types of visual stimuli in distinct ways and some vision related brain areas process nature visual stimuli similar to principal component analysis (PCA).

Research questions:

1. Do different brain regions process different aspects of visual information?
2. Do different brian regions have different degrees of contribution in encoding semantic information carried by a visual stimulus?
3. Are there any statistical properties underlying naturalistic images?
4. Do brain regions encode visual information in a manner similar to principal component analysis (PCA)?

Result: heatmaps

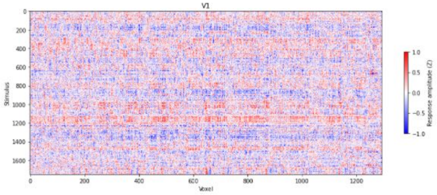

Fig 1b. heatmap of V1 brain activity

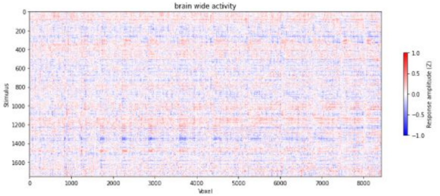

Fig 1a. heatmap of brain wide activity

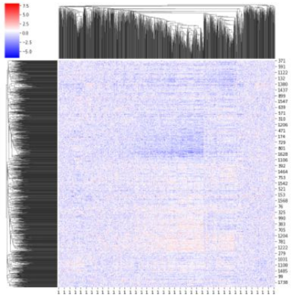

Fig 1c. cluster map of V1 activity

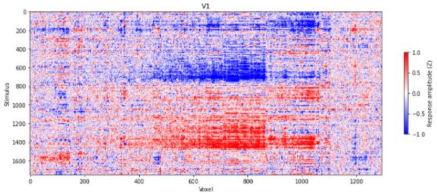

Fig 1d. heatmap of V1 brain activity after clustered

*<u>*All figures and images done by myself</u>*

Result & analysis:

1. After hierarchically clustered my dataset, I found that there are clusters in my reordered heatmaps. The clusters of heatmaps indicate that there are some voxels of the brain region firing in a similar fashion towards a certain set of images.
   a. The hetamp of V1 exhibited the biggest cluster, indicating that it has the most number of voxels fire synchronously toward the most number of images
   b. As we go along the central visual pathway (V2, V3, V4 etc.) clusters become smaller and less obvious
   c. This accord with the study that areas located more upstream of the visual pathway process less specific visual information while areas more downstream are in charge of encoding more detailed visual information.
2. V3A, V3B, and LatOcc have relatively big clusters though they are relatively downstream in the visual pathway. However, the clusters are smaller compared to that of V1. This phenomenon may arise from that these synchronous firing voxels are the ones receiving information from their upstream areas or there are other interesting features in the images causing synchronous firing in V3A, V3B, and LatOcc.

Result: heatmaps

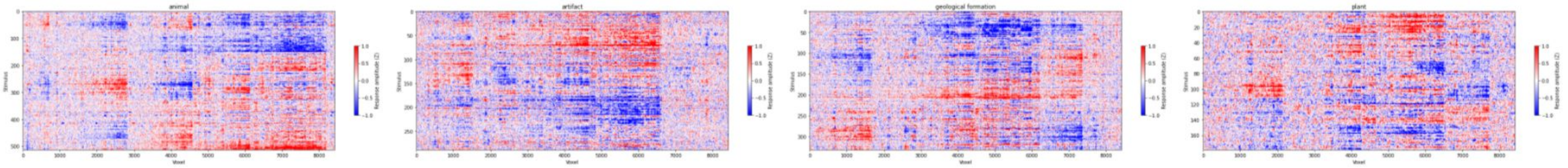

Fig 2a. heatmaps of brain-wide activities stimulated by images under the category of “animal”, “artifact”, “geological formation”, and “plant”

Result & analysis:

Plotting the heatmap and perform hierarchical clustering on the dataset containing brain-wide activities to different categories of images shows small clusters among each semantic category of stimuli (*Kay dataset provides labels for each image in the dataset generated by BERT).

To investigate specifically how different content of images affect the activities of different brain regions, I further divided the voxel activities based on the brain regions that these voxels belong to. Heatmap of how the entire brain respond to four example categories of images were shown in the above image. Each of the four categories have four heatmaps plotted corresponding to voxel activities of V1, V2, V3, and V4 in response to their presentation. These heatmaps will be shown on the next slide.

Similar to the trend I saw when analysing the response of each brain regions to all visual stimuli, I found that voxel responses of all categories of images also exhibit the trend of having decreasing cluster size as the voxels belong to more downstream part of central visual pathway.

Result: heatmaps

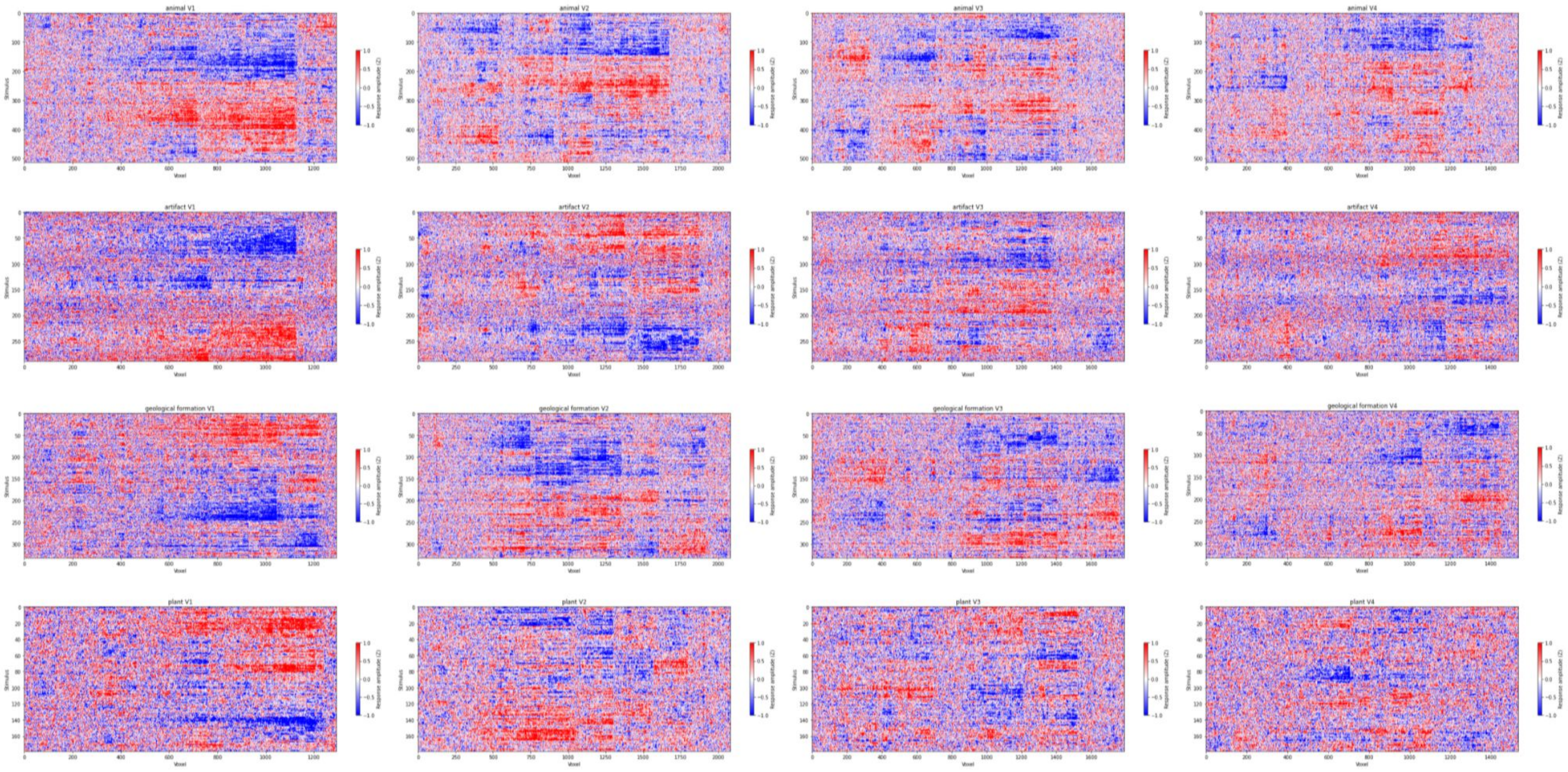

Fig 2b. heatmap of V1, V2, V3, and V4 activities stimulated by images under the category of "animal", "artifact", "geological formation", and "plant"

Result: PCA and PCA based image reconstruction

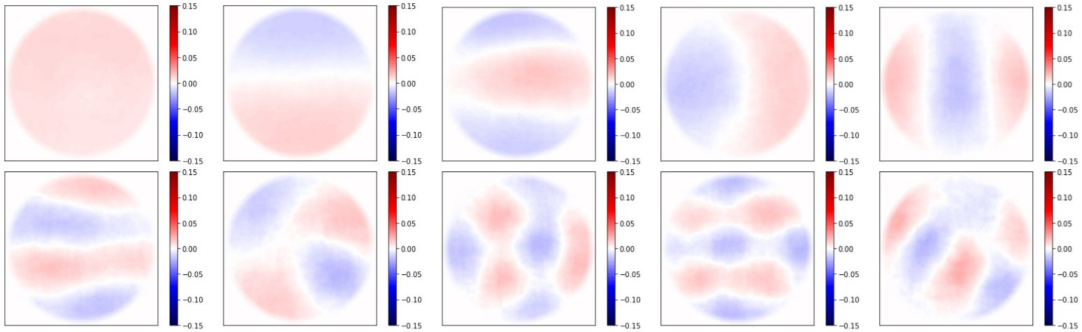

Fig 3a. the first ten eigenvectors (1st - 5th and 6th - 10th from left to right)

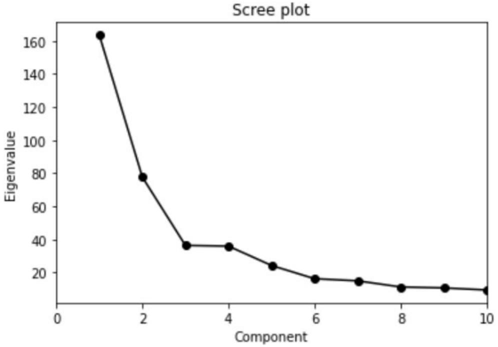

Fig 3b. the first ten explained variance (eigenvalues)

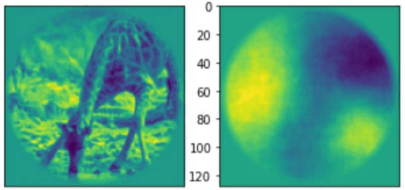

Fig 3c. reconstructed image of 10 pc

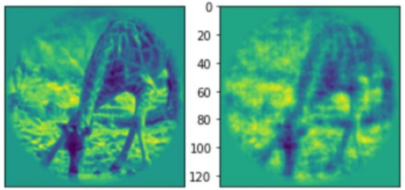

Fig 3d. reconstructed image of 300 pc

Result & analysis:

By using principal component analysis, I reduced the dimensionality of my image dataset to explore whether there are any hidden statistical properties of the image dataset.

- The later the principle component is extracted the less variance of the image dataset it can explain (Fig 3a), meaning that it encodes more detailed information about image features.
-
- Fig 3c and 3d are examples of reconstructed images based on the first 10 and 300 PCs respectively. Construction using the first 10 PCs captures the general spatial features of the image while construction using the first 300 PCs adds more refined details to the reconstruction without changing the general spatial feature of the image.

- This result helped me decide to use the first ten eigenvectors for the next part of my analysis because I am more interested in investigating the encoding of general spatial features of the images

Result: correlate brain activities responding to images and their projections on PCs

PC	Brain Regions
1	V1>V2>V4>V3>LatOcc>V3B>V3A
2	LatOcc>V1>V2>V4>V3>V3B>V3A
3	V1>V2>LatOcc>V3>V3B>V4>V3A
4	V1>V2>V3>V3B>V3A>V4>LatOcc
5	V1>V3B>V4>V2>V3>LatOcc>V3A
6	LatOcc>V2>V1>V3>V3A>V4>V3B
7	V3>V1>V2>V3A>LatOcc>V3B>V4
8	V4>V3A>LatOcc>V3>V3B>V2>V1
9	V1>V3A>V3B>V4>V2>V3>LatOcc
10	V3>V1>V3B>LatOcc>V4>V2>V3A

Fig 4a. order of correlation of the first ten PC with brain region

Result & analysis:

My result showed that V1 voxel activities has the highest average correlation with the images' projections on the first 5 PCs, and as I move to later PCs, brain regions more downstream in the visual pathway become more correlated, such as V3, whose voxel activities highly correlated with image projections on the 7th, 9th, and 10th PCs.

This result supports the fact that V1 processes the most general features of images. As I move to later extracted PCs, they carry more detailed information of the images and therefore, images' projections on them are more correlated with activities of voxels located more downstream of the central visual pathway..

Result: correlate brain activities responding to images and their projections on PCs

PC	Image Categories
1	entity>fruit>fungus>plant>person>gf>artifact>animal
2	entity>fruit>fungus>plant>gf>artifact>person>animal
3	entity>fruit>fungus>plant>artifact>gf>person>animal
4	entity>fruit>fungus>plant>person>gf>artifact>animal
5	entity>fruit>fungus>plant>gf>person>artifact>animal
6	entity>fruit>fungus>plant>gf>person>artifact>animal
7	entity>fruit>fungus>plant>person>artifact>gf>animal
8	entity>fruit>fungus>plant>gf>person>artifact>animal
9	entity>fruit>fungus>plant>gf>person>artifact>animal
10	entity>fruit>fungus>plant>person>gf>artifact>animal

Fig 4b. order of correlation of the first ten PC with brain region

PC	Overlap ('entity')
1	V3A>V3>V2>V4>LatOcc>V1>V3B
2	LatOcc>V4>V2>V3>V3B>V3A>V1
3	LatOcc>V3>V2>V4>V1>V3B>V3A
4	V4>V3>V1>LatOcc>V2>V3B>V3A
5	LatOcc>V3A>V4>V2>V3A>V3>V1
6	V3A>V2>V3>V3B>V4>LatOcc>V1
7	LatOcc>V3>V4>V2>V1>V3B>V3A
8	LatOcc>V3A>V4>V2>V3B>V3>V1
9	V1>LatOcc>V4>V2>V3B>V3>V3A
10	V2>LatOcc>V3>V1>V4>V3B>V3A

Fig 4c. order of correlation of the first ten PC with brain regions activated by ‘entity’ images

Result & analysis:

By dividing the dataset based on semantic categories of images, I found that brain activities responding to the category ‘entity’ yielded the highest correlation and the category ‘animal’ yielded the lowest with their image projections on the first 10 PCs (fig 4b). This difference may arise from differences in the variability of their intra-category image information.

Since brain activities corresponding to ‘entity’ images have the highest correlation with the image projection on all PCs, I only further divided this dataset by different brain regions (fig 4c). As a result, LatOcc voxel activity has the highest average correlation with the PC projections of ‘entity’ images, indicating that among all brain regions I analyzed, it has the most similar way of processing images with PCA on ‘entity’ images.

Discussion

Limitation:

1. Some image labels are inaccurate because I was unable to identify the content of them due to the level of complexity of the semantic info. they carry. (E.g.: there is an image with an old man with two children, and all of them wore cowboy hats, which makes it difficult for me to assign it into either the ‘person’ or the ‘entity’ category)
   a. As a solution, I always chose the most obvious semantic component I identified in the image to be the label, but this can cause inaccuracies since the subject n the Kay experiment might not first recognize the same component of the image as I did. At the same time, due to the mixed semantic information in some images, the subjects could also have their brain activities encoding mixed visual information.
   b. Further analysis: look into how these ambiguous images affect the activities of the brain by separating them to a category of their own, e.g. a woman wearing Indian ornaments can be assigned to the category of “person+artifact”
2. I only used general semantic categories to divide image stimuli in this project.
   a. Further research: investigate how more detailed semantic information of the image can affect brain activities by using natural language processing algorithms like Word2vec.
   b. Word2vec, for example, can assign a 300 dimensional vector to its word input which can make the differences between more detailed semantic information encoded in images more quantifiable. In the future, I want to investigate similarities between the semantic distances of visual stimuli with their respectively evoked brain activities.