Cortical Specialization in Four Brain Regions: An fMRI Study

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Introduction to fMRI Research

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Abstract

The goal of this study is to localize cortical specialization in four brain regions - the fusiform face area/parahippocampal place area, human middle temporal complex, temporoparietal junction, and the superior temporal gyrus through fMRI scans and four localizers. The first localizer consisted of stimuli that targeted the FFA/PPA through facial features. The second localizer consisted of stimuli that targeted the hMT+ region through motion. The third localizer consisted of stimuli that targeted the TPJ region through showing social tasks. The fourth localizer consisted of auditory stimuli that targeted the STG region through speech. Our results were that the FFA/PPA region showed activation in both hemispheres for the face localizer with greater activation in PPA, the hMT+ region showed activation in both hemispheres for the motion localizer, with greater activation in the right hemisphere, the TPJ region showed activation for the social localizer, with greater activation in the right hemisphere and the STG region showed activation for the speech localizer and activation in the left hemisphere was greater. Our conclusion was that through cortical localization, we are able to determine the responsibility of the four brain regions in facial recognition, motion, social tasks and speech respectively.

Introduction

Although we have limited information on the complexity of the brain and how it

processes information, we do know for certain that some regions are specialized in performing

certain tasks. Certain cognitive functions are processed in regions with cortical specialization,

and identifying these regions makes it possible to understand how brain damage can alter the

patients' cognitive ability. The goal of this study is to identify which regions are responsible for

processing motion, faces/places, social, and speech stimuli. Based on previous research, it can be

predicted that the regions that specialize in processing these cognitive functions are the human

middle temporal complex (hMT+), the face fusiform area (FFA)/the parahippocampal place area

(PPA), the temporoparietal junction (TPJ), and the superior temporal gyrus (STG), respectively.

The hMT+ is responsible for processing motion. Previous studies have shown that it is

topographically organized into columns, similar to the primary visual cortex's spatial

organization (Zimmermann et al., 2011). This organization was first identified in monkeys using

fMRI scans, but was able to be mapped out in the human medial temporal complex. The hMT+

is selective in its processing. It is able to enhance the representation of visual stimuli that is being

attended to, but can also reduce the influence of stimuli that is not within the field of visual

attention, despite how salient the latter stimuli might be. This indicates that attention can

influence motion processing during the early stages of the dorsal pathway (Treue & Maunsell,

1999). The hMT+ is also able to discriminate motion thresholds, but has no effect on contrast

thresholds. In a study conducted on monkeys, they concluded that the medial temporal visual

area had an elevated motion threshold when identifying the direction of a moving signal, but

showed no effect in contrast threshold when identifying the orientation of stationary gratings

(Newsome & Pare, 1988). From these findings, it is clear that the hMT+ plays a role in selectively processing visual motion information.

The FFA is part of the human visual system and plays an important role in facial recognition. It is a small region located in the inferior temporal lobe and is typically activated in imaging studies when parts of faces or pictures of facial expressions are presented to participants. Based on a 1996 fMRI study by Nancy Kanwisher et al., intended to identify brain regions linked to facial recognition, **BOLD** levels increased in the temporo-occipital cortex when participants were asked to identify a face and low otherwise. They measured neural activity when participants looked at faces versus when they looked at familiar objects and concluded that there was a brain region in the temporal lobe that corresponded to the recognition of faces (Kanwisher et al., 1996). Additionally, a 1985 review paper by neuroscientist A.R. Damasio investigated the hypothesis that prosopagnosia patients, who have lost the ability to recognize faces, may still demonstrate increased brain activity when they see familiar versus unfamiliar faces. They measured participants' skin conductance response (SCR) and found that subjects had significantly higher SCRs when viewing familiar faces. The study demonstrated that an early step of the physiological process of recognition is still occurring but without their awareness (Damasio and Tranel, 1985). To add onto this, a 1974 study by J.C. Meadows presented evidence that patients with prosopagnosia have lesions in the right occipital anterior inferior temporal junction. Many cases also had additional lesions in the left hemisphere but it was not always symmetrical with the right hemisphere. The data demonstrates that the inability of patients to retrieve memories of well-known faces is the result of a disconnection between facial perception and memory in the brain area where the FFA is located (Meadows, 1974).

The PPA has previously been identified for specializing in spatial recognition. It is located in the posterior region of the parahippocampal cortex (PHC). The PHC has an episodic memory function, and therefore specializes in associations between two items. The PPA then, located within the PHC, specializes in processing contextual associations, specifically spatial associations (Aminoff et al., 2013). This was further reinforced in a study that utilized PET scans in order to determine the episodic memory function of the PPA. After showing a series of stimuli and administering a recognition task, the researchers found that the PPA was more active when viewing a novel spatial scene, and played a significant role in recognition of this scene in the recognition task (Köhler et al., 2002). A causal role of the PPA was identified by inducing topographic visual hallucinations in subjects, which seemed to elicit a spatial hallucination (Megevand et al., 2014). One participant reported seeing a train station in the neighborhood where he lived, despite being physically located in the lab. The researchers concluded that the PPA was directly involved in the visual perception of places.

The TPJ is responsible for a variety of social processes. A review of literature reveals the TPJ's involvement in many cognitive operations requiring self-other distinction, overall supporting the ability to control self and other representations (Quesque & Brass, 2019). Self-other distinction can include control over imitation, a cognitive process traced back to the TPJ in a study using repetitive transcranial magnetic stimulation (rTMS) to the right TPJ (rTPJ). rTMS to the rTPJ impaired participants' ability to control the tendency to imitate, leading to the conclusion that the rTPJ is involved in switching between the self and other representations (Sowden & Catmur, 2013). Additionally, the TPJ is involved in perspective-taking, yet another important social process. In a study that assessed the perspective-tracking and perspective-taking

of participants that received high-definition transcranial direct current stimulation (tDCS) to either their rTPJ or dorsomedial prefrontal cortex (dmPFC), it was found that high-definition tDCS to either the rTPJ or dmPFC did not affect perspective-tracking, but stimulation to the rTPJ had a effects on perspective-taking (while stimulation to the dmPFC did not). This ultimately supports the theory that the rTPJ has a causal involvement with the embodied processes relevant for social cognition (Martin et al., 2020). Furthermore, a meta-analysis of 25 experiments focusing on attentional reorientation and theory of mind — two vital social processes — found the anterior rTPJ is involved in attentional shifting and the posterior rTPJ is involved in social interaction capacities (Krall et al., 2014). Overall, it is clear that the TPJ is involved in social cognition.

The STG region is responsible for a variety of auditory processes, including but not limited to the encoding of speech sounds and phonological information, as seen in a review of literature on the role of the STG region in determining meaning from auditory information (Yi et al., 2019). More specifically, the STG region has been found to be strongly linked to the processing of auditory timing. In one such study, the STG region was interfered with utilizing TMS to increase the amount of neural noise, and participants were asked to determine the pitch and tone of a sound. It was found that when there was TMS stimuli present and the STG region was interfered with, participants were significantly less accurate with their answers, showing the importance of STG region in discriminating auditory information and processes (Bueti et al., 2008). Both hemispheres of the STG region have also been shown in one study to play a role in speech perception. Specifically, the left hemisphere showed more activation for speech processing, but there was also a small cluster of activation in the right hemisphere, indicating

that the right hemisphere of the STG region provides support to the left hemisphere of the STG region with speech processing (Ramos Nuñez et al., 2020). Additionally, the STG region is shown to be critically involved with the perception of auditory dissonance in one such study where a woman who had lesions in the auditory cortex underwent a series of CT scans and auditory tasks that ultimately showed that the STG region is involved in all judgments and perception related to auditory dissonance (Peretz et al., 2001). Overall, it is clear that the STG region is essential to auditory perception and processing, which is why it would be crucial to speech processing.

Research on these regions helped identify the cognitive functions that they specialize in, and how this information is processed. The goal of the current research is to provide deeper insight into how these cortical regions are involved in different cognitive methods by utilizing fMRI scans in order to localize and identify these areas.

Methods

Participants

The data set contains three subjects including two males and one female all of whom are right-handed. The data was collected at Carnegie Mellon University (CMU) with funding by the National Institute of Health and received approval by the Institutional Review Board at CMU. There were no **contraindications**, as all participants were willing and able to participate.

Localizers

Participants were asked to engage in four separate tasks, each of which had two runs. These tasks consisted of a combination task which localized the fusiform face area (FFA) and parahippocampal place area (PPA) with nine conditions, a motion task which localized the human middle temporal complex (hMT+) with two conditions, a social task which localized the temporoparietal junction (TPJ) with two conditions, and a speech task which localized the superior temporal gyrus (STG) with two conditions.

FFA/PPA Localizer

The combination task consisted of 19 blocks that were each 16 seconds in length and had two blocks per condition in each scan. The stimuli were each repeated once over the course of the scan and can be separated into nine categories - limbs, bodies, adult's faces, children's faces, houses, corridors, instruments, cars, and scrambled. For the limbs stimulus, participants were shown images of different legs, arms, hands, and feet in varying postures and skin colors. They were shown headless bodies that varied in gender, clothing, and stance for the bodies stimulus. For the adult's and children's faces, participants were shown a diverse range of faces that varied in gender, race, expression, and age. For the house stimulus, participants were shown images that

ranged from one to four stories, and differed in modernness and curb appeal. The corridors

stimulus consisted of long hallways that could be attributed to homes, office buildings, hotels,

storage facilities, or religious architecture. They were shown images of guitars and other similar

string instruments for the instrument stimulus, several different models of cars for the car

stimulus, and images of gray textures for the scrambled stimulus. These same gray textures were

used as the background for the images shown in the other eight categories.

hMT+ Localizer

In the motion task, there were eight blocks each 15 seconds in length and had seven

blocks per condition per scan. The task consisted of two conditions, static and motion.

Participants were shown a moving optic flow image of many black dots with a fixed dot in the

center for the motion condition. The center dot would alternate between green and red. In the

static condition, the black dots would remain fixed, while the center dot continued to alternate

colors.

TPJ Localizer

The social task consisted of eight blocks, each 20 seconds in length, and had six blocks

per condition per scan. The conditions included social and mechanical. The stimuli involved

several moving images with balls and sticks performing different actions. The social actions

included purple balls following a larger blue ball and a representation of a purple ball fishing

while the mechanical action involved a red tow truck carrying a stick, among other short

animations as part of a longer video.

STG Localizer

The final task was known as the speech task and consisted of 16 second blocks with six

blocks per condition per scan. The two conditions were described as speech and scramspeech.

The participants were required to listen for either spoken words used in everyday language as

part of the speech condition or indistinct sounds that may not be immediately recognizable and

often sounded like groans or snoring as part of the scramspeech condition.

Image Acquisition

The data was collected on a 3 Tesla Siemens scanner, and images were produced utilizing

the BOLD response which arises from the hemodynamic response function (**HRF**). Anatomical

scans were collected with a **T1-weighted** scan, with a voxel resolution of 1x1x1 mm. Functional

scans were collected with **T2*-weighted** scans, with a voxel resolution of 2x2x2 mm. 69 slices

for each scan were acquired. 229 volumes were collected for the combination tasks, 110 volumes

were collected for the motion tasks, 141 volumes were collected for the speech tasks, and 121

volumes were collected for the social tasks. Our scans were acquired in the axial plane. The

temporal parameters were a sample rate of **TR** = 2000 (ms). Images were acquired interleaved,

with 3 slices measured simultaneously at each time point, and slices were acquired 87.5 ms apart.

Preprocessing

In order to ensure we are working with data with as little noise as possible, we conducted

preprocessing procedures on all of our scans. We registered our subjects' anatomy scans to the

Talairach atlas by manually aligning the subjects' **AC/PC** scans and applying Talairach

transformations through scaling of the brain using landmarks to match the Talairach atlas. The

landmarks used to scale the brain to the atlas space are the anterior commissure (AC), the

posterior commissure (PC), the anterior point (AP), the posterior point (PP), the most superior

point (SP), the most inferior point (IP), the rightmost point (RP), and the leftmost point (LP).

Our preprocessing procedures also included spatial smoothing using a Gaussian filter with a full

width at half maximum of 4 mm in order to account for any misalignments between subjects to

correct for individual differences in anatomy, motion correction to correct for human subject

motion, slice time correction to correct for the differences in timing when slices were collected,

and temporal filtering/smoothing implemented using a 0.01 Hz frequency-space filter in order to

remove any apparent scanner drift to correct for time-varying contaminants, scanner drift, and

machine noise. We aligned the scans to the Talairach space for each of the subjects by using

Talairach coordinates, and also performed co-registration by registering and aligning the

functional data collected to our native anatomical images. Our motion correction parameters

included 3 translations (X, Y, Z, measured in millimeters) and 3 rotations (X, Y, Z, measured in

degrees).

Statistical Analysis

For each of the four localizers being studied, multi-subject general linear models (GLM)

brain maps were obtained using **statistical design matrices** (which predict brain response

predicted directly tied to the condition timing, while taking HRF into account) to identify the

regions of the brain being targeted. Five out of the six scans from the two runs of all three

subjects were chosen at random to construct the brain map and the statistical threshold was

adjusted to ensure that the contrast was set. Using the coordinates for the areas of activation

obtained from Neurosynth as guidance, we were able to determine the location of all five brain

areas from the data.

When localizing the human middle temporal complex (hMT+), the first run for subject two was excluded and used only for visualization. The statistical contrast was adjusted for the two predictors, static and motion, to demonstrate which voxels were more active during the motion condition compared to the static condition. Following this, the calculated statistical threshold was found to be $p < 0.000047$.
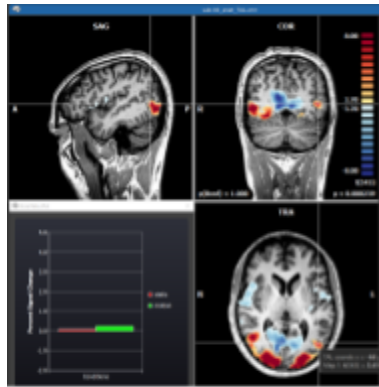
When localizing the fusiform face area (FFA) and parahippocampal place area (PPA), the second run from the first subject was excluded. The statistical contrast was adjusted as follows: (+) adult faces, (+) child faces, (-) houses, (-) corridors, (-) instruments, (-) cars, and (-) scrambled. The statistical threshold was determined to be less than 0.000102.

For the localization of the temporoparietal junction (TPJ), the scan from the first run of subject three was excluded from the localization and used only for visualization. The statistical threshold was also adjusted to show the voxels that were more active in the social predictor compared to the mechanical predictor and the statistical threshold was determined to be less than 0.003908.
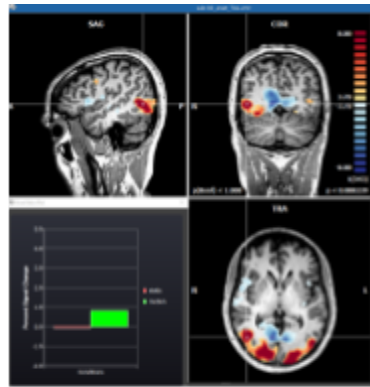
For the localization of the superior temporal gyrus (STG), the first run of subject one was excluded from the brain map. The statistical contrast was adjusted to demonstrate that the voxels for the speech predictor were more active than the for the scramspeech predictor. The new statistical threshold was calculated to be that p is less than 0.000950.

Results

The hMT+ could be visualized in both brain hemispheres; however, greater activation could be seen in the right hemisphere. In the left hemisphere, it was found at the Talairach


coordinates x = -44, y = -68, and z = 7, and in the right hemisphere, was found at x = 46, y = -65, and z = 3. An independent time series was obtained after linking the excluded scan to the brain map

Activation map of the left hemisphere of the hMT+   Activation map of the right hemisphere of the hMT+

and the results demonstrated a deterioration in the levels of noise and activation. The average for the left hemisphere was found to be 0.26 percent and 0.53 percent for the right hemisphere. The time series tended to show peaks in the motion condition (green) and fell back down in the static condition (red) demonstrating that activation was greater for the motion condition.
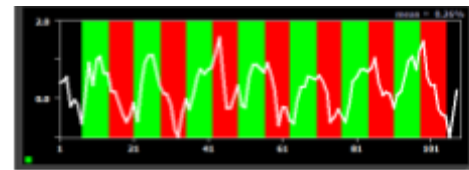

Independent time series for the left hemisphere of the hMT+
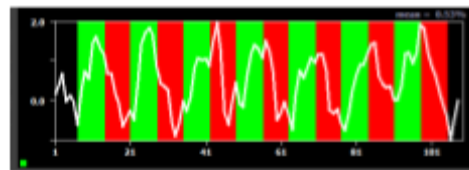
Independent time series for the right hemisphere of the hMT+

Both the FFA and PPA, brain regions associated with face recognition and scene and place recognition, respectively, were identified from the brain map and were bilaterally symmetrical. The Talairach coordinates for the right hemisphere of the FFA were found to be x = -37, y = -39, and
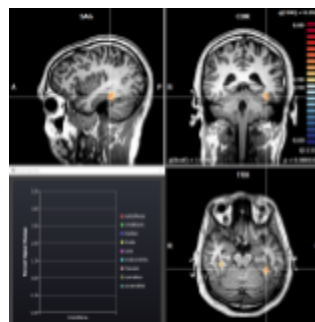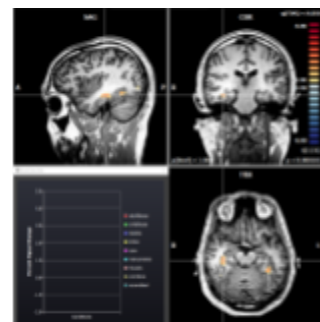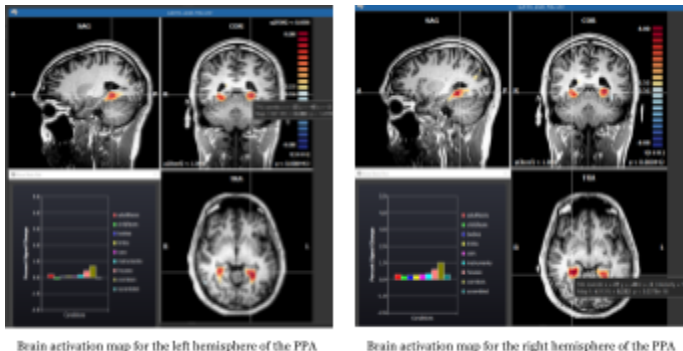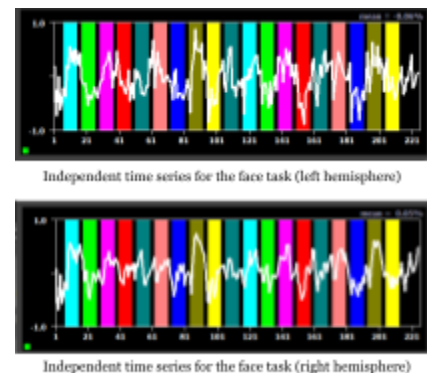

FFA activation map for the left hemisphere   FFA activation map for the right hemisphere

z = -16, while the coordinates for the left hemisphere were found to be x = 39, y = -24, and z =

Brain activation map for the left hemisphere of the PPA



Brain activation map for the right hemisphere of the PPA

-13. The levels of activation were not significant but there was slightly more in the left hemisphere. The levels of activation for the PPA were much greater, possibly due to the PPA being larger in size than the FFA. The Talairach coordinates for the PPA were found to be x = -25, y = -45, and z = -5 for the left hemisphere and x = 27, y = -42, and z = -5 for the right hemisphere. After linking the excluded scan to the brain map, a time series for the region of interest was obtained and gave an average of 0.06 percent for the left hemisphere and an average of 0.05 percent for the right hemisphere. Based on the time series, there was greater activation for the conditions that were

Independent time series for the face task (left hemisphere)

Independent time series for the face task (right hemisphere)

marked with a + (adult and child faces) compared to the conditions that were marked with a - (houses, corridors, instruments, cars, and scrambled) as seen by the the areas in the graph where the activation rises and falls.
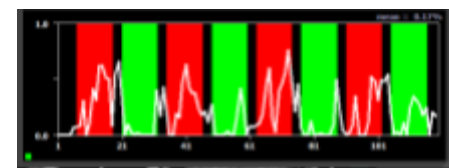
The localization of the temporoparietal junction (TPJ), the brain region important for several aspects of social cognition, was found from the activation map and was bilaterally symmetrical. For the left hemisphere, the Talairach coordinates were found to be x = -41, y = -63, z = 20, and for the right hemisphere were x = 48, y = -52, and z = 21. The areas of activation were not significant but it was greater in the right hemisphere. After the excluded scan was

Activation map for the left hemisphere of the TPJ

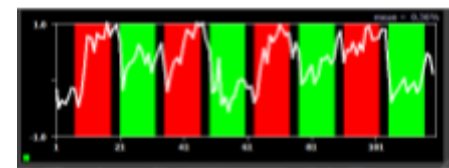

Activation map for the right hemisphere of the TPJ
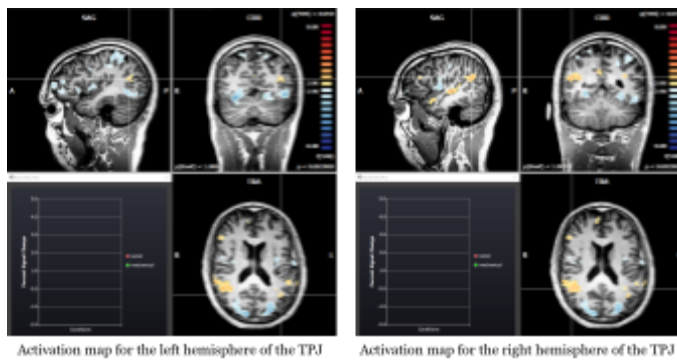
linked to the brain map and an independent time series was obtained, the average for the left hemisphere was found to be 0.17 percent while the average for the right hemisphere was found to be 0.36 percent. There were additional brain structures associated with social processing identified in the brain map such as the posterior cingulate cortex, which is involved in evaluating and judging social interactions and modulating social perceptions. The independent time series demonstrated that there was an enhanced selective response in the TPJ for the social condition compared to the

Independent time series for for the left hemisphere of the TPJ

Independent time series for for the right hemisphere of the TPJ

mechanical condition. However, the percent signal change was higher for the left hemisphere compared to the right hemisphere.
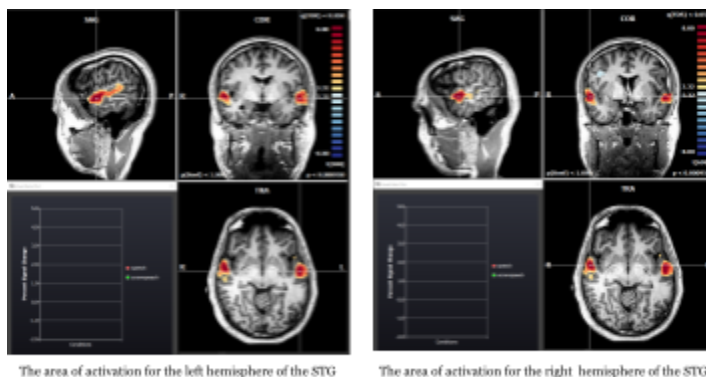
The superior temporal gyrus (STG) is the site of the auditory association cortex and therefore plays an important role in spoken word recognition. The Talairach coordinates for the STG localized in the left hemisphere of the brain map was x = -56, y = -5, and z = -4, and in the right hemisphere was x = 57, y = -1, and z = -4. The STG was bilaterally symmetrical in both hemispheres and there was slightly

The area of activation for the left hemisphere of the STG

The area of activation for the right hemisphere of the STG

more activation that could be seen in the left hemisphere. After the excluded scan was linked to

the brain map, the time series for the left hemisphere resulted in an average of 0.24 percent and

0.42 percent for the right hemisphere. The independent

time series for the STG did not demonstrate functional

selectivity as it was not entirely clear as to whether

there was greater activation in the speech or

scramspeech condition as there were some peaks

during the scramspeech condition (green) and drops

during the speech condition (red).
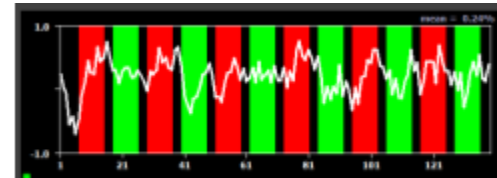
The independent time series for the left hemisphere of the STG
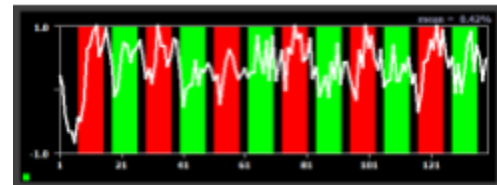
The independent time series for the right hemisphere of the STG

Discussion

Our study aimed to identify and locate key brain regions associated with motion, faces and places, social, and speech stimuli. Through statistical analysis of fMRI imaging, we were able to localize cortical specialization, determining the responsibility of the hMT+ in motion processing, the FFA and PPA in face and place/scene perception, the TPJ in social processing, and the STG in speech processing.

The hMT+, which is responsible for processing visual motion information, was the brain region expected to be identified for the study's testing of brain activation for visual motion stimuli. Based on comparing activation for motion versus static stimuli, we saw that the corresponding time series showed greater activation during motion stimuli as opposed to static stimuli. Additionally, we were able to identify the location of this activation in our activation maps, which we could then compare with Neurosynth's meta-analytic maps. By comparing these Talairach coordinates to the coordinates determined by the Neurosynth meta-analytic map for the hMT+, we determined that our hypothesis about the hMT+'s function of processing of visual motion stimuli was correct, as our study's coordinates were incredibly close to Neurosynth's coordinates. The Neurosynth meta-analytic map places the hMT+ at Talairach coordinates of $x = -46$, $y = -72$, and $z = 2$ in the left hemisphere, and $x = 46$, $y = -68$, and $z = 2$ in the right hemisphere. Similarly, our study identified this brain region at $x = -44$, $y = -68$, and $z = 7$ in the left hemisphere, and at $x = 46$, $y = -65$, and $z = 3$ in the right hemisphere. Our location of the hMT+ in the right hemisphere was closer to what was expected, and was also the hemisphere in which we found greater activation.

The FFA and PPA are regions responsible for the perception of faces and places/scenes, respectively. In this study, we expected to identify the FFA as the brain region most active when presented with facial stimuli, and to identify the PPA based on activation when places and scenes were presented. Based on the time series, we saw greater activation for stimuli such as corridors and cars, and some activation for stimuli such as children and adult faces. Neurosynth's meta-analytic map places the FFA at $x = -40$, $y = -52$, and $z = -22$ for the left hemisphere, and at $x = 42$, $y = -50$, and $z = -22$ for the right hemisphere. Our study identified the FFA at $x = -37$, $y = -39$, $z = -16$ for the left hemisphere, and $x = 39$, $y = -24$, and $z = -13$ for the right hemisphere, which is notably different from Neurosynth's values. This may be due to the fact that in our observations of the FFA, the levels of activation were not significant, and thus led to a slightly inaccurate identification of the FFA. For the PPA, Neurosynth identifies coordinates of $x = x = -28$, $y = -38$, and $z = -10$ for the left hemisphere, and $x = 26$, $y = -38$, and $z = -12$ for the right hemisphere. Our study identified the PPA at moderately similar coordinates, differing mostly at our z value: $x = -25$, $y = -45$, and $z = -5$ (left hemisphere) and $x = 27$, $y = -42$, and $z = -5$ (right hemisphere).

The TPJ is a brain region associated with many important social processes and functions, such as theory of mind. Our time series demonstrated that there was significantly greater activation when social stimuli were processed as opposed to mechanical stimuli, consistent with the TPJ's function. Neurosynth identifies the TPJ at $x = -50$, $y = -56$, and $z = 22$ (left hemisphere) and $x = 52$, $y = -54$, and $z = 14$ (right hemisphere). Our study found similar coordinates for the TPJ: $x = -41$, $y = -63$, and $z = 20$ for the left hemisphere, and $x = 48$, $y = -52$, and $z = 21$ for the right hemisphere. Differences in coordinates may be explained by the

anatomical makeup of the TPJ, as it is made up of several subregions throughout the brain.

Additionally, our finding of greater activation in the right hemisphere is consistent with literature

that suggests the right TPJ is what is most active and responsible for cognitive processing of

social stimuli.

The STG is a brain region responsible for spoken word recognition. Our time series did

not show much functional selectivity when comparing activation for speech and scrambled

noises, but we were still able to identify the STG based on our activation map. While Neurosynth

identified the STG at x = -60, y = -20, and z = 0 for the left hemisphere, and x = 60, y = -10, and

z = 0 for the right hemisphere, we identified the STG at x = -56, y = -5, and z = -4 for the left

hemisphere, and x = 57, y = -1, and z = -4 for the right hemisphere. While our x values were

similar, our y and z values differed moderately. However, when visually comparing our

activation map to Neurosynth's meta-analytic map, we see that our identification still fits the

expected location of the STG.

Overall, based on the creation of time series and activation maps using fMRI imaging and

data analysis, as well as comparisons to meta-analytic studies, our study was able to localize

cortical specialization in the hMT+, FFA and PPA, TPJ, and STG. However, it is important to

note that this study was heavily limited by the number of subjects available. Using more than

three subjects in future studies may allow more accurate localization and be more reflective of

the general population.

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Key Terms

1. <u>BOLD:</u> blood oxygenation level dependent (BOLD) imaging depends on differing blood flow through different regions in the brain — reflecting regional activity — to produce images in fMRI studies.

2. <u>Contraindications:</u> a situation in which a person should not receive a drug/treatment/procedure because they are at risk of harm.

3. <u>Hemodynamic response or hemodynamic response function (HRF):</u> the rapidly-changing and quick delivery of blood to active neural tissues in response to neural events.

4. <u>Preprocessing:</u> the steps taken to prepare MRI data and images for statistical analysis.

5. <u>Statistical design matrix:</u> a statistical model that has data on the independent variables that attempt to explain dependent variables (observed data).

6. <u>T1-weighted:</u> MR images constructed using longitudinal relaxation, where the rate of relaxation is determined by fixed properties of the tissue; useful for anatomical images.

7. <u>T2*-weighted:</u> MR images constructed based on properties of the local magnetic fields and of relative deoxygenation levels in the blood that fluctuate based on neural activity; useful for functional images.

8. <u>TR:</u> repetition time, the amount of time between pulse sequences in a slice.

9. <u>AC/PC:</u> the axis created by the Anterior Commissure/Posterior Commissure, providing a reference for standardizing brain orientation for acquiring images.