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Localising the social brain with fMRI in relation to different types of love

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Abstract

One often feels love towards the people closest to them, but love can also be felt towards different objects, such as strangers, pets or nature. The social brain is essential in human interaction and relationships, but how is it involved when feeling love towards different targets? This thesis examines the relationship between different types of love and the theory of mind (ToM) network. The theory of mind network is part of the social brain that is activated when thinking about other people's mental state, including thoughts, beliefs and intentions. In this study the ToM network was localized using data from a functional magnetic resonance imaging (fMRI) experiment where subjects had passively viewed an animated short movie. Eight regions of interest were chosen from the localized ToM network. In the main fMRI experiment, subjects had listened to stories featuring six different types of love and a control story. The activity of each type of love in each region of interest were compared both during listening to the story and during a mental imagery period after each story. Overall, the activity of the theory of mind network was higher when feeling love towards another human, as opposed to love towards a pet or nature. Love towards strangers had most variance between regions, with especially high activation in left temporoparietal junction. Activations during the imagery period generally followed the pattern of the listening period with lower responses. Additionally, the subjects had filled out questionnaires about passionate and compassionate love. Correlations between activity of brain regions and questionnaire results were analysed to look for similarities between a person's own perception of the level of love and the brain response. In the ToM network correlations were found between compassionate love questionnaire results and brain activations.

Keywords fMRI, functional magnetic resonance imaging, theory of mind, love, social brain

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Tiivistelmä

Rakkaus mielletään usein tunteeksi, joka kohdistuu läheisiin ihmisiin. Rakkaudella voi kuitenkin olla muitakin kohteita kuten tuntematon ihminen, lemmikki tai luonto. Sosiaaliset aivot ovat merkittävässä roolissa ihmisten välisessä vuorovaikutuksessa ja ihmissuhteiden muodostuksessa, mutta kuinka ne osallistuvat rakkauden tuntemukseen eri kohteita kohtaan? Tämä työ tutkii eri rakkauden tyyppien ja aivojen mielenteoriaverkon suhdetta. Mielenteoriaverkko on sosiaalisten aivojen osa, joka käsittelee toisten ihmisten mielentilaa, esimerkiksi toisten ajatusten, uskomusten ja aikomusten tulkitsemista. Tässä tutkimuksessa mielenteoriaverkko paikannettiin toiminnallisen magneettikuvantamisen (fMRI) avulla. Koehenkilöt katsoivat animoidun lyhytelokuvan, jonka perusteella paikannettiin kahdeksan aivoaluetta mielenteoriaverkosta. Pääkokeessa koehenkilöt kuuntelivat tarinoita kuudesta erityyppisestä rakkaudesta ja kontrollitarinoita fMRI-kuvantamisen aikana. Erityyppisten rakkauden aktivaatioita aivoissa vertailtiin paikannettujen aivoalueiden välillä tarinoiden kuuntelun aikana sekä kuuntelun jälkeisen kuvitteluvaiheen aikana. Mielenteoriaverkon aktivaatio oli selvästi korkeampi, kun rakkauden kohteena oli toinen ihminen eikä luonto tai lemmikki. Eniten variaatiota tutkimusalueiden välillä oli tuntematonta henkilöä kohtaan tunnetussa rakkaudessa, joka aktivoi ohimolohkon ja päälaenlohkon yhdyskohtaa (engl. temporoparietal junction, TPJ) erityisen voimakkaasti. Kuvitteluvaiheen vasteet olivat samankaltaisia kuin kuuntelunaikaiset, mutta selvästi heikompia. Lisäksi koehenkilöt vastasivat kyselyihin intohimoisesta ja myötätuntoisesta rakkaudesta. Kyselytuloksia verrattiin rakkaustarinakokeen tuloksiin, jotta saataisiin selville, miten henkilöiden oma tuntemus rakkaudesta vastaa aivokuvantamisen tuloksia. Mielenteoriaverkossa havaittiin korrelaatioita myötätuntoisen rakkauden kyselytulosten ja aivoaktivaation välillä.

Avainsanat fMRI, toiminnallinen magneettikuvaus, mielen teoria, rakkaus, sosiaaliset aivot

Contents

Abbreviations

dmPFC	dorsal medial prefrontal cortex
fMRI	functional magnetic resonance imaging
lMTG	left middle temporal gyrus
lPC	left precuneus
lTPJ	left temporoparietal junction
mPFC	medial prefrontal cortex
MTG	middle temporal gyrus
PAG	periaqueductal gray matter
PC	precuneus
rMTG	right middle temporal gyrus
rPC	right precuneus
rTPJ	right temporoparietal junction
ROI	region of interest
ToM	theory of mind
TPJ	temporoparietal junction
vMPFC	ventral medial prefrontal cortex

1 Introduction

Interaction and communication with others is an important part of human behaviour. Efficient exchange of information enables complex cooperation between multiple people, which is the basis of society. The social brain hypothesis suggests that humans have evolved a large brain specifically to be able to build and maintain a large quantity of complex relationships (Dunbar, 1998). Human social interactions are complicated and require a lot of processing power for many reasons. The social situation is unpredictable and constantly changing. A persons behaviour is expected to follow a set of unwritten rules of social interaction. Social cues can be subtle and complex, conscious or unconscious, verbal or nonverbal, and they may vary between cultures. Due to the complex nature of social cognition, advancements in brain research about it have been achieved only relatively recently (Hari et al., 2015).

The social brain consists of regions of the brain that are involved with the processing of social situations. Different aspects of human social brain have been identified with functional brain imaging. For example, processing the visual data of a person's face is essential in human-to-human interaction. It allows one to possibly identify if they have previous information about the other person and also gives clues about their emotional state and intentions. Brain regions involved in face perception include the fusiform face area (Kanwisher et al., 1997), occipital face area (Gauthier et al., 2000) and anterior temporal cortex (Kriegeskorte et al., 2007).

Another important aspect of the human social brain is the mirror neuron system. Mirror neurons are neurons that activate both during observation of another person's action and execution of the same action (Rizzolatti et al., 1996). Mirror neurons allow us to better understand other peoples actions and the intentions and reasons behind them.

1.1 Theory of Mind

In order to have a successful social interaction, one needs to understand and anticipate the other person's actions. The ability to understand one's own and other people's minds is referred to as mentalizing or theory of mind (ToM). Theory of mind network is the set of brain regions that are involved in ToM. Many studies have been conducted to localise theory of mind network using different kinds of stimuli and tasks. False belief tasks are a common way of studying ToM (Saxe and Kanwisher, 2003). In a false belief task, the subject is made to think about how an incorrect belief affects another persons thoughts. For an example, Lee et al. (2011) had the subject read a description in which a person holds a false belief. Then the subject answers a question about the thoughts and intentions of that person. Other types of experiments can also be used to study ToM. Villarreal et al. (2012) used videos with people gesturing as stimuli. The subject was tasked with choosing the right intention behind the expression. Gallagher et al. (2002) had the subject play "stone, paper, scissors" with a human opponent. In a meta-analysis of ToM studies, Schurz et al. (2014) found that temporoparietal junction (TPJ), medial prefrontal cortex (mPFC) and precuneus (PC) are consistently associated with ToM.

Jacoby et al. (2016) utilised fMRI to compare three social cognitive tasks for localising the brain regions relevant to ToM and for the perception of physical pain. The tasks were a verbal false-belief story task, a verbal task describing physical pain versus emotional suffering and a passive movie watching task. All of these tasks were successful in localising pain and ToM networks. The movie used in the passive movie watching task was an animated short film "Partly Cloudy" (Pixar Animation Studios 2009). The movie is suitable for studying both observing pain and theory of mind because there are multiple scenes with characters experiencing pain as well as scenes where the viewer is led to think about a character's mental state and feelings. Partly cloudy has been used thereafter for example in studying the development of ToM and pain networks in children (Richardson and Saxe, 2020) (Richardson et al., 2018).

1.2 Love

The strongest social bonds are our relationships with those we love. Love plays an important role in many stages of life. An infant's attachment to caretaker, attachment towards friends and partners as well as a parent's attachment towards their offspring are all examples of different types of love. Love is a subjective feeling that may be defined in many ways. For an example in neuroscience love has been defined by Cacioppo et al. (2012): "the existence of an emotional state involving chemical, cognitive, rewarding and goal-directed behavioral components".

The neurobiological basis of love has been studied during the past decades. These studies suggest that the neurotransmitters oxytocin and vasopressin are essential in developing attachment with others. Oxytocin can reach many parts of the brain in a coordinated way that allows it to regulate multiple social and emotional functions. It is connected with the feeling of safety and selective social behaviour. Vasopressin works as a regulator for oxytocin and together the two molecules enable selective social behaviour like attachment and love (Carter, 2017). Furthermore, dopaminergic reward system plays an important role in the motivation of attachment. Oxytocin is involved in the dopamine pathway in nucleus accumbens and ventral pallidum as the synaptic plasticity is increased through oxytocin signaling (Shih et al., 2022).

As the relevant technology has developed, brain regions involved with romantic and maternal love have been investigated in neuroimaging studies. Bartels and Zeki (2000) compared fMRI scans of subjects looking at pictures of a romantic partner to looking at pictures of friends. Pictures of romantic partners caused increased activity in caudate nucleus and putamen, which are subcortical areas involved with the dopaminergic reward system. Furthermore, increased activity was found in insula and anterior cingulate cortex. Deactivations were found in amygdala and posterior cingulate gyrus. In a similar study Aron et al. (2005) compared fMRI responses of subjects viewing pictures of loved ones and neutral acquaintances. Romantic love was again found to cause higher activity in dopamine rich subcortical areas: caudate nucleus and ventral tegmental area. Bartels and Zeki (2004) conducted a neuroimaging study about maternal love, comparing the results to those of romantic love. fMRI scans were taken with subjects looking at pictures of their own child and an acquainted child of similar age. Maternal love was found to cause activity in similar areas to

romantic love with an addition of periaqueductal gray matter (PAG) that seems to be specific to parental love. In another fMRI study Noriuchi et al. (2008) also found PAG to have increased activity while subjects were looking at videos of their own child compared to videos of unknown children.

1.3 Aims of this Thesis

The goal of this thesis is to find out about the relationship of social brain and love. However, the concept of social brain is broad and hard to define for analysis. In order to conduct focused analysis, this thesis focuses on the theory of mind network. Previous neuroimaging studies of love have focused on maternal and romantic love. In this thesis I examine how the theory of mind network participates in feelings of different types of love. The types of love included are romantic love towards a partner, parent's love towards their child, love towards a friend, compassionate love towards a stranger, owner's love towards a pet and love towards nature. To address the question about the relationship of the theory of mind network and types of love, I analyzed data from two experiments. First, in order to choose regions of interest from the brain, the theory of mind network was localised from the subjects using data from a passive movie watching task. Localising the theory of mind network independently from this set of subjects is important for the reliability of the analysis. From the localised theory of mind network, regions of interest were selected for further analysis. The main experiment was a task with auditory stimuli with stories involving the six different types of love. Average activations during different types of love were calculated in the functionally localised regions of interest. In addition to the fMRI experiments, behavioural data was gathered from the subjects with two questionnaires. Questionnaires about passionate love and compassionate love for humanity were utilized in a correlation analysis to find if the subjects own perception about the scale of emotion corresponds with brain responses during the love story experiment.

2 Materials and Methods

2.1 fMRI data

The data analyzed in this thesis is part of a larger study that examines the neural correlates of love. fMRI data had been collected from 55 participants (29 females, 26 males; aged 20–50). All participants were Finnish-speaking healthy adults with at least one child and a loving relationship.

MRI data had been collected on a 3-T MR scanner at the Advanced Magnetic Imaging Centre of Aalto University in Otaniemi, Espoo. The whole-brain functional volumes had been acquired using a T2*-weighted EPI sequence with imaging parameters: repetition time 852 ms, 60 slices with 3 mm slice thickness, field of view 192 mm × 192 mm, imaging matrix 64 × 64, voxel size 3 × 3 × 3mm^3, echo time 30 ms, and flip angle 55°. Anatomical images with 1×1×1mm^3 voxel size had been collected using a T1-weighted MPRAGE sequence.

The fMRI data had been preprocessed using SPM12 (Wellcome Department of Imaging Neuroscience) Matlab toolbox. The functional images had been corrected for head motion, spatially smoothed using a 6 mm Gaussian smoothing kernel, and spatially normalized to Montreal Neurological Institute standard space.

2.2 Movie watching task

In order to localise the theory of mind network, fMRI scans were collected from the subjects during a passive movie watching task. The experimental design followed the experiment by Jacoby et al. (2016). In the experiment, subjects watched the animated short movie "Partly cloudy" (Pixar Animation Studios). Timings of four different conditions were coded, based on the events of the movie and the expected reaction of the viewer. The conditions were mental, pain, social and control. In the mental condition the viewer is led to think about what a character in the movie is thinking or feeling. In other words, the theory of mind network of the watcher is supposed to activate, for an example when a cloud person falsely believes that a bird person has abandoned it. There were four events with mental condition with a total duration of 44 seconds. The pain condition was marked when a character in the movie experiences physical pain, for an example when a character is bitten by an alligator. Seven events with pain condition had a total duration of 26 seconds. The social condition was marked in events with characters interacting, but with no high emotions, such as a group of cloud people laughing. Five events with social condition had a total duration of 28 seconds. The control condition was marked in scenes with no events involving characters like a shot of the scenery. Three events with control condition had a total duration of 24 seconds. The movie lasted for 5 minutes and 49 seconds with a total of 2 minutes and 2 seconds marked for conditions.

2.3 Love story task

Subjects listened to different types of love stories and control stories while being scanned with fMRI. The types of stories were of love towards romantic partner, child, friend, stranger, pet and nature. Each narrative lasted circa 13–15 seconds and was followed by a 10-second imagery period and a 10-second wash-out period before the next narrative. The experimental design followed the study by Saarimäki et al. (2018). Six different narratives were used for each love category and the control condition. Six fMRI experimental runs were collected that each contained each category once in a pseudorandom order.

2.4 Questionnaires

Subjects filled two questionnaires about love. Passionate love scale by Hatfield and Sprecher (1998) is designed to measure romantic love defined as "a state of intense longing for union with another". The second questionnaire used was a revised short version of the compassionate love for humanity scale (Chiesi et al., 2020).

2.5 Analysis

The analysis was conducted using the SPM12 software package with Matlab. In SPM a general linear model for a single subject is specified based on a design matrix with scans as rows and variables as columns. In this case, the variables were the timings of the stimuli: the conditions in the movie and the stories in the listening task. The onsets and durations of the timings were modeled as boxcar functions. The boxcar model was convolved with a hemodynamic impulse response function to take into account the delay and shape of the slow fMRI response. Beta weights were then estimated for each condition with a restricted maximum likelihood algorithm. Contrast maps were made by conducting t-tests with the beta weights of chosen conditions and each voxel to find where the conditions have statistically meaningful differences. Group level analyses were conducted using contrast images from each subject as data for a second level model using random effect analysis. The social brain was localised with the movie watching experiment. A group level analysis of the contrast mental > pain with $p < 0.05$ was used to create a map of the theory of mind network of the subjects.

Based on the localisation of the theory of mind network, regions of interest (ROIs) were selected to investigate how different types of love affect the social brain. The selected regions were right and left precuneus, right and left temporoparietal junction and right and left middle temporal gyrus. The ROI was defined as the local peak T value of the region and 125 closest voxels (+/- 2 voxels along x, y, and z-axis). For these regions of interest, mean activity was calculated for listening to each each type of love story and control story as well as for an imagery period after the story. Additionally 90% confidence intervals were calculated by creating a student t-distribution using the samples standard deviation and finding the 90% bounds for the distribution. As a result the true mean is between this interval 90% of the time.

Correlation maps were made to find correlation between brain activity during love story task and questionnaires measurement of love. Correlations of passionate and compassionate love measurements were analysed by comparing the results of Passionate Love Scale and the Compassionate Love for Humanity Scale questionnaires to the brain activity during the love story task. For passionate love, the contrast used was activity during listening to stories about love towards a romantic partner compared to control. For compassionate love, the contrast used was activity during listening to stories about love towards a stranger compared to control. For the selected ROIs, a scatter plot was plotted with the mean activity of the ROI during the relevant contrast for each subject and the subject's questionnaire score as variables. Whole-brain correlation analyses were conducted by calculating Pearson correlation and p-value with a permutation test for each voxel. In the permutation test the data was randomly permutated 5000 times and p-value is the percentage of the random permutation with higher correlation than the original. The threshold of the p-value for significant results was set at 0.05. Positive and negative correlations that passed the p-value threshold were mapped to anatomical brain images.

3 Results

3.1 Localising theory of mind network

Figure 1 shows the whole-brain image of the theory of mind network localised with group analysis from the 'mental > pain' contrast of the movie watching experiment. Peak T values with their coordinates and brain regions are listed in Table 1. Notable brain regions located include precuneus in the superior parietal lobule, temporoparietal junction bilaterally and middle temporal gyrus bilaterally. These results are similar to those of Jacoby et al. (2016) achieved with the same experimental design. As a difference, here precuneus has distinct peaks on the right and on the left hemispheres. Ventral medial prefrontal cortex and dorsal medial prefrontal cortex were included in further analysis despite having slightly lower peak T values due to them being significant parts of theory of mind network according to Jacoby et al. (2016) and the meta-analysis of Schurz et al. (2014).

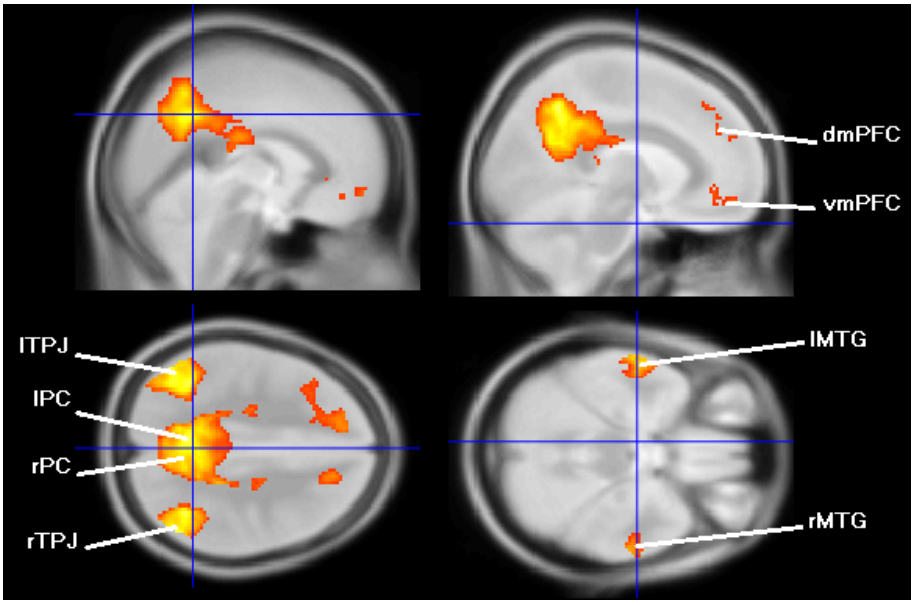

Figure 1: Theory of mind network. The brain regions of the theory of mind network were localized from the passive movie watching experiment using the contrast 'mental > pain'. Images uncorrected with $p < 0.005$. Images are cross sections of the brain: x = 0, y = -52, z = 38 on the left and x = -8, y = -8, z = -26 on the right.

Table 1: Active brain regions in the theory of mind contrast (mental > pain, $p < 0.001$, coordinates in mm).

Region	Coordinates (X, Y, Z)	Peak T
Left precuneus (lPC)	-4, -56, 38	7.20
Right precuneus (rPC)	10, -54, 28	6.97
Left temporoparietal junction (lTPJ)	-46, -62, 32	7.27
Right temporoparietal junction (rTPJ)	50, -58, 34	6.89
Left middle temporal gyrus (lMTG)	-56, -4, -30	5.54
Right middle temporal gyrus (rMTG)	62, -12, -22	5.22
Ventral medial prefrontal cortex (vmPFC)	-4, 54, -12	3.78
Dorsal medial prefrontal cortex (dmPFC)	-12, 50, 26	3.26

3.2 ToM network response to different types of love

The eight ROIs selected from the ToM network (table 1) were analysed to find how the ToM network is involved with feelings of different types of love. Figures 2, 4, 6, 8, 10, 12, 14 and 16 show the locations of each ROI. Figures 3, 5, 7, 9, 11, 13, 15 and 17 show the mean activity and the 90% confidence interval of the mean of the ROI during listening and imagery periods of each type of love story. Overall, the activity was higher during romantic love, parental love and love towards a friend. Love towards a pet and love towards nature had lowest responses in almost all ROIs. Generally the response during the imagery period follows the same pattern as the response during listening, but the responses are clearly lower.

3.2.1 Left precuneus

In lPC the activation was highest during love towards a friend condition, with activity during love towards a stranger, a pet and nature being significantly lower. However only condition to differ from control with 90% confidence is the imagery of love towards a friend.

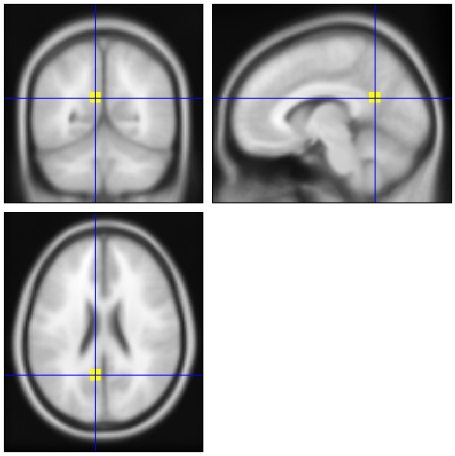

Figure 2: Location of lPC ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = -4, Y = -56, Z = 38.

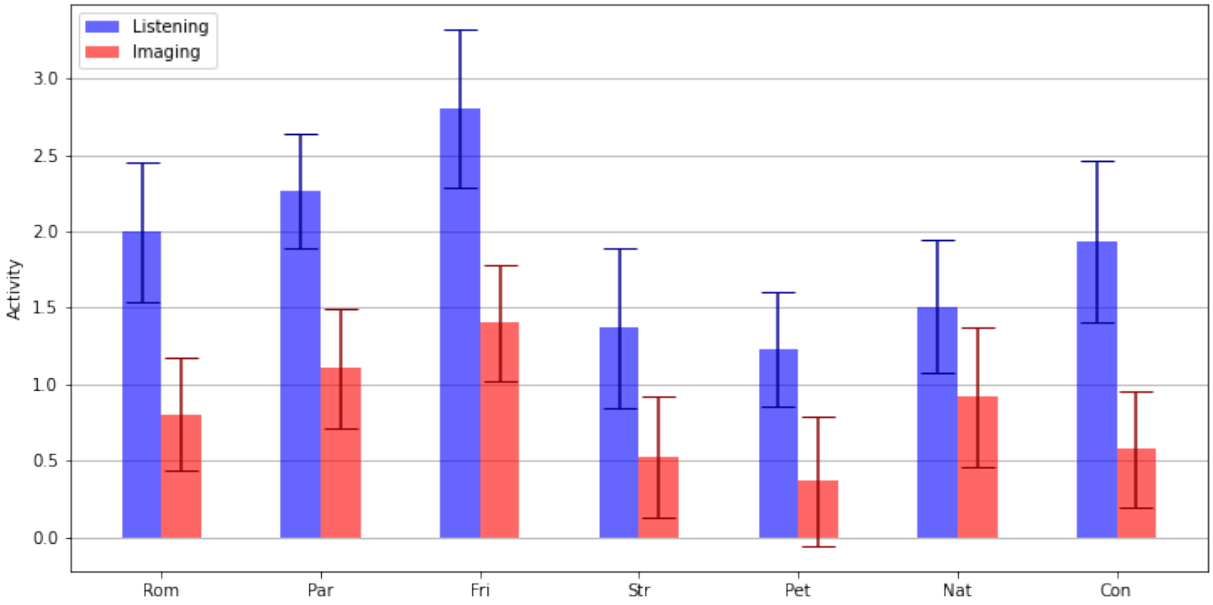

Figure 3: Mean activity of lPC during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.2 Right precuneus

In rPC there is a clear difference between the first three and the other conditions. Love towards nature has deactivation during both both listening and imagery, while love towards a pet and control have deactivations during the imagery period.

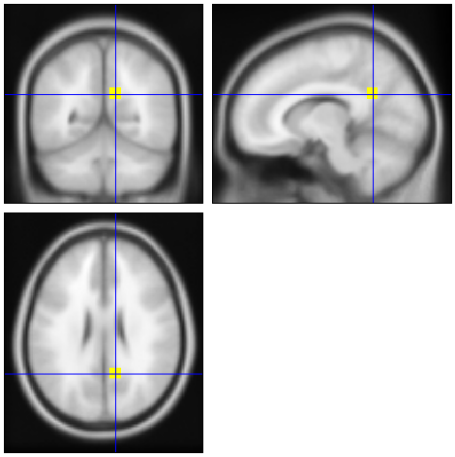

Figure 4: Location of rPC ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = 10, Y = -54, Z = 28.

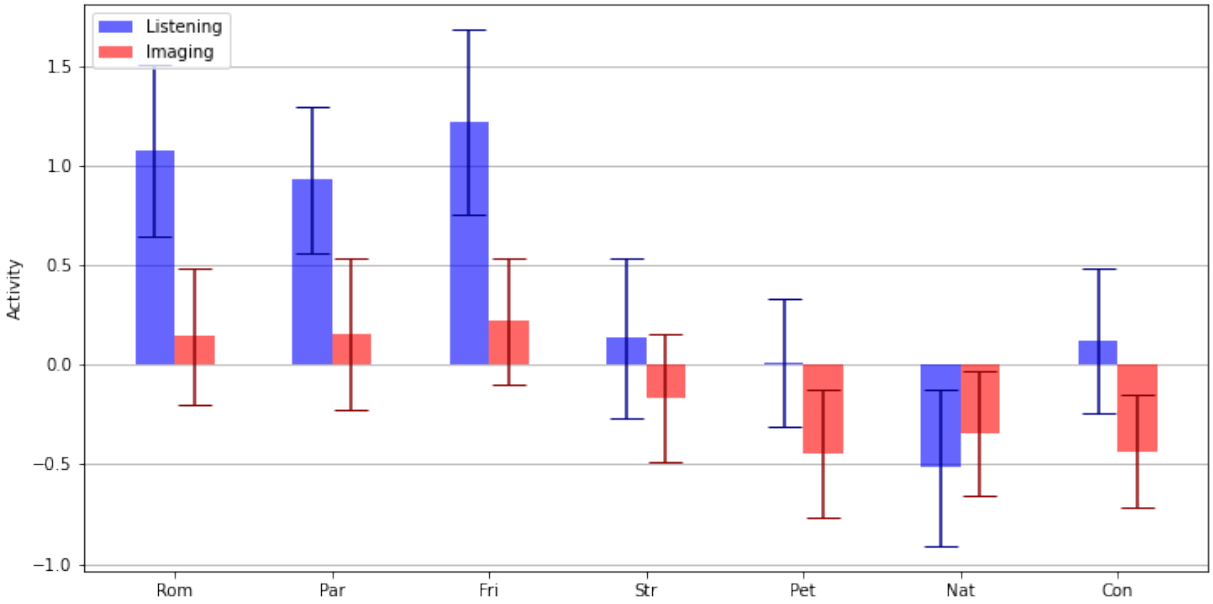

Figure 5: Mean activity of rPC during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.3 Left temporoparietal junction

In lTPJ love towards a stranger has high activation along with the first three conditions, all of them having significantly higher activation than control in the listening period.

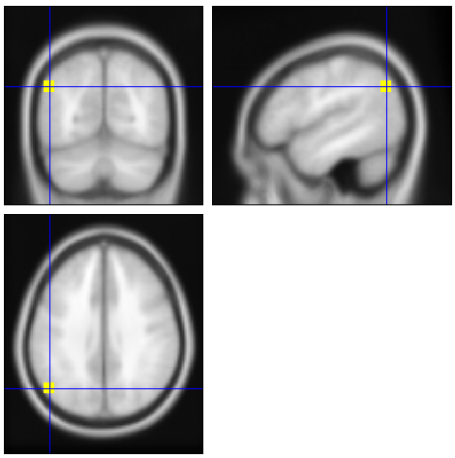

Figure 6: Location of lTPJ ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = -46, Y = -62, Z = 32.

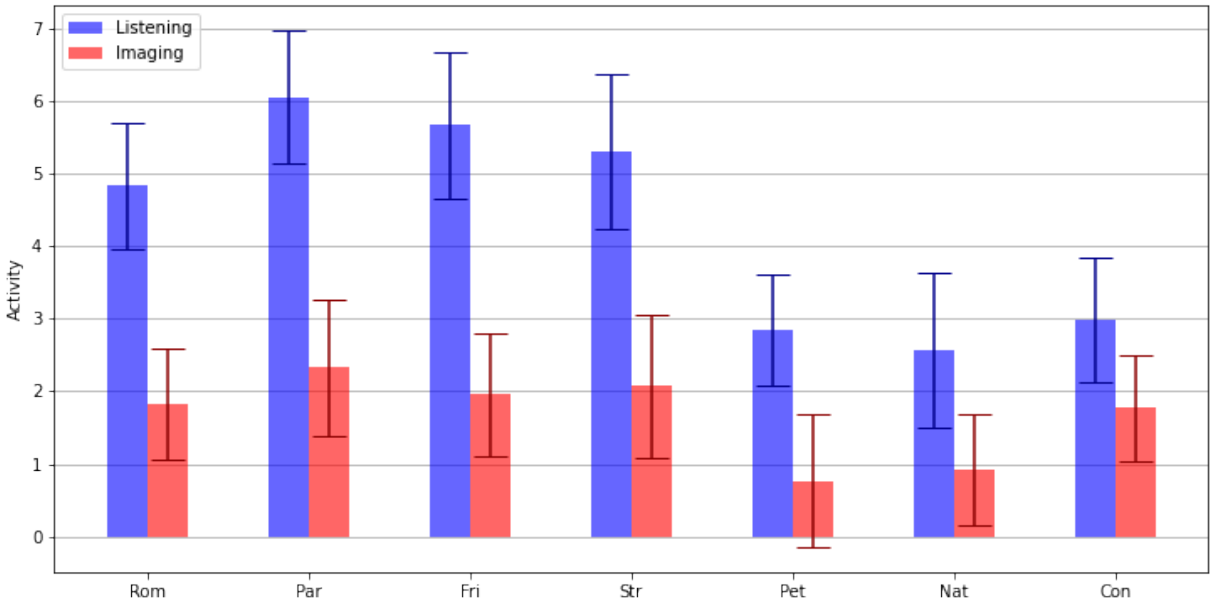

Figure 7: Mean activity of lTPJ during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.4 Right temporoparietal junction

In rTPJ the differences between the types of love are less significant. Still, the first three listening conditions have higher mean activation. Overall the activations during imagery periods are low, with clear deactivation during love towards a stranger, a pet and nature.

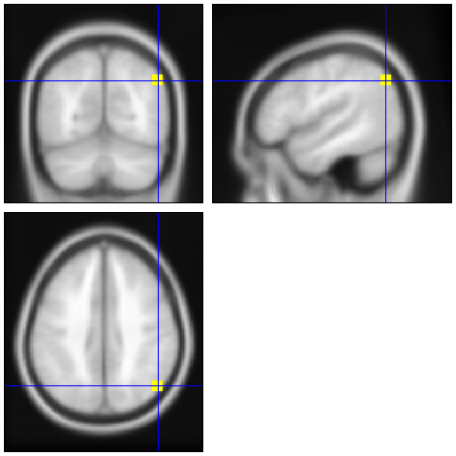

Figure 8: Location of rTPJ ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = 50, Y = -58, Z = 34.

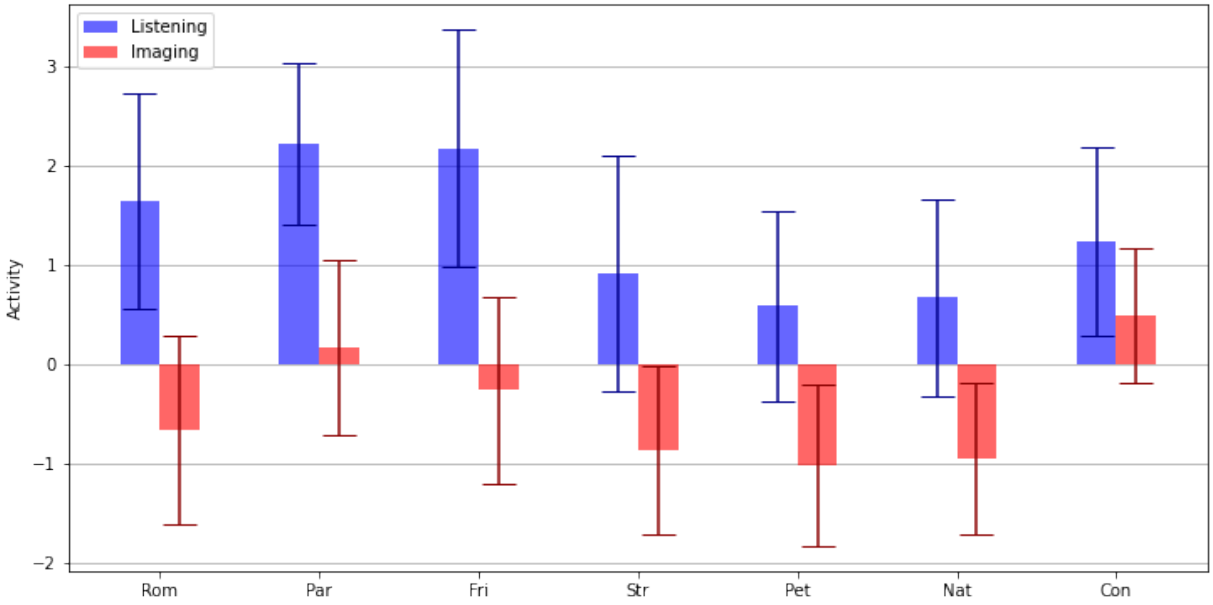

Figure 9: Mean activity of rTPJ during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.5 Left middle temporal gyrus

In lMTG love towards a stranger is again higher than love towards a pet or nature along with the first three conditions. However no condition differs from the control with 90% confidence.

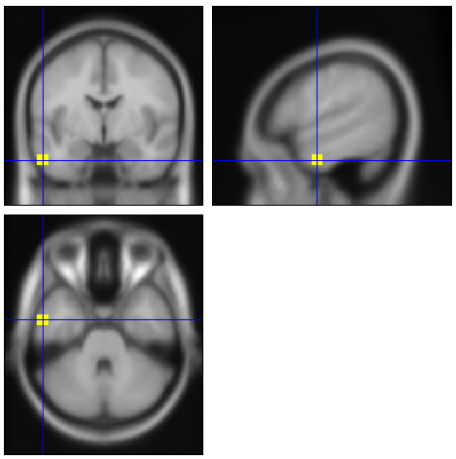

Figure 10: Location of lMTG ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = -56, Y = -4, Z = -30.

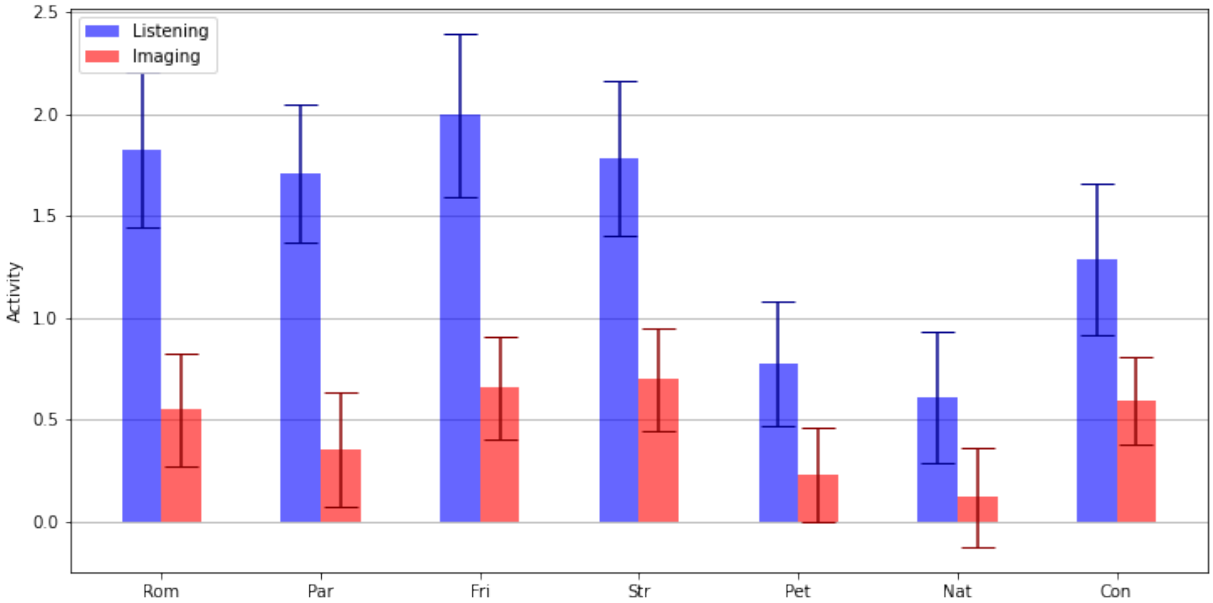

Figure 11: Mean activity of lMTG during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.6 Right middle temporal gyrus

In rMTG the differences between types of love are smaller, with love towards nature having lowest activation. However the activations during imagery periods are very low, every love condition having lower mean activation than control.

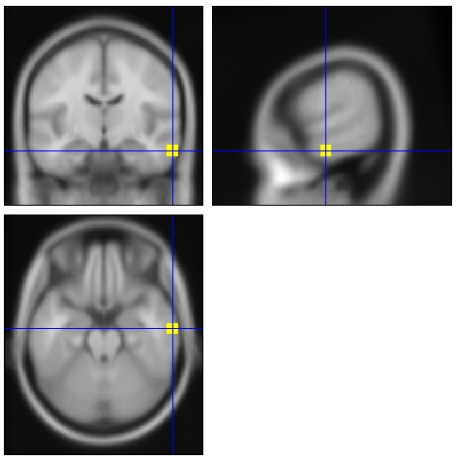

Figure 12: Location of rMTG ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = 62, Y = -12, Z = -22.

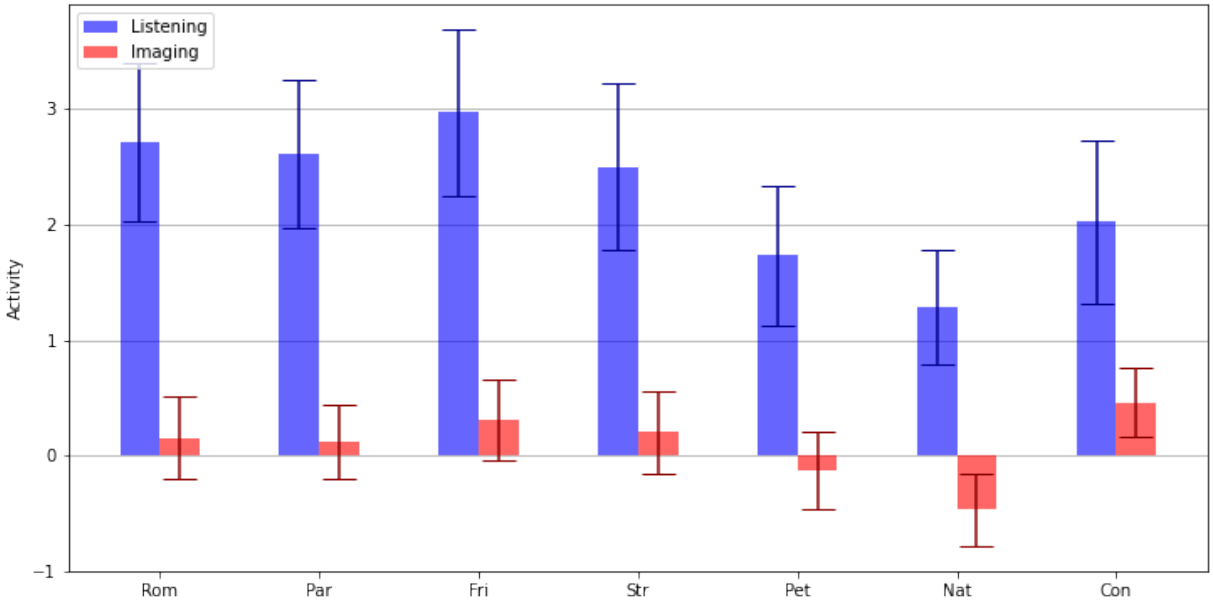

Figure 13: Mean activity of rMTG during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.7 Ventral medial prefrontal cortex

In vmPFC love towards a romatic partner, parent's love towards a child and love towards a friend have clearly the highest activations. Every love condition has activity clearly higher than zero. The activations during imagery periods are relatively high compared to the listening period.

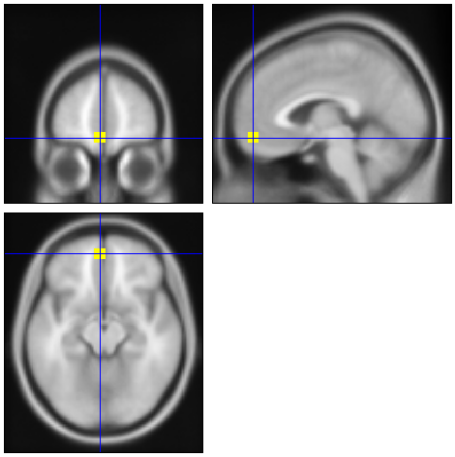

Figure 14: Location of vmPFC ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = -4, Y = 54, Z = -12.

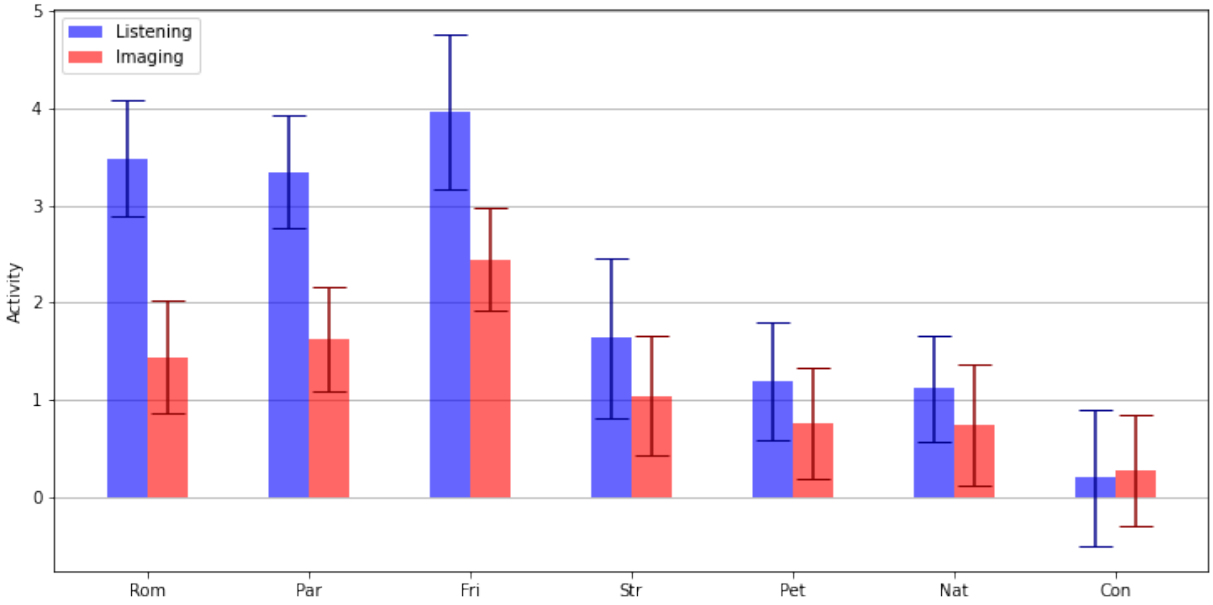

Figure 15: Mean activity of vmPFC during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.2.8 Dorsal medial prefrontal cortex

In dmPFC love towards a stranger and love towards a pet are relatively high compared to the other ROIs. Similarly to vmPFC, the activations during imagery periods are relatively high.

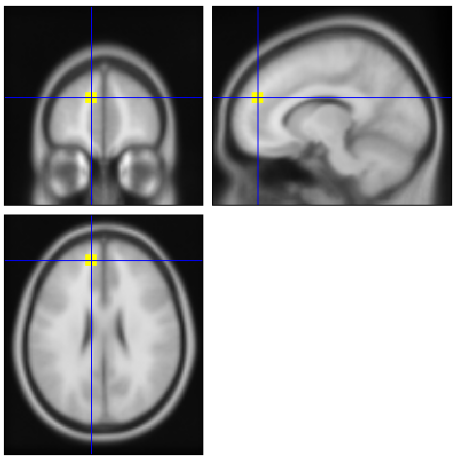

Figure 16: Location of dmPFC ROI. Size of ROI is 125 voxels. Coordinates of center voxel: X = -12, Y = 50, Z = 26.

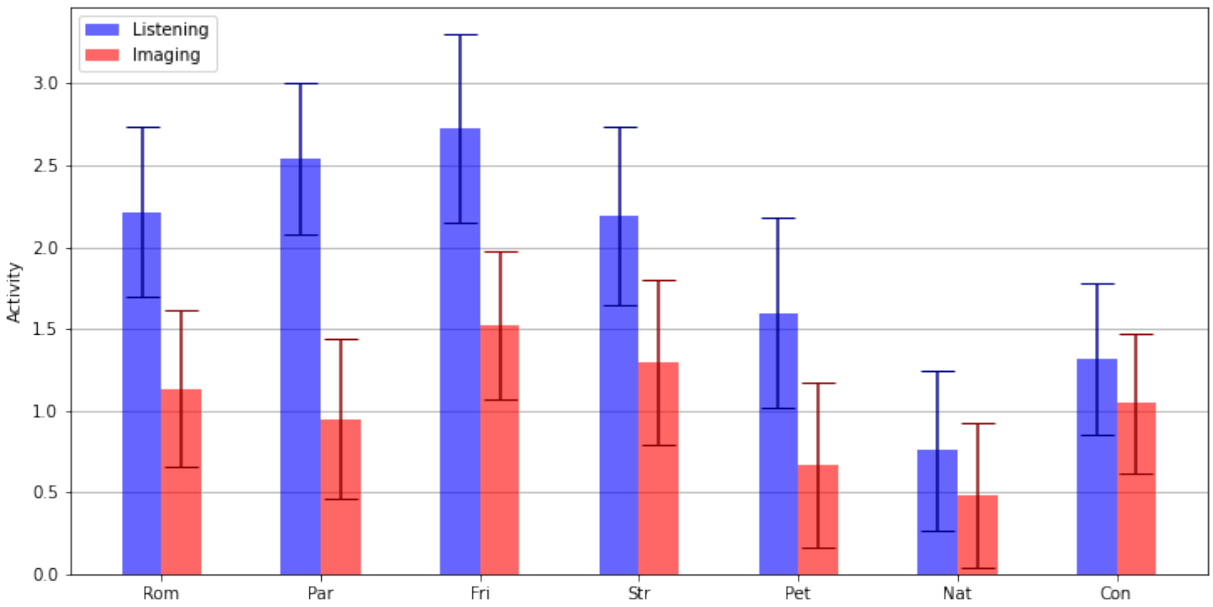

Figure 17: Mean activity of dmPFC during different types of love stories. 90% confidence interval is marked around the mean. Blue bars represent activity during listening phase and red bars represent activity during imagery phase. Abbreviations: Rom, love towards romantic partner; Par, parent's love towards a child; Fri, love towards a friend; Str, love towards a stranger; Pet, love towards a pet; Nat, love towards nature; Con, Control.

3.3 Correlation between questionnaire results and fMRI images of passionate and compassionate love

3.3.1 Regions of interest

In the ROIs of the ToM network, there were no significant correlations between the results of Passionate Love Scale and mean activity during listening to stories with love towards a romantic partner compared to the control condition. Three ROIs had significant negative correlations between the results of Compassionate Love for Humanity Scale and mean activity during listening to stories with love towards a stranger compared to the control condition. In rTPJ the correlation was -0.2884 with a p-value 0.0342, in dmPFC the correlation was -0.3100 with a p-value 0.0216 and in vmPFC the correlation was -0.2629 with a p-value of 0.0444. Figures 18, 19 and 20 show the scatter plots of these variables in the ROIs.

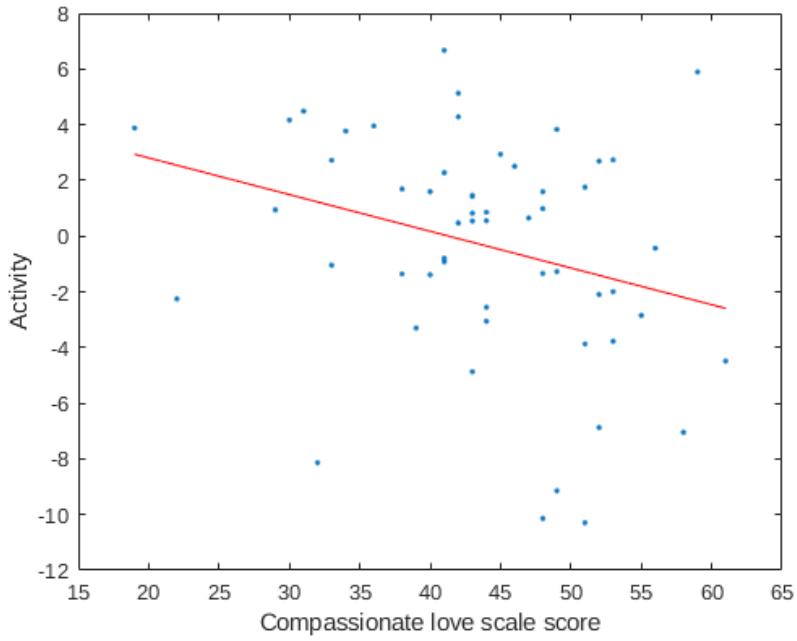

Figure 18: Scatter plot of compassionate love scale score and activity of rTPJ during love towards stranger contrast is shown. The blue dots show the individual data points and the red line shows the line fitted to these points.

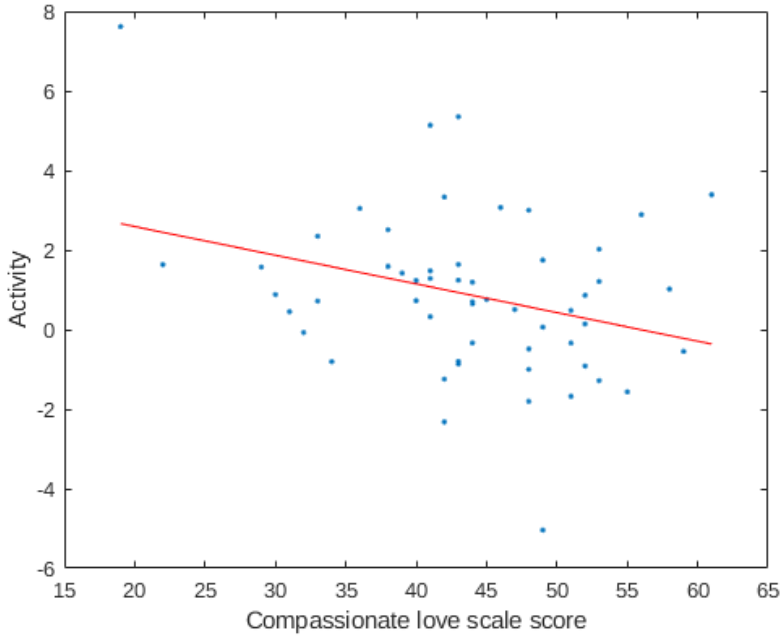

Figure 19: Scatter plot of compassionate love scale score and activity of dmPFC during love towards stranger contrast is shown. The blue dots show the individual data points and the red line shows the line fitted to these points.

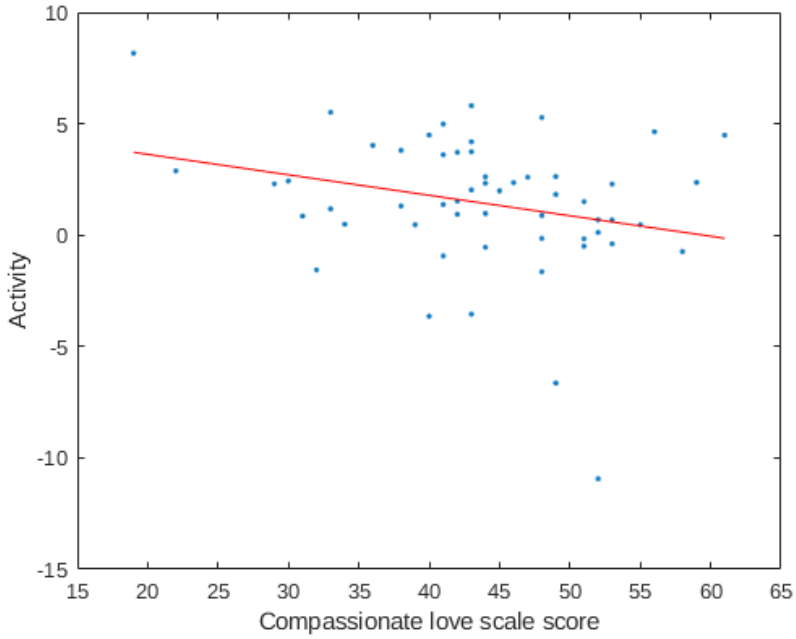

Figure 20: Scatter plot of compassionate love scale score and activity of vmPFC during love towards stranger contrast is shown. The blue dots show the individual data points and the red line shows the line fitted to these points.

3.3.2 Whole-brain correlation maps

Figures 21, 22 and 23 show the whole-brain map of the correlations between measurements of passionate and compassionate love and the overlap between them. Pearson correlation was calculated for each voxel and the maps show voxels with correlation that pass the $p < 0.05$ threshold of the permutation test projected onto an anatomical brain map. A lot of the positive correlations are in white matter and ventricles. However both passionate and compassionate love have some significant positive correlation in the caudate nucleus. In comapssionate love correlation map, despite not passing the p-value threshold in the ROI correlation analysis, there are some voxels with significant negative correlations in PC, lTPJ, MTG bilaterally, and mPFC.

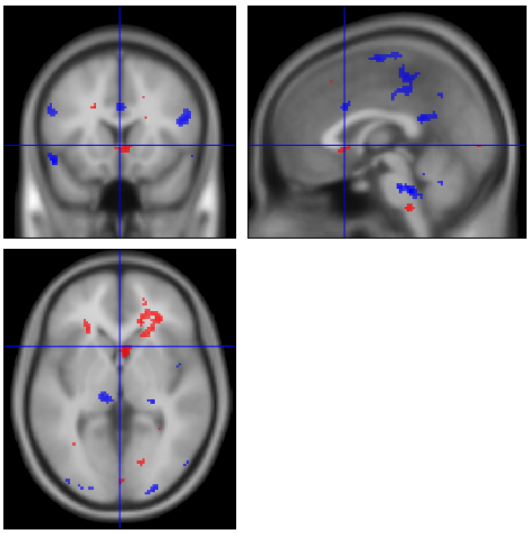

Figure 21: Voxels with significant correlations between the passionate love questionnaire and the fMRI results of romantic love love are projected onto an anatomical brain image. Shown correlations passed $p < 0.05$ threshold of permutation test. Positive correlations are marked with red and negative correlations with blue. Crosshair is positioned at $x = 0$, $y = 15$, $z = 0$ mm.

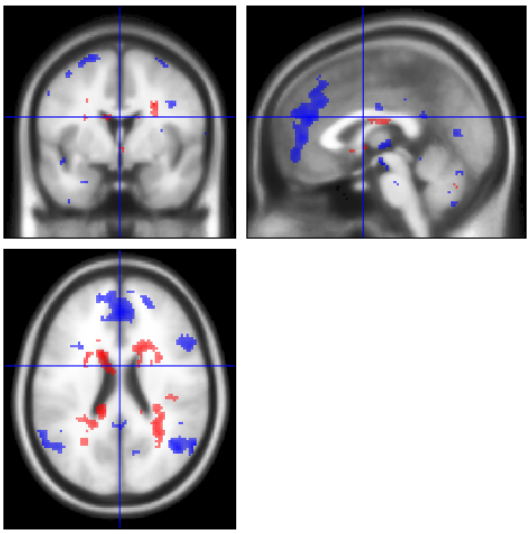

Figure 22: Voxels with significant correlations between the compassionate love questionnaire and fMRI results of compassionate love are projected onto an anatomical brain image. Shown correlations passed $p < 0.05$ threshold of permutation test. Positive correlations are marked with red and negative correlations with blue. Crosshair is positioned at x = 0, y = 0, z = 22 mm.

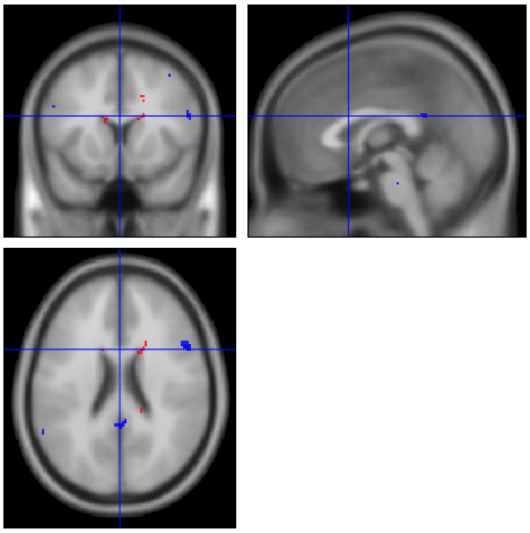

Figure 23: Voxels where correlations between the passionate love questionnaire and the fMRI results of romantic love and the compassionate love questionnaire and fMRI results of compassionate love overlap are projected onto an anatomical brain image. Shown voxels passed $p < 0.05$ threshold of permutation test for both correlations. Red voxels had positive correlations and blue voxels had negative correlations in both passionate and compassionate love results. Crosshair is positioned at x = 0, y = 12, z = 22 mm.

4 Discussion

Voxels where correlations between the passionate love questionnaire and the fMRI results of romantic love and the compassionate love questionnaire and fMRI results of compassionate love overlap

The aim of this thesis was to investigate the role of ToM network in feeling different types of love. In order to achieve this, first I localized the ToM network with data from an animated movie watching fMRI experiment. The localised ToM network matched the network that was localised by Jacoby et al. (2016) with the same experiment. Localising the ToM network independently was required to have reliable and independent results for further analysis with this group of subjects. Eight ROIs were chosen around peak T values from the movie watching tasks 'mental > pain' contrast. These ROIs are all involved in ToM, but have unique functional roles in it.

Precuneus is a highly connected region of the brain. It is involved in the default mode network, that is active while a person is awake and aware but not focused on a specific task, and central executive network (Dadario and Sughrue, 2023). Furthermore precuneus is involved in complex cognitive functions. It is consistently found to be involved in ToM. One of it's functions is the mental imagery of another person's mental state (Schurz et al., 2014).

Temporoparietal junction has been connected with self-awareness and false belief reasoning (Schurz et al., 2014). Left temporoparietal junction has been shown to be more involved with social interaction where as right temporoparietal junction is also involved in attention shifting (Krall et al., 2015). This fits with results of the love story experiment where lTPJ has more significant differences to control when listening to stories about love towards other humans.

Middle temporal gyri are part of the anterior temporal lobes. Anterior temporal lobes have a function in social semantic concepts, allowing efficient social interaction (Schurz et al., 2014). Middle temporal gyrus bilaterally is also consistently involved in ToM false-belief tasks (Van Veluw and Chance, 2014).

Medial prefrontal cortex is involved in the processing of social information (Schurz et al., 2014). mPFC seems to be less involved in processing beliefs and more about evaluating others based on social properties. Additionally, mPFC is involved in decision making and choosing the right motoric and emotional reaction to different situations (Euston et al., 2012).

As the main analysis, the response of these ROIs to different types of love was analysed. Conditions for this analysis were listening to six different types of love stories and control stories and an imagery period after each story. The types of love in the stories were love towards romantic partner, child, friend, stranger, pet and nature. The mean activity was compared between the different love conditions for each ROI. While many of the differences between the conditions were not greater than the 90% confidence interval, similar patterns between the ROIs strengthen the observations. The imagery periods had clearly lower activations than the listening periods, which is reasonable because the feelings evoked by the stories are strongest while the listening to the story and diminish with time. A robust pattern can be observed where love towards a romantic partner, parent's love towards a child and love towards a friend

had the highest activations in the ToM network. These conditions are all about love towards another human, which suggests that ToM is used more when one feels love towards another human being. Further research could be conducted to find if pet owners have higher ToM network response to love towards a pet than non pet owners. Love towards a stranger has high activation along with the other conditions with love towards a person in lTPJ, lMTG, rMTG and dmPFC. This suggests that these parts of the ToM network are more involved with social tasks that involve people one does not personally know.

The results from the love story task were compared to questionnaire results from Passionate Love Scale and Compassionate Love for Humanity scale. Positive correlations in both passionate and compassionate love measurements were observed in the caudate nucleus region. Caudate nucleus has been found to be involved in passionate love (Bartels and Zeki, 2000) as well as compassionate love (Klimecki and Singer, 2017). This result suggests that people who feel love strongly, have increased response in caudate nucleus to feeling both passionate and compassionate love. Negative correlations were observed between the compassionate love scale score and activity during love towards a stranger in almost every ROI in the ToM network. A speculative reason for this could be that compassionate people feel love towards unknown people more easily and with less conditions about the mind of the stanger. This means that caring about a stranger requires less involvement from ToM network that is used to decipher the thoughts and intentions of others.

A limitation in this thesis was the method of determining the regions of interest. The ROIs were determined as the 125 closest voxels of the peak activation in the mental > pain condition of the movie watching task. With this method, a ROI is a cube around the peak activation regardless of whether the voxels had significant activity in the localizer condition. This is a simple way of choosing the ROIs, but could extend the ROI outside the functional region of the brain and leave out some voxels that could be relevant to the desired region. This method may have caused some variation in the analysis of the ROIs. A better would be to determine the ROIs as voxels within certain distance of the peak activation that had significant activity in the localiser condition.

5 Conclusion

In this thesis the theory of mind network was localised from the group of subjects with data from fMRI movie watching experiment. Eight regions of interest were chosen from the network. Activity of these regions of interest during different types of love was analysed with data from an fMRI love story experiment. The activity in the regions of interest was consistently higher during listening to stories about love towards a romantic partner, parents love towards a child and love towards a friend. Along with these, listening to stories about love towards a stranger caused higher activation in lTPJ, lMTG, rMTG and dmPFC. Finally correlations between subjects' brain activity during listening to stories about romantic love and scores of passionate love scale were analysed as well as correlations between subjects' brain activity during listening to stories about love towards a stranger and scores of compassionate love for humanity scale. Notably both types of correlations were observed in caudate nucleus. Furthermore negative correlations between the compassionate love scale score and activity during love towards a stranger were observed in most of the regions of interest in the theory of mind network.

References

Aron, A., Fisher, H., Mashek, D. J., Strong, G., Li, H., and Brown, L. L. (2005). Reward, motivation, and emotion systems associated with early-stage intense romantic love. *Journal of neurophysiology*, 94(1):327–337.

Bartels, A. and Zeki, S. (2000). The neural basis of romantic love. *Neuroreport*, 11(17):3829–3834.

Bartels, A. and Zeki, S. (2004). The neural correlates of maternal and romantic love. *Neuroimage*, 21(3):1155–1166.

Cacioppo, S., Bianchi-Demicheli, F., Hatfield, E., and Rapson, R. L. (2012). Social neuroscience of love. *Clinical Neuropsychiatry*, 9(1).

Carter, C. S. (2017). The role of oxytocin and vasopressin in attachment. *Psychodynamic Psychiatry*, 45(4):499–517.

Chiesi, F., Lau, C., and Saklofske, D. H. (2020). A revised short version of the compassionate love scale for humanity (cls-h-sf): evidence from item response theory analyses and validity testing. *BMC psychology*, 8(1):1–9.

Dadario, N. B. and Sughrue, M. E. (2023). The functional role of the precuneus. *Brain*.

Dunbar, R. I. (1998). The social brain hypothesis. *Evolutionary Anthropology: Issues, News, and Reviews: Issues, News, and Reviews*, 6(5):178–190.

Euston, D. R., Gruber, A. J., and McNaughton, B. L. (2012). The role of medial prefrontal cortex in memory and decision making. *Neuron*, 76(6):1057–1070.

Gallagher, H. L., Jack, A. I., Roepstorff, A., and Frith, C. D. (2002). Imaging the intentional stance in a competitive game. *Neuroimage*, 16(3):814–821.

Gauthier, I., Tarr, M. J., Moylan, J., Skudlarski, P., Gore, J. C., and Anderson, A. W. (2000). The fusiform "face area" is part of a network that processes faces at the individual level. *Journal of cognitive neuroscience*, 12(3):495–504.

Hari, R., Henriksson, L., Malinen, S., and Parkkonen, L. (2015). Centrality of social interaction in human brain function. *Neuron*, 88(1):181–193.

Hatfield, E. and Sprecher, S. (1998). The passionate love scale. *Handbook of sexuality-related measures*, 449:451.

Jacoby, N., Bruneau, E., Koster-Hale, J., and Saxe, R. (2016). Localizing pain matrix and theory of mind networks with both verbal and non-verbal stimuli. *Neuroimage*, 126:39–48.

Kanwisher, N., McDermott, J., and Chun, M. M. (1997). The fusiform face area: a module in human extrastriate cortex specialized for face perception. *Journal of neuroscience*, 17(11):4302–4311.

Klimecki, O. M. and Singer, T. (2017). The compassionate brain. *The Oxford handbook of compassion science*, 1:109–120.

Krall, S. C., Rottschy, C., Oberwelland, E., Bzdok, D., Fox, P. T., Eickhoff, S. B., Fink, G. R., and Konrad, K. (2015). The role of the right temporoparietal junction in attention and social interaction as revealed by ale meta-analysis. *Brain Structure and Function*, 220:587–604.

Kriegeskorte, N., Formisano, E., Sorger, B., and Goebel, R. (2007). Individual faces elicit distinct response patterns in human anterior temporal cortex. *Proceedings of the National Academy of Sciences*, 104(51):20600–20605.

Lee, J., Quintana, J., Nori, P., and Green, M. F. (2011). Theory of mind in schizophrenia: exploring neural mechanisms of belief attribution. *Social neuroscience*, 6(5-6):569–581.

Noriuchi, M., Kikuchi, Y., and Senoo, A. (2008). The functional neuroanatomy of maternal love: mother's response to infant's attachment behaviors. *Biological psychiatry*, 63(4):415–423.

Richardson, H., Lisandrelli, G., Riobueno-Naylor, A., and Saxe, R. (2018). Development of the social brain from age three to twelve years. *Nature communications*, 9(1):1–12.

Richardson, H. and Saxe, R. (2020). Development of predictive responses in theory of mind brain regions. *Developmental science*, 23(1):e12863.

Rizzolatti, G., Fadiga, L., Gallese, V., and Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive brain research*, 3(2):131–141.

Saarimäki, H., Ejtehadian, L. F., Glerean, E., Jääskeläinen, I. P., Vuilleumier, P., Sams, M., and Nummenmaa, L. (2018). Distributed affective space represents multiple emotion categories across the human brain. *Social cognitive and affective neuroscience*, 13(5):471–482.

Saxe, R. and Kanwisher, N. (2003). People thinking about thinking people: the role of the temporo-parietal junction in "theory of mind". *Neuroimage*, 19(4):1835–1842.

Schurz, M., Radua, J., Aichhorn, M., Richlan, F., and Perner, J. (2014). Fractionating theory of mind: a meta-analysis of functional brain imaging studies. *Neuroscience & Biobehavioral Reviews*, 42:9–34.

Shih, H.-C., Kuo, M.-E., Wu, C. W., Chao, Y.-P., Huang, H.-W., and Huang, C.-M. (2022). The neurobiological basis of love: A meta-analysis of human functional neuroimaging studies of maternal and passionate love. *Brain Sciences*, 12(7):830.

Van Veluw, S. J. and Chance, S. A. (2014). Differentiating between self and others: an ale meta-analysis of fmri studies of self-recognition and theory of mind. *Brain imaging and behavior*, 8:24–38.

Villarreal, M. F., Fridman, E. A., and Leiguarda, R. C. (2012). The effect of the visual context in the recognition of symbolic gestures. *PloS one*, 7(2):e29644.