Association Between Individual Differences in Self-Generated Thought and Morphology of Gray Matter Structures

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Abstract

This thesis will be looking to see if there are any correlations between the volume of gray matter of various brain regions with the content of stimulus-independent thought, thought that doesn’t arise from external stimulus. This was done by administering a thought-sampling task to participants asking about their eight most common thoughts and probing them about the content of those thoughts on a variety of categories. The volume of gray matter was obtained through MRI, and six regions of interest were looked at specifically. Three of those regions are a part of the default mode network, which is a network of brain regions that are known to be more active when the brain is involved in internal mentation rather than processing external stimuli. The other three regions are not part of the default mode network but have functions that could be related to stimulus-independent thought. Significant results were found for only two regions, the precuneus and the anterior midcingulate cortex, both of which are a part of the default mode network. Both regions had positive correlations with measures of the emotional valence of the participants’ thoughts, more specifically greater brain volume was associated with a greater degree of positively valenced thoughts.

1. Introduction

1.1 Stimulus-Independent Thoughts

Stimulus-independent thought refers to thoughts that arise due to intrinsic changes within an individual rather than thought driven by external cues and changes that are occurring in the environment around the individual (Smallwood & Schooler, 2015). There are many benefits associated with stimulus-independent thoughts, including problem solving, processing of memories, emotional regulation, and decision making (Christoff et al., 2011; Smallwood et al., 2006). While associated with many benefits, stimulus-independent thought can also be associated with cons, including overthinking, cognitive dissonance, and inability to focus on the task at hand (Killingsworth & Gilbert, 2010; McVay & Kane, 2010). In addition, impairments in stimulus-independent thought are the basis of many mental health disorders that are seen in today's society, including repetitive negative thinking and rumination that is seen in depression and anxiety (Ehring et al., 2011; Harvey et al., 2004). The content of stimulus-independent thought is also thought to play a role in whether people are able to reap the benefits of their thoughts, or if they are left with the obstacles that they pose (Smallwood & Andrews-Hanna, 2013). Doing research on this topic can help us to better understand the brain regions involved in these mental health disorders, and maybe allow us to know how to better obtain all the benefits we can out of our thoughts (Rahrig et al., 2022). These investigations may allow for more personalized and modern treatment of these disorders.

Although the content of stimulus-independent thought is something that hasn't been studied quite as much, it is something that is still very important, and will allow us to make many positive impacts on society the more we are able to understand how it works. Repetitive stimulus-independent thoughts can be associated with both working through trauma, and improving mental health outcomes (Pennebaker, 1997), but also has been associated with the prediction of future depression (Ingram, 1990). It is possible that harnessing the positive aspects of these stimulus-independent thoughts can help people with these types of disorders.

Most people, when asked about their self-generated thoughts, rated them as highly personally significant, goal-oriented, and as having strong personal value. Based on this, it has been hypothesized that the basis of human thought relies heavily on personal concerns of the individual (Andrews-Hanna et al., 2013; Stawarczyk et al., 2013).

The content regulation hypothesis is one that states that the relationship between the content of stimulus-independent thought and psychological well-being depends on how the person is able to regulate their thoughts, with the goal being to maximize thoughts with a productive outcome, and minimize those with harmful effects (Andrews-Hanna et al., 2014; Smallwood & Andrews-Hanna, 2013). A previous study has shown that people who have thoughts that are more personally significant, more negative, and less detailed/specific showed higher levels of poor psychological wellbeing and psychopathology. Conversely, people whose thoughts are less personally significant, more positive, and more specific had higher levels of better psychological wellbeing and less psychopathology (Andrews-Hanna et al., 2013). In the current study, we will be utilizing a thought sampling method based on this study (see Methods).

Researchers have also investigated which brain regions might be associated with and involved in stimulus-independent thought. The default mode network (DMN) is a network of regions in the brain that have been found to be involved in internal mentation processes, with specific subsystems in this network contributing to different functions of cognition (Andrews-Hanna et al., 2010). The main regions that are associated with the default network of the brain include the ventral medial prefrontal cortex, the posterior cingulate cortex, the inferior parietal lobule, the lateral temporal cortex, the dorsal medial prefrontal cortex, and the hippocampal formation (Buckner et al., 2008). These regions are shown below in figure 1, which is a figure from Andrews-Hanna et al., 2010 describing the structure of the DMN.

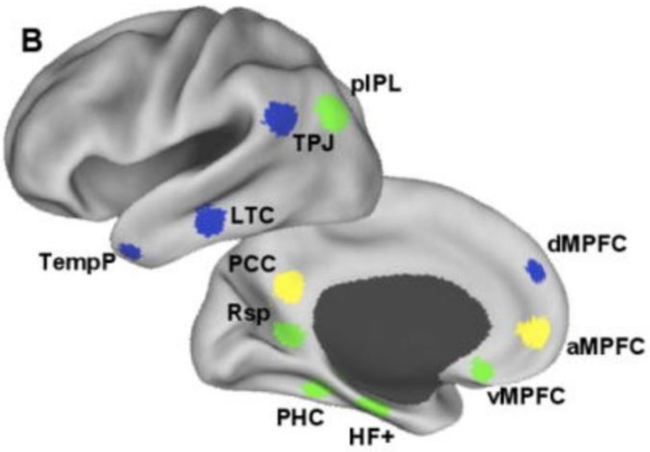


Figure 1: Regions of the Default Mode Network. This figure from Andrews-Hanna et al., 2010 shows the locations of the main regions that are a part of the default mode network. Abbreviations: PCC = Posterior Cingulate Cortex, pIPL = posterior inferior parietal lobule, TPJ = temporoparietal junction, LTC = lateral temporal cortex, TempP = temporal pole, Rsp = retrosplenial cortex, PHC = parahippocampal cortex, HP+ = hippocampal formation, vMPFC = ventral medial prefrontal cortex, aMPFC = anterior medial prefrontal cortex, dMPFC = dorsal medial prefrontal cortex.

The current study wanted to see if the content of stimulus-independent thoughts is correlated with the size of gray matter in certain brain regions, most notably those that are portions of the DMN. Regions that are both in the DMN and others not in the DMN were included in the study. Regions not in the DMN were included in the study to broaden the scope of the study, to see if there were any additional regions that are involved in this type of thought that hadn't previously been looked at. The regions below were selected because they have known functions that could be related to stimulus-independent thought, and this study wanted to see if those functions played a role in the morphology of those regions.

1.2 Regions of Interest for the Current Study

In this portion of the paper, we discuss the various brain regions that we examined and our reasons for thinking that their neuroanatomical characteristics might be related to stimulus-independent thoughts.

Various regions of the default mode network were examined in the present study. These regions include the anterior midcingulate cortex (aMCC) [BA 24, 32, 33], the posterior midcingulate cortex (pMCC) [BA 24, 32], and the precuneus [BA 7, 31].

The aMCC, which is found in the ventral medial prefrontal cortex has a wide variety of functions, including emotional processing, negative affect, and reward-based decision-making (Bush et al., 2002; Lindquist et al., 2012; Sheth et al., 2012; Spunt et al., 2012; Touroutoglou et al., 2020). Based on this, there is good reason to believe that this region may be involved in stimulus-independent thought considering that stimulus-independent thought is generally involved in predictions and decision-making.

The pMCC [BA 24, 32] has been shown to be less active when the brain is actively involved in an activity, and more active when there is no external stimuli directly at hand, suggesting that it could play a role in stimulus-independent thought (Hahn et al., 2007; Mason et al., 2007). The posterior cingulate cortex may play a role in memory by virtue of its linkage to the hippocampus, and autobiographical memory (Buckner et al., 2008; Leech & Sharp, 2014). It has also been seen to be coactivated with the insula (Vega et al., 2016), which is a region of interest in the current study, and will be discussed below. Due to these reasons, this region could be involved in stimulus-independent thought, including thoughts of the self, and memories.

The precuneus [BA 7, 31] was also included because it shares many connections with surrounding regions that allow the brain to integrate much of its internal and external stimuli (Buckner et al., 2008; Cavanna & Trimble, 2006). In previous research, it was also found that higher levels of anxious apprehension, which is a measure of worry and repetitive negative thinking, correlated with lower thickness of the left precuneus in adolescents (Smolker et al., 2022). These findings go well with the topic of interest that we are looking at and make the precuneus an interesting region to add to the analysis.

The next regions of interest that are included in the current study were the inferior and superior frontal gyri which are in the cognitive control network (Li et al., 2013). The left side inferior frontal gyrus (IFG) [BA 44, 45, 47] is typically associated with supporting language and speech (Friederici, 2011). The right side of the IFG is associated with cognitive processes, including attention, and inhibition (Corbetta & Shulman, 2002; Friederici, 2011; Hartwigsen et al., 2019). With the main function of the left IFG being speech, it could be hypothesized that it could also be involved in inner speech, which is associated with stimulus-independent thought, and is the main reason that it was included in this analysis. The right IFG was also included because of its involvement in imagery, which may play a large role in stimulus-independent thought, and its role in inhibitory control, which may enable control over the contents and repetitive nature of thought.

The superior frontal gyrus (SFG) [BA 11, 12] is involved in the working memory system along with executive functioning and processing (Boisgueheneuc et al., 2006). A previous study showed that this region was involved in spontaneous thoughts (Knyazev et al., 2012). In addition, it has been found that the SFG is involved in introspection and self-awareness (Goldberg et al., 2006). Introspection is thought to be similar to stimulus-independent thought, and can play a large role in self-identity, and the content of those stimulus-independent thoughts could possibly influence this region of the brain.

The last region that was investigated was the insula, which is a part of the salience network (Uddin et al., 2017). The main role of the insula [BA 14, 15, 16, 17] is socio-emotional processing, emotional intensity, and evaluation of internal bodily states (Tisserand et al., 2023; Uddin et al., 2017). These functions of this region allow the insula to be a good region of interest when trying to understand the contents of stimulus-independent thought, especially because it plays such a large role in introspection, and the sense of self (Tisserand et al., 2023).

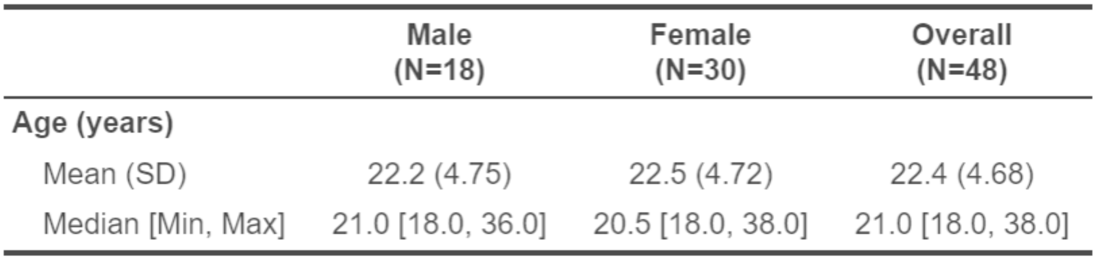
This project is going to look at how the content of stimulus-independent thought, mostly the valence of these thoughts, is correlated with the morphology of gray matter in the brain regions discussed above, as they have some known functions that could relate to those of stimulus-independent thought. Also, previous studies have shown correlations between connectivity between brain regions when looking at the content and valence of stimulus-independent thoughts (Rahrig et al., 2022), so it would be interesting to see if morphology is also related to this connectivity.

This paper will be looking at the relationship between the content of stimulus independent thought and attributes of gray matter in multiple brain regions by measuring the volume of each region. We hypothesize that as the scores in the more positive constructs of the thought-sampling task increase, the volume of the above states brain regions will increase due to their involvement in executive function, emotional regulation, and stimulus integration.

2. Methods

2.1 Participants

Participants were 71 adults who were recruited from the University of Colorado Boulder campus and the surrounding community. 8 participants were removed from analysis due to missing thought-sampling task data, and 10 participants were removed from analysis due to missing imaging data, and 5 people were removed from analysis due to missing age data. The removal of these participants from the data set resulted in a final sample of 48 participants aged 18-38 (m = 22.4, sd = 4.68) (Table 1). Each of the participants was screened for compatibility with the MRI machine, including that they were not claustrophobic, nor had metal in their body that would be a contraindication for scanning. All participants were free of psychopathology and history of traumatic brain injury. Informed consent was obtained from all the participants before participating in the study. All procedures and practices were approved by the University of Colorado Institutional Review Board. The MRI and thought-sampling task were completed by the participants during the same visit, with the thought-sampling task being done after the MRI scan.



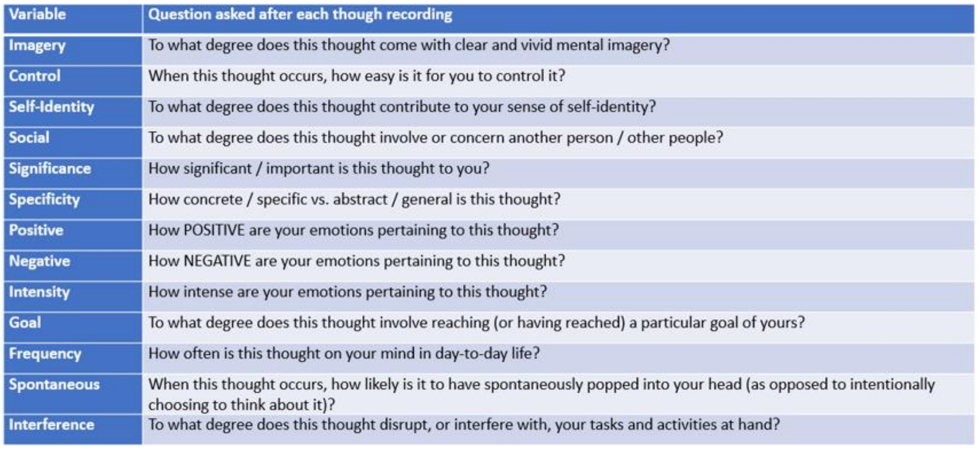
	Male (N=18)	Female (N=30)	Overall (N=48)
Age (years)			
Mean (SD)	22.2 (4.75)	22.5 (4.72)	22.4 (4.68)
Median [Min, Max]	21.0 [18.0, 36.0]	20.5 [18.0, 38.0]	21.0 [18.0, 38.0]

Table 1: Age demographics of participants in the current study. The average age of participants in the current study is 22.4 years, with the standard deviation of 4.68 years. Other information that was looked at was the median age, along with the minimum and maximum. The range of age of participants in this study was 18-36 years.

2.2 Data Acquisition - Thought-Sampling Task

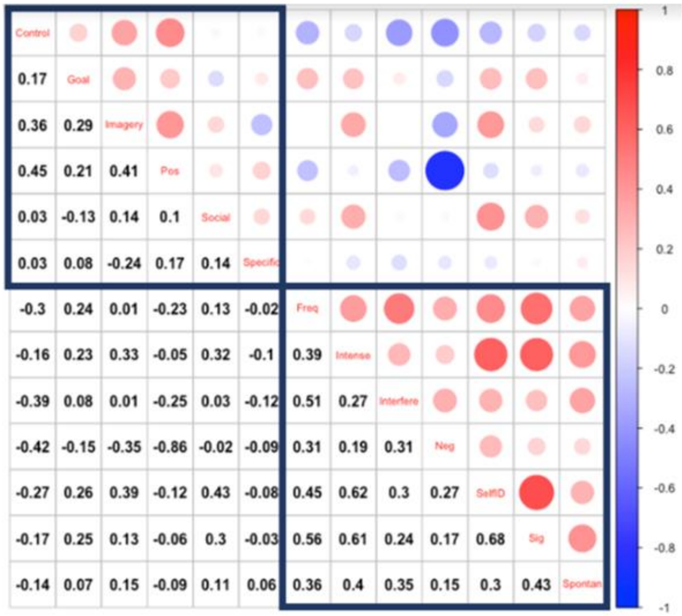
In this study, to measure the content of stimulus-thought, a thought-sampling task was administered (Andrews-Hanna et al., 2013) that probes about participants' eight most common thoughts, and asks them to rate each of them on multiple scales, including frequency, how goal-driven each thought is, how vivid the thought is, how well they are able to control it. This task is given to get an idea of what the participants' most common stimulus-independent thoughts are, and what the participants feel about those thoughts.

The categories included on the thought-sampling task were Imagery, Control, Self-Identity, Social, Significance, Specificity, Positive, Negative, Intensity, Goal, Frequency, Spontaneous, Interference (examples of questions asked in Figure 2). With an initial correlation plot, it was found that these categories can separate into two groups (Figure 3). One group was primarily about goal-defined thoughts and the other seemed to be tapping into self-focused brooding. As seen in figure 3, the constructs each contain categories that had generally high positive correlations with each other, and generally high negative correlations with the categories that ended up in the other construct. The categories that ended up in the goal-defined thoughts construct seem to be generally associated with being more positive and advantageous, while the categories that ended up in the self-focused brooding category seem to be generally associated as being more negative and harmful.



Variable	Question asked after each though recording
Imagery	To what degree does this thought come with clear and vivid mental imagery?
Control	When this thought occurs, how easy is it for you to control it?
Self-Identity	To what degree does this thought contribute to your sense of self-identity?
Social	To what degree does this thought involve or concern another person / other people?
Significance	How significant / important is this thought to you?
Specificity	How concrete / specific vs. abstract / general is this thought?
Positive	How POSITIVE are your emotions pertaining to this thought?
Negative	How NEGATIVE are your emotions pertaining to this thought?
Intensity	How intense are your emotions pertaining to this thought?
Goal	To what degree does this thought involve reaching (or having reached) a particular goal of yours?
Frequency	How often is this thought on your mind in day-to-day life?
Spontaneous	When this thought occurs, how likely is it to have spontaneously popped into your head (as opposed to intentionally choosing to think about it)?
Interference	To what degree does this thought disrupt, or interfere with, your tasks and activities at hand?

Figure 2: Questions that were about each thought during the thought-sampling task. There was a total of 13 categories that each participant was asked to answer regarding each of the eight thoughts they were asked to provide. Each category was scored on a sliding scale from 0-1, and these scores were averaged across each of the eight thoughts for each of the categories to get a final score in each category.



Control												
0.17	Goal											
0.36	0.29	Imagery										
0.45	0.21	0.41	Pos									
0.03	-0.13	0.14	0.1	Social								
0.03	0.08	-0.24	0.17	0.14	Specific							
-0.3	0.24	0.01	-0.23	0.13	-0.02	Freq						
-0.16	0.23	0.33	-0.05	0.32	-0.1	0.39	Intense					
-0.39	0.08	0.01	-0.25	0.03	-0.12	0.51	0.27	Interfere				
-0.42	-0.15	-0.35	-0.86	-0.02	-0.09	0.31	0.19	0.31	Neg			
-0.27	0.26	0.39	-0.12	0.43	-0.08	0.45	0.62	0.3	0.27	SelfID		
-0.17	0.25	0.13	-0.06	0.3	-0.03	0.56	0.61	0.24	0.17	0.68	Sig	
-0.14	0.07	0.15	-0.09	0.11	0.06	0.36	0.4	0.35	0.15	0.3	0.43	Spontan

Figure 3: Correlation table with each of the 13 categories that were on the thought-sampling task. This correlation table was used to group the categories into two constructs: concrete goal-defined thought and self-focused repetitive brooding. The former seems to be more associated with positivity, while the latter seems to be more associated with negativity.

Once these correlations were found, the two separate constructs were created by averaging the z-scores of the respective categories in each construct for each participant. The concrete goal-defined thought category consisted of the means of control, goal, imagery, and specificity. The self-focused repetitive brooding category consisted of frequency, intensity, interference, self-identity, significance, and spontaneous. The social category was not used in the final analysis as it did not correlate well with other constructs in this task (Figure 3). The positive and negative categories were taken out and looked at separately for each region of interest. The ways that valence was looked at are explained below. For each of the individual categories, the participants rated how they viewed each of their eight thoughts on a sliding scale from 0-1, 0 being not very much and 1 being very much. The categories and scoring for the thought-sampling task was inspired by a previous publication from our laboratory (Andrews-Hanna et al., 2013).

In addition to the constructs used above, positive and negative valence of thoughts were also looked at. The valence of thoughts was looked at in three different ways: Overall positive valence, valence intensity, and valence ratio. The overall positive valence category was calculated by adding the score from the positive valence mean category with the reverse scores of the negative valence mean category. The valence intensity category was calculated by taking the average of the absolute value of the positive valence and negative valence means. Finally, valence ratio was calculated by dividing the positive valence means by the absolute value of negative valence means.

2.2.2 <u>MRI Acquisition</u>

All structural MRI data were performed at the Intermountain Neuroimaging Consortium (INC) at the University of Colorado Boulder using a Siemens PRISMA 3-T MRI scanner. The structural scans were acquired with T1-weighted sequence with the following parameters: repetition time (TR) = 2400ms, echo time (TE) = 2.07 ms, field of view (FOV) = 256mm, with a 0.8 x 0.8 x 0.8 mm^3 voxel size, acquired across 224 coronal slices (Kim et al., 2020).

The analyses and quantification of the gray matter morphology were done using the FreeSurfer analysis suite (<u>http://surfer.nmr.mgh.harvard.edu/</u>). The quality of the data and images was checked both by the FreeSurfer software and by visual inspection to ensure proper segmentation of subcortical structures. The regions of interest (ROIs) that were analyzed were defined the by the Destrieux atlas (DESTRIEUX et al., 2010). Only volume is used in the current study as it is constructed from thickness and surface area (Figure 4).

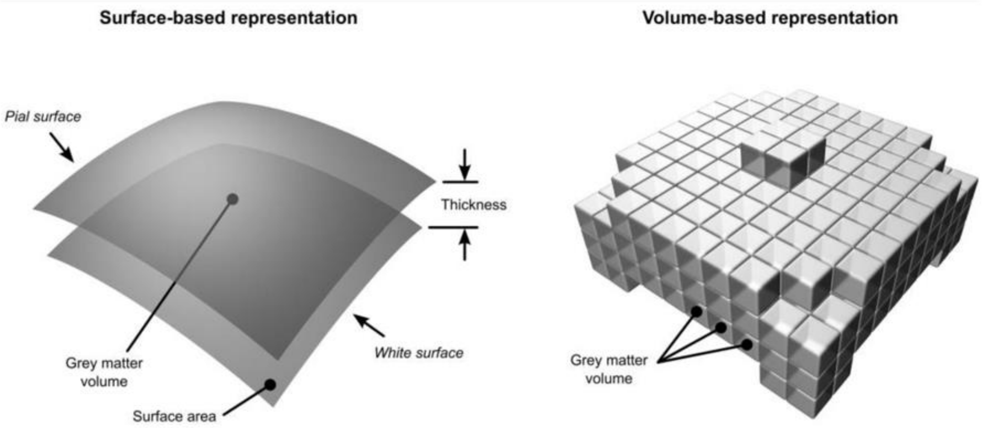


Figure 4: How volume is calculated from surface area and thickness data (Winkler et al., 2010). The volume of gray matter regions is a quadratic function of distances in the surface area and a linear function of the thickness.

2.3 Regression Analyses

All of the statistical analysis for the data was done using RStudio software version 2023.12.1+402. Models were run using a robust regression approach (https://CRAN.R-project.org/view=Robust). The robust regression approach down-weighs outliers so they don't influence the model as much, but without removing them completely, so that the model still retains its power, which we felt was important given our relatively modest sample size. Models were constructed to predict the volume of each region of interest using the derived measures from thought-sampling task (e.g. goal-defined thought, self-focused brooding). Nuisance variables included for each model were age and sex because prior literature has shown that brain volume is associated with both age (Peters, 2006) and sex (Ruigrok et al., 2014).

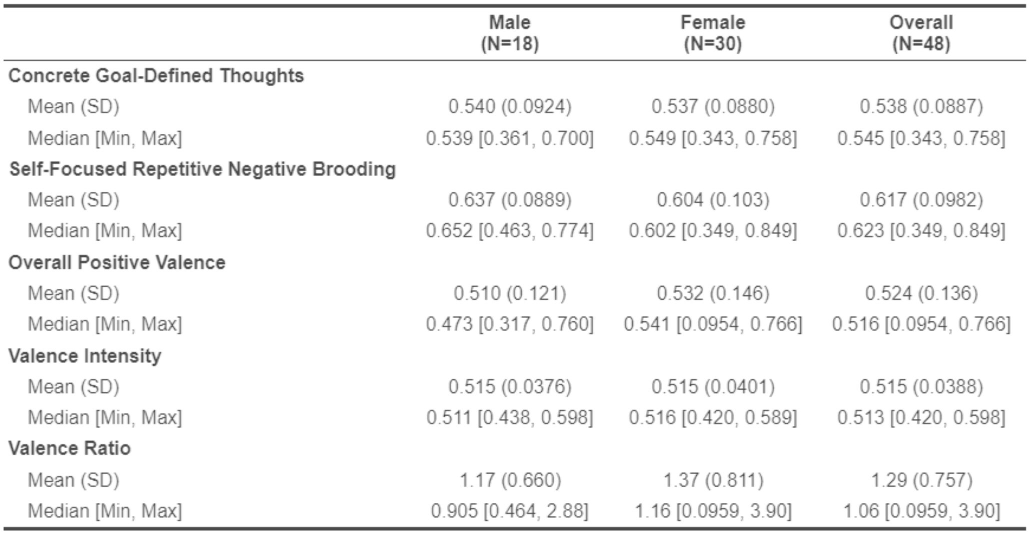
Another set of models were run that included estimated total intracranial volume as a nuisance variable to test the specificity of these regional effects over and beyond any whole brain correlations that may be observed.

To correct for multiple comparisons, the false discovery rate (FDR) methods was used to correct over the eight regions used in the current study. The eight regions stated include the six regions of interest, with the inferior frontal gyrus being broken up into an opercular part, triangular part, and an orbital part. The two hemispheres of the brain were looked at separately. The fdr function was used in R studio in order to correct p-values over groups of models (https://CRAN.R-project.org/package=fdrtool). Using FDR will show which results in the current study are robust and reliable.

3. Results

3.1 General Descriptive Data, Sex Differences, and Age Correlations for TSQ

Basic descriptive statics for each of the underlying constructs in for the derived measures used in the model are found in Table 2. The descriptive data for the individual categories of the thought-sampling task can be found in the supplementary data (Figure S3).



	Male (N=18)	Female (N=30)	Overall (N=48)
Concrete Goal-Defined Thoughts			
Mean (SD)	0.540 (0.0924)	0.537 (0.0880)	0.538 (0.0887)
Median [Min, Max]	0.539 [0.361, 0.700]	0.549 [0.343, 0.758]	0.545 [0.343, 0.758]
Self-Focused Repetitive Negative Brooding			
Mean (SD)	0.637 (0.0889)	0.604 (0.103)	0.617 (0.0982)
Median [Min, Max]	0.652 [0.463, 0.774]	0.602 [0.349, 0.849]	0.623 [0.349, 0.849]
Overall Positive Valence			
Mean (SD)	0.510 (0.121)	0.532 (0.146)	0.524 (0.136)
Median [Min, Max]	0.473 [0.317, 0.760]	0.541 [0.0954, 0.766]	0.516 [0.0954, 0.766]
Valence Intensity			
Mean (SD)	0.515 (0.0376)	0.515 (0.0401)	0.515 (0.0388)
Median [Min, Max]	0.511 [0.438, 0.598]	0.516 [0.420, 0.589]	0.513 [0.420, 0.598]
Valence Ratio			
Mean (SD)	1.17 (0.660)	1.37 (0.811)	1.29 (0.757)
Median [Min, Max]	0.905 [0.464, 2.88]	1.16 [0.0959, 3.90]	1.06 [0.0959, 3.90]

Table 2: Basic descriptive data of the thought-sampling task constructs. This table shows the mean, standard deviation, median, and range for the scores on the concrete goal-defined thought, self-focused repetitive negative brooding, and the three ways that emotional valence was looked at. T-tests were run for all these data to see if there were significant sex differences, and no significant results were found.

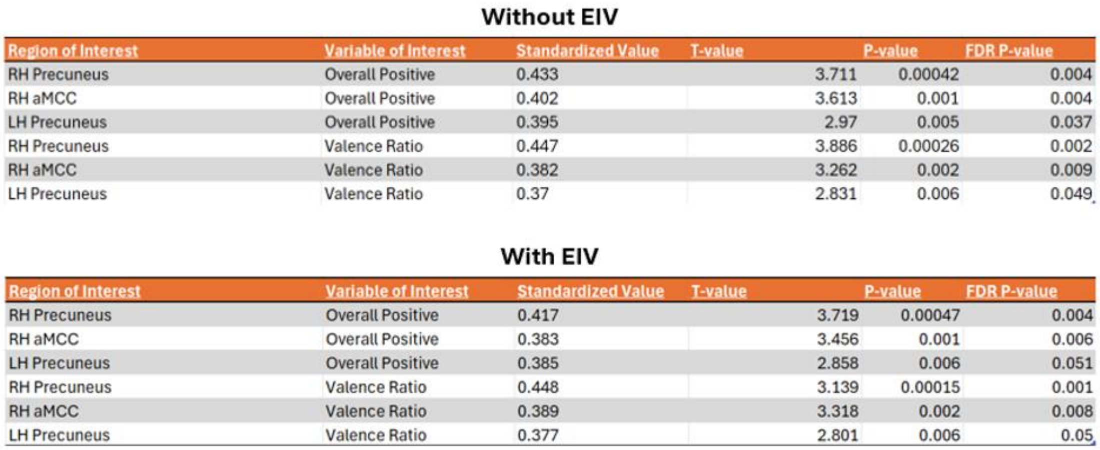
To determine whether there were significant differences between the sexes when it came to the measures of interest, t-tests were run for each category of the thought-sampling task, and for the volume measure of the regions of interest. Table 2 shows the descriptive data for each sex for the two constructs, concrete goal-defined thought, and self-focused repetitive brooding, and the three different ways that valence was looked at, overall positive valence, valence intensity, and valence ratio. There were no significant results when t-tests were run between the sexes, therefore there is no significant difference between the scores on this task between the sexes.

There were more significant differences between the sexes when looking at the brain regions of interest. This data can be found in table S2 in the supplementary data.

To determine whether there was a correlation between the scores on thought-sampling task categories with the ages of the participants, or a correlation between the volume of the regions of interest and the ages of the participants, correlation values were calculated for each of those interactions. The data for these correlations can be found in the supplementary data in table S1.

3.2 Regression Models

Only results that passed FDR correction will be reported for this manuscript. A summary of these results is provided in Table 3 below. The results below show the model run with and without estimated total intracranial volume as a nuisance variable.



Without EIV

Region of Interest	Variable of Interest	Standardized Value	T-value	P-value	FDR P-value
RH Precuneus	Overall Positive	0.433	3.711	0.00042	0.004
RH aMCC	Overall Positive	0.402	3.613	0.001	0.004
LH Precuneus	Overall Positive	0.395	2.97	0.005	0.037
RH Precuneus	Valence Ratio	0.447	3.886	0.00026	0.002
RH aMCC	Valence Ratio	0.382	3.262	0.002	0.009
LH Precuneus	Valence Ratio	0.37	2.831	0.006	0.049

With EIV

Region of Interest	Variable of Interest	Standardized Value	T-value	P-value	FDR P-value
RH Precuneus	Overall Positive	0.417	3.719	0.00047	0.004
RH aMCC	Overall Positive	0.383	3.456	0.001	0.006
LH Precuneus	Overall Positive	0.385	2.858	0.006	0.051
RH Precuneus	Valence Ratio	0.448	3.139	0.00015	0.001
RH aMCC	Valence Ratio	0.389	3.318	0.002	0.008
LH Precuneus	Valence Ratio	0.377	2.801	0.006	0.05

Table 3: Significant results from regression models run on regions of interest when looking at constructs of interest. Significant results were found bilaterally in the precuneus and in the right hemisphere of the anterior midcingulate cortex. Both of these regions had significant positive correlations with both overall positive valence and valence ratio. All results were put through FDR corrections to correct over the number of regions that were looked at. The models were run both with and without estimated intracranial volume (EIV) as a nuisance variable to see if total brain size was affecting the size of the regions of interest.

Increased volume of the right precuneus was found to be associated with higher overall positive ratings of thoughts both when estimated intracranial volume was not included as a covariate of interest (Std.- β = 0.433, t(43) = 3.711, p = 0.0004, FDR-p = 0.004), and when it was (Std.- β = 0.417, t(43) = 3.719, p = 0.00047, FDR-p = 0.004). A similar association was observed for the ratio of positive to negative thoughts (valence ratio), both when estimated intracranial volume was not included as a covariate of interest (Std.- β = 0.447, t (43)= 3.886, p = 0.0003, FDR-p = 0.002), and when it was (Std.- β = 0.448, t(43) = 3.139, p = 0.00015, FDR-p = 0.001).

Increased volume of the left precuneus was found to be associated with higher overall positive ratings of thoughts when estimated intracranial volume was not included as a covariate of interest (Std.- β = 0.395, t(43) = 2.97, p = 0.005, FDR-p = 0.037), and had a trending result when it was (Std.- β = 0.385, t(43) = 2.858, p = 0.006, FDR-p = 0.051). A similar association was observed for the ratio of positive to negative thoughts (valence ratio), both when estimated intracranial volume was not included as a covariate of interest (Std.- β = 0.37, t(43) = 2.831, p = 0.006, FDR-p = 0.049), and when it was (Std.- β = 0.377, t(43) = 2.801, p = 0.006, FDR-p = 0.05).

Increased volume of the right anterior midcingulate cortex was found to be associated with higher overall positive ratings of thoughts both when estimated intracranial volume was not included as a covariate of interest (Std.-β = 0.402, t(43) = 3.613, p = 0.001, FDR-p = 0.004), and when it was (Std.- β = 0.383, t(43) = 3.456, p = 0.001, FDR-p = 0.006). A similar association was observed for the ratio of positive to negative thoughts (valence ratio), both when estimated intracranial volume was not included as a covariate of interest (Std.- β = 0.382, t(43) = 3.262, p = 0.002, FDR-p = 0.009), and when it was (Std.- β = 0.389, t(43) = 3.318, p = 0.002, FDR-p = 0.008).

The residual plots for each of these regions against overall positive valence and valence ratio are shown in figures 5 and 6 respectively.

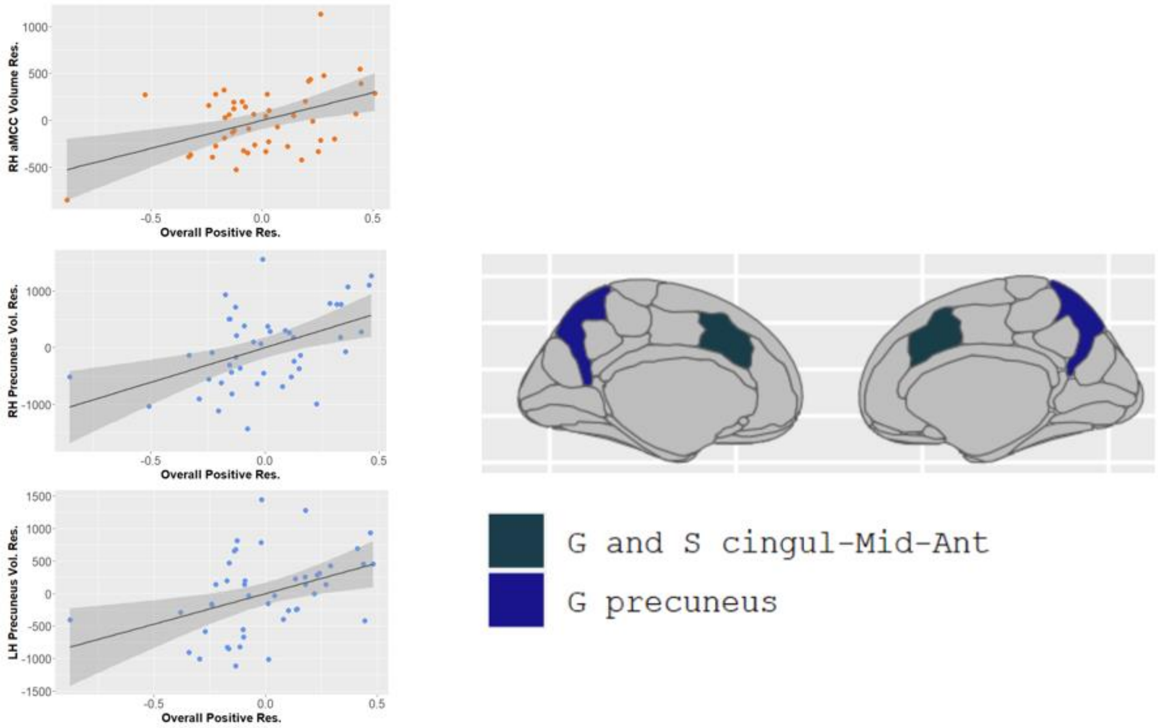


Figure 5: Residual plots for regions of interest that had significant results with overall positive valence. Residual plots above show the correlation between the region of interest with overall positive valence after taking into account sex, age, and estimated intracranial volume. The regions that had significant correlations were the right hemisphere of the anterior midcingulate cortex, and the bilateral precuneus. The brain map to the right highlights the regions that were significant, with the anterior midcingulate cortex being in dark blue, and the precuneus being in dark green.

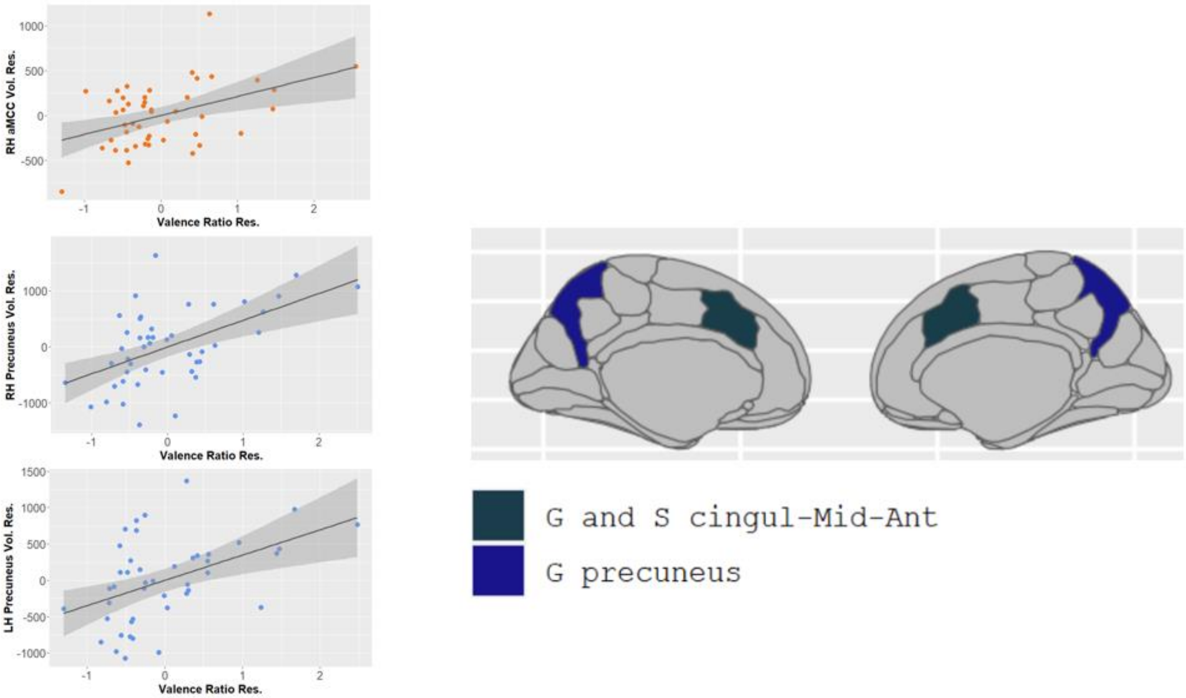


Figure 5: Residual plots for regions of interest that had significant results with valence ratio. Residual plots above show the correlation between the region of interest with valence ratio after taking into account sex, age, and estimated intracranial volume. The regions that had significant correlations were the right hemisphere of the anterior midcingulate cortex, and the bilateral precuneus. The brain map to the right highlights the regions that were significant, with the anterior midcingulate cortex being in dark blue, and the precuneus being in dark green.

4. Discussion

The original hypothesis of this study was that there would be a difference in the sizes of six different brain regions of interest depending on the score in the varying categories of the thought-sampling task. This hypothesis was confirmed for only two regions of interest, the precuneus bilaterally, and the right anterior midcingulate cortex. Both of these regions were found to be significantly correlated when comparing them to the scores the participants had in the thought-sampling task categories of valence ratio and overall positive valence. Valence ratio was the score that was derived by taking the positive valence category and dividing it by the negative valence category, and overall positive valence was the score derived by adding the positive valence scores to the reverse-scored negative valence scores.

In both hemispheres of the precuneus, significant results were found when measuring volume of the region and were found to be significant for both overall positive valence and valence ratio. This suggests that there is a positive correlation between the volume of the precuneus with the overall positivity of one's thoughts, and with the ratio of positivity to negativity. It was shown in a previous study that the precuneus had less thickness when adolescent participants had higher anxious-apprehension specific factor scores, which is typically associated with negative thoughts (Smolker et al., 2022). This previous result supports the result in the current study that the volume and area of the precuneus shows a positive correlation with positive thoughts and experiences. The precuneus is also part of a network of regions in the brain that allow integration of self-generated information (Cavanna & Trimble, 2006). This makes sense in the context of the current study, as it is looking at self-generated thoughts, which have been shown to include this region.

The anterior midcingulate cortex yielded significant results only in the right hemisphere of the brain. It was significant for both overall positive valence and valence ratio. This suggests that the size of a person's anterior midcingulate cortex in the right hemisphere positively correlations with how positive the person's stimulus-independent thoughts are overall, as well as with the valence ratio, or their thoughts' positivity over their negativity. Seeing that the anterior midcingulate cortex has a positive correlation with the positivity of one's thoughts is interesting, because this region of the brain has been implicated in the function of emotions, but it has been found to be involved in both positive and negative emotions (Lindquist et al., 2012; Touroutoglou et al., 2020). In one study, the aMCC was shown to have increased activity during times of fear perception than any other emotion (Lindquist et al., 2012). In contrast to this fact, the aMCC has also been found to be engaged in positive experiences, particularly reward-based decision-making (Touroutoglou et al., 2020). The results in the current study support the idea that the aMCC is involved in positive experiences and thoughts.

Although the precuneus yielded significant results in both hemispheres, the anterior midcingulate cortex only yielded significant results in the right hemisphere. This is interesting because the right hemisphere of the brain is thought to be implicated in the modulation of primary emotion (Ross, 2021). This corroborates our results, because the anterior midcingulate cortex is involved in emotional regulation, and significant results were found when looking at the valence of emotions.

Some of the regions that were expected to have significant results but did not produce any included the posterior midcingulate cortex, inferior frontal gyrus, superior frontal gyrus, and the insula. All these regions were previously found to have functions that could relate to self-generated thought and/or emotional regulation. The most surprising regions that were found to not have significant results were the posterior midcingulate cortex and the insula. The posterior midcingulate cortex is a part of the default mode network (DMN) of the brain, which is a set of regions in the brain that are generally involved when people are engaged in stimulus-independent thought, including memory, envisioning the future, and mind-wandering when the brain is unoccupied (Buckner et al., 2008; Mason et al., 2007). It was surprising that no significant results were found in this region due to the major role it plays in the default mode network, and stimulus-independent thought. The insula has many functions, but one of its crucial functions is the processing and the experience of emotions and subjective feeling states (Uddin et al., 2017). The insula covers a wide range of emotions, including disgust, fear, sadness, as well as happiness

(Uddin et al., 2017), so this could account for the fact that no significant results were found when looking at positive valence.

It was also surprising that no significant results were found when looking at any of the regions of interest when it came to the two other categories of thought content: concrete goal-defined thought and self-focused repetitive brooding. Most of the regions of interest play some role in one of the thought-sampling categories, such as control, specificity, self-identity, or goal-oriented. Although not all of the regions play a role in all of these factors, it is surprising that none of the regions had significant results in either of the concrete goal-defined thought or self-focused repetitive negative brooding categories. One possible reason is that concrete goal-defined thought may be linked to regions that have more involvement in control and executive function, and regions in the current study didn’t have many of those functions. On the same note, self-focused repetitive negative brooding may be associated with subcortical regions, such as the amygdala, which wasn’t involved in this study.

Overall, the hypothesis proposed by this study was met by two regions of interest, and with two valence categories that they were compared to. These regions, the anterior midcingulate cortex and the precuneus, showed positive correlational relationships with the valence categories they were found to be significant with, overall positive valence and valence ratio.

5. Limitations and Future Directions

One of the biggest limitations to this study was the small sample size of only 48 participants. This didn’t give much power to the results, and more results may have been statistically significant if there were a larger sample size to look at. Initially, the sample size was larger, but once the missing data were removed, it decreased the sample size by a substantial amount.

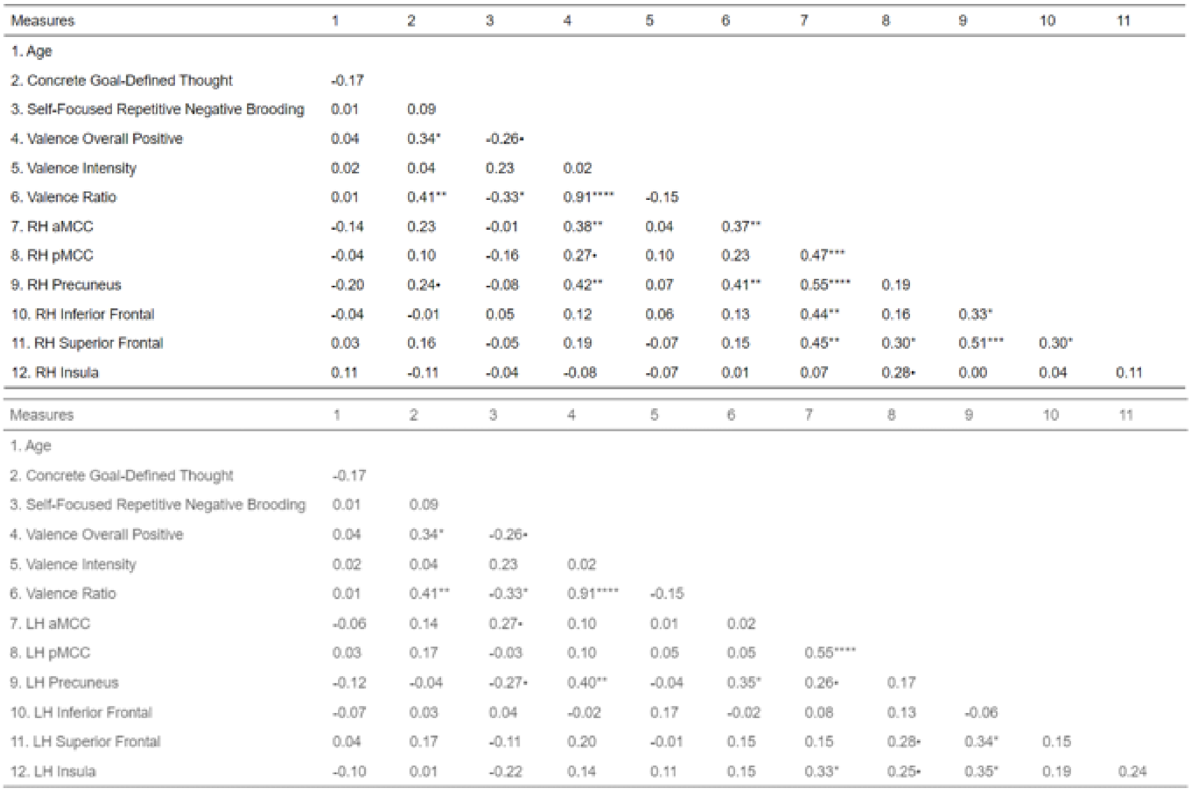
Another limitation of this study was the limited number of regions of interest that were looked at. There are likely many more regions that would be interesting to look at, but due to time constraints in this study, it was most feasible to only look at a small subset of those regions, including the ones that seemed like they were the most involved in stimulus-independent thoughts. It would be interesting to look more into regions that are involved in other aspects of thought content, such as control, goal-oriented, specificity, etc., to see if any significant results would be found with our two broad constructs. Specific regions of interest that would be interesting to look at in future studies include the amygdala because of its involvement in repetitive negative thoughts and anxiety (Li et al., 2016), and regions in the frontoparietal network, as they are involved in control and goal-driven thoughts (Marek & Dosenbach, 2018).

Finally, this study initially wanted to look at the time-orientation of thoughts, and if that was correlated with any of the regions of interest that were looked at. The current study collected data regarding the time orientation of each of the thoughts stated by the participant, but due to time constraints of this study, it couldn't be looked at in the current context. It would be interesting to look at this time-orientation because obsessively thinking about past events is associated with depression, while constantly thinking about future events is associated with anxiety (Eysenck et al., 2006).

After this study, another similar study with more participants would be very helpful in increasing the power of the sample, and determining if there are truly more significant regions of interest that are involved in stimulus-independent thought.

Because of the significant results found in the precuneus and anterior midcingulate cortex, it would be interesting to look further at these regions and ask participants who do have more positive thoughts and a relatively larger precuneus and/or anterior midcingulate cortex more in depth about the positivity of their thoughts, and how they are able to harness that positivity. Looking at these results could allow more knowledge about the harnessing of positive thoughts, and this could allow more resources for those who are dealing with certain mental illnesses to try to harness those positive thoughts.

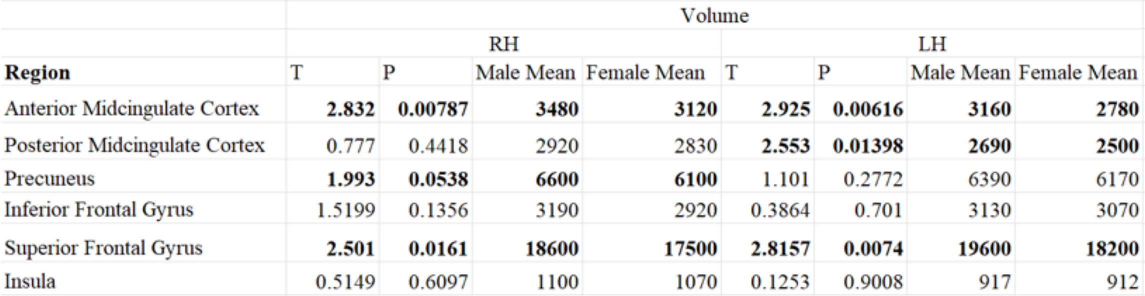
Supplemental Figures



Measures	1	2	3	4	5	6	7	8	9	10	11
1. Age											
2. Concrete Goal-Defined Thought	-0.17										
3. Self-Focused Repetitive Negative Brooding	0.01	0.09									
4. Valence Overall Positive	0.04	0.34*	-0.26•								
5. Valence Intensity	0.02	0.04	0.23	0.02							
6. Valence Ratio	0.01	0.41**	-0.33*	0.91****	-0.15						
7. RH aMCC	-0.14	0.23	-0.01	0.38**	0.04	0.37**					
8. RH pMCC	-0.04	0.10	-0.16	0.27•	0.10	0.23	0.47***				
9. RH Precuneus	-0.20	0.24•	-0.08	0.42**	0.07	0.41**	0.55****	0.19			
10. RH Inferior Frontal	-0.04	-0.01	0.05	0.12	0.06	0.13	0.44**	0.16	0.33*		
11. RH Superior Frontal	0.03	0.16	-0.05	0.19	-0.07	0.15	0.45**	0.30*	0.51***	0.30*	
12. RH Insula	0.11	-0.11	-0.04	-0.08	-0.07	0.01	0.07	0.28•	0.00	0.04	0.11

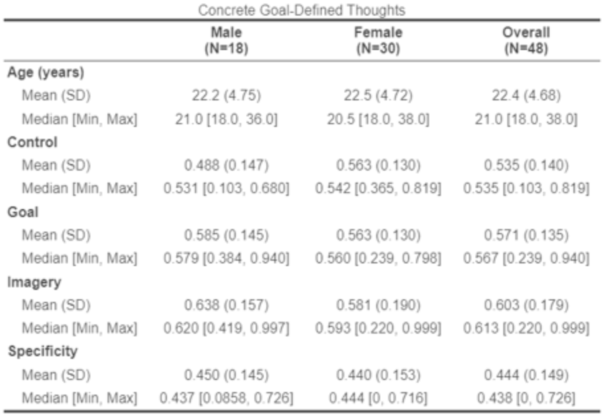
Measures	1	2	3	4	5	6	7	8	9	10	11
1. Age											
2. Concrete Goal-Defined Thought	-0.17										
3. Self-Focused Repetitive Negative Brooding	0.01	0.09									
4. Valence Overall Positive	0.04	0.34*	-0.26•								
5. Valence Intensity	0.02	0.04	0.23	0.02							
6. Valence Ratio	0.01	0.41**	-0.33*	0.91****	-0.15						
7. LH aMCC	-0.06	0.14	0.27•	0.10	0.01	0.02					
8. LH pMCC	0.03	0.17	-0.03	0.10	0.05	0.05	0.55****				
9. LH Precuneus	-0.12	-0.04	-0.27•	0.40**	-0.04	0.35*	0.26•	0.17			
10. LH Inferior Frontal	-0.07	0.03	0.04	-0.02	0.17	-0.02	0.08	0.13	-0.06		
11. LH Superior Frontal	0.04	0.17	-0.11	0.20	-0.01	0.15	0.15	0.28•	0.34*	0.15	
12. LH Insula	-0.10	0.01	-0.22	0.14	0.11	0.15	0.33*	0.25•	0.35*	0.19	0.24

Supplemental Table 1 (S1): Basic correlation table of the regions of interest with the variables of interest. This basic correlation was done in both of the hemispheres of the brain. In the right hemisphere correlation plot, significant results were found between the precuneus with both overall positive valence and valence ratio, and the anterior midcingulate cortex had significant correlations with overall positive valence and valence ratio. In the left hemisphere plot, the precuneus had significant results with overall positive valence and valence ratio.



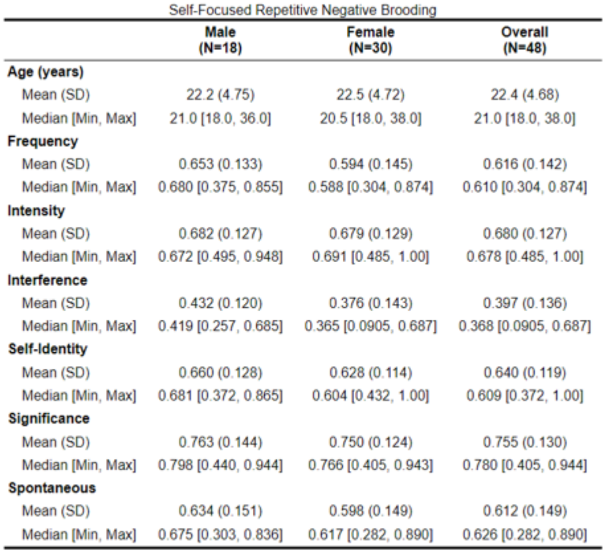
	Volume							
	RH				LH			
Region	T	P	Male Mean	Female Mean	T	P	Male Mean	Female Mean
Anterior Midcingulate Cortex	**2.832**	**0.00787**	**3480**	**3120**	**2.925**	**0.00616**	**3160**	**2780**
Posterior Midcingulate Cortex	0.777	0.4418	2920	2830	**2.553**	**0.01398**	**2690**	**2500**
Precuneus	**1.993**	**0.0538**	**6600**	**6100**	1.101	0.2772	6390	6170
Inferior Frontal Gyrus	1.5199	0.1356	3190	2920	0.3864	0.701	3130	3070
Superior Frontal Gyrus	**2.501**	**0.0161**	**18600**	**17500**	**2.8157**	**0.0074**	**19600**	**18200**
Insula	0.5149	0.6097	1100	1070	0.1253	0.9008	917	912

Supplemental Table 2 (S2): T-tests of brain regions of interest between the sexes. There were some significant differences in the volumes of some of the brain regions that were being looked at in the current study. The results that are bolded are those that are statistically significant. Significant results were found in both the left and right hemispheres.



Concrete Goal-Defined Thoughts

	Male (N=18)	Female (N=30)	Overall (N=48)
Age (years)			
Mean (SD)	22.2 (4.75)	22.5 (4.72)	22.4 (4.68)
Median [Min, Max]	21.0 [18.0, 36.0]	20.5 [18.0, 38.0]	21.0 [18.0, 38.0]
Control			
Mean (SD)	0.488 (0.147)	0.563 (0.130)	0.535 (0.140)
Median [Min, Max]	0.531 [0.103, 0.680]	0.542 [0.365, 0.819]	0.535 [0.103, 0.819]
Goal			
Mean (SD)	0.585 (0.145)	0.563 (0.130)	0.571 (0.135)
Median [Min, Max]	0.579 [0.384, 0.940]	0.560 [0.239, 0.798]	0.567 [0.239, 0.940]
Imagery			
Mean (SD)	0.638 (0.157)	0.581 (0.190)	0.603 (0.179)
Median [Min, Max]	0.620 [0.419, 0.997]	0.593 [0.220, 0.999]	0.613 [0.220, 0.999]
Specificity			
Mean (SD)	0.450 (0.145)	0.440 (0.153)	0.444 (0.149)
Median [Min, Max]	0.437 [0.0858, 0.726]	0.444 [0, 0.716]	0.438 [0, 0.726]



Self-Focused Repetitive Negative Brooding

	Male (N=18)	Female (N=30)	Overall (N=48)
Age (years)			
Mean (SD)	22.2 (4.75)	22.5 (4.72)	22.4 (4.68)
Median [Min, Max]	21.0 [18.0, 36.0]	20.5 [18.0, 38.0]	21.0 [18.0, 38.0]
Frequency			
Mean (SD)	0.653 (0.133)	0.594 (0.145)	0.616 (0.142)
Median [Min, Max]	0.680 [0.375, 0.855]	0.588 [0.304, 0.874]	0.610 [0.304, 0.874]
Intensity			
Mean (SD)	0.682 (0.127)	0.679 (0.129)	0.680 (0.127)
Median [Min, Max]	0.672 [0.495, 0.948]	0.691 [0.485, 1.00]	0.678 [0.485, 1.00]
Interference			
Mean (SD)	0.432 (0.120)	0.376 (0.143)	0.397 (0.136)
Median [Min, Max]	0.419 [0.257, 0.685]	0.365 [0.0905, 0.687]	0.368 [0.0905, 0.687]
Self-Identity			
Mean (SD)	0.660 (0.128)	0.628 (0.114)	0.640 (0.119)
Median [Min, Max]	0.681 [0.372, 0.865]	0.604 [0.432, 1.00]	0.609 [0.372, 1.00]
Significance			
Mean (SD)	0.763 (0.144)	0.750 (0.124)	0.755 (0.130)
Median [Min, Max]	0.798 [0.440, 0.944]	0.766 [0.405, 0.943]	0.780 [0.405, 0.944]
Spontaneous			
Mean (SD)	0.634 (0.151)	0.598 (0.149)	0.612 (0.149)
Median [Min, Max]	0.675 [0.303, 0.836]	0.617 [0.282, 0.890]	0.626 [0.282, 0.890]

Supplemental Table 3 (S3): Basic descriptive data of each individual thought-sampling task category. The descriptive data that is shown includes the mean, standard deviation, median, and range. The categories are divided into the constructs that they ended up in, either concrete goal-directed thought or self-focused repetitive negative brooding. T-tests were run for all of these categories to test for significant differences in the scores between the sexes, and no significant differences were found.

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