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THE RELATIONSHIP BETWEEN RESTING-STATE FUNCTIONAL CONNECTIVITY AND THE VIVIDNESS OF MENTAL IMAGERY IN A HEALTHY POPULATION

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by

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Under the Direction of Jessica Ann Turner, PhD

Abstract

Mental imagery is the act of using the “mind’s eyes and ears” to generate and experience sensory information that is absent in the external environment. The vividness of mental imagery varies across individuals, but not much is known about what contributes to these differences. This exploratory study investigates the possible relationship between resting-state functional connectivity and the vividness of mental imagery. We performed a seed-based connectivity analysis on resting-state scans of two groups of healthy control subjects with Brodmann area 19, the precuneus, the superior temporal gyrus, the hippocampus, and the posterior cingulate cortex as regions of interest. Although the underlying functional network connectivity was the same across groups, there was no groupwise replication of pairwise connectivities associated with either visual or auditory mental imagery vividness. The lack of replication may be due to a number of factors, but we highlight the impact of asking one group about the vividness of their imagery after each task-based trial and not the other. This may have primed the individuals in the former group to be in a self-referential state of mind during the resting-state scan, affecting the pairwise connectivity relationships to either imagery modality.

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Introduction

Mental imagery is the act of using the “mind’s eyes and ears” to generate and experience sensory information that is absent in the external environment. For most people, mental imagery is an important aspect of conscious experience as it allows us to daydream, mentally travel through time by envisioning the future and remembering the past, and understand the experiences of others. However, the vividness of mental imagery varies between individuals, where some people can imagine with great detail, while others struggle to obtain a basic mental picture. While differences in perception can be explained by how external stimuli interact with the nervous system, there is less knowledge available to explain differences in mental imagery. The subjective nature of imagination versus the objective nature of perception has provoked questions about how to accurately determine the experiential range of internally generated mental images, and how the brain is able to produce them.

Quantifying Vividness of Mental Imagery

The vividness of mental imagery is quantified primarily through self-report questionnaires that ask subjects to imagine something and then rank the vividness of their mental image. Functional neuroimaging studies have shown that scores on these assessments correlate with regional brain activity while an individual is actively imagining, in that better scores are related to increased activity in brain regions involved in imagination, and vice versa.

Vividness of Visual Imagery Questionnaire (VVIQ): Fulford et al. (2018) reviewed the relationship between imagery-evoked neural activity and visual imagery vividness measured using the Vividness of Visual Imagery Questionnaire (VVIQ). The VVIQ asks participants to imagine familiar individuals and experiences and then rank how vivid their image is, on a scale of “Perfectly clear and as vivid as normal vision,” to “No image at all.” Across the studies included in this review, regions with activity associated with VVIQ scores included secondary visual areas (Brodmann area (BA) 19 and 18), posterior cingulate (BA 29/31), and precuneus (BA 7).

Bucknell Auditory Imagery Scale (BAIS): Although there are numerous studies investigating auditory imagery (Hubbard, 2010), not as much is known about its neural correlates. Halpern (2015) found that the Bucknell Auditory Imagery Scale (BAIS) is a reliable predictor of auditory imagery vividness as well as related neural activity. The BAIS asks participants to imagine a familiar sound and then rank the vividness of their mental image on a scale of “No image present at all,” to “As vivid as the actual sound.” A previous study by Herholz et al. (2012) found that participants with high vividness of auditory imagery, as measured by the BAIS, had increased activity in the right anterior superior temporal gyrus (STG).

Neural Substrates of Mental Imagery

Task-based imagery studies have found the neural correlates of mental imagery to comprise regions associated with secondary sensory processing and self-referential memory. For this paper, we focus on six regions previously found to be involved in mental imagery and related cognitive processes: BA 19, the precuneus, the inferior frontal gyrus (BA 44/45), the superior temporal gyrus (STG), the hippocampus, and the posterior cingulate cortex (PCC).

Brodmann Area (BA) 19: BA 19, also referred to as the peristriate area or preoccipital cortex, is a visual association area that is comprised of the fusiform gyrus, superior occipital gyrus, and parts of the lingual gyrus. This region has been found to contribute not only to visual processes, such as spatial mental imagery (Knauff et al., 2000), visual mental imagery (Daselaar et al., 2010); Huijbers et al., 2011; McNorgan, 2012; Stephan-Otto et al., 2017), and the vividness of visual mental imagery (Fulford et al., 2018), but also auditory processes, such as encoding familiar tunes (Herholz et al., 2012) and imagined words (Sugimori et al., 2014).

Precuneus: The precuneus (BA 7) is located in the postero-medial parietal cortex. It plays a role in visual processes such as spatial mental imagery (Knauff et al., 2000), visual mental imagery (Daselaar et al., 2010; McNorgan, 2012; Stephan-Otto et al., 2017), the vividness of visual mental imagery (Fulford et al., 2018), and auditory processes such as encoding familiar tunes (Herholz et al., 2012), and imagined words (Sugimori et al., 2014), and recalling previously experienced events (Tulving et al., 1994).

Inferior Frontal Gyrus (BA 44/45): The inferior frontal gyrus, commonly coincident with BA 44/45, is comprised of the pars opercularis and pars triangularis, and is a part of the prefrontal cortex. Activity in the inferior frontal gyrus has been correlated with auditory imagery (Daselaar et al., 2010; Lu et al., 2019) and encoding imagined words (Sugimori et al., 2014), and its activity is negatively correlated with the vividness of visual mental imagery (Fulford et al., 2018).

Superior Temporal Gyrus (STG): The STG is an auditory association cortex and a crucial hub for processing speech and language in the brain (Yi et al., 2019). Activity in this region correlates with auditory imagery (Lu et al., 2019), encoding, imagining, and recognizing familiar tunes (Herholz et al., 2012), encoding heard words (Sugimori et al., 2014; Yi et al., 2019), and the vividness of visual imagery (Fulford et al., 2018).

Hippocampus: The hippocampus, part of the limbic system, plays a vital role in learning, memory encoding and consolidation, and spatial navigation. It provides a spatiotemporal context for memories (Knierim, 2015), and also aids in visual and auditory imagery abilities (Daselaar et al., 2010; Huijbers et al., 2011; Fulford et al., 2018).

Posterior Cingulate Cortex (PCC): The PCC is located in the medial parietal cortex and is a key node in the default mode network, where it plays a primary role in supporting internally directed thought (Leech & Sharp, 2014). Studies have shown that this region also contributes specifically to visual and auditory imagery (Fulford et al., 2018; Huijbers et al., 2011) and modality-independent imagery more generally (Daselaar et al., 2010).

Imagery Networks

As evident in the previous section, much work has been done to investigate what areas of the brain are active during imagination and its related mental processes. However, since we know that there is no one brain region responsible for a given cognitive process, it is important to look at the interaction and connection between regions involved in imagination. Focusing only on the activation of specific brain regions does not tell the whole story of how imagination is possible.

McNorgan (2012) conducted a meta-analytic review of 61 functional neuroimaging studies associated with imagery ability and identified functional networks involved in both modality-general and modality-specific imagery. His review concluded that modality-specific imagery generally activates corresponding sensory processing and motor execution areas, and also that there is a more foundational network of regions involved in mental imagery, regardless of sensory-modality. While this review provides substantial evidence for a general-imagery network that is active during imagination, the literature surrounding the neural correlates of mental imagery has yet to explore how the resting-state brain contributes to mental imagery vividness.

Role of Resting-State Networks

Resting-state networks (RSNs), also known as intrinsic connectivity networks (ICNs), are anatomically separate yet functionally connected brain regions that demonstrate synchronous activity and are related to various aspects of cognition (Seitzman et al., 2019). Resting-state functional connectivity (rs-FC) determines the connection between regions in the network (Smitha et al., 2017)

RSNs have been studied in people of all ages to understand how cognition is related to RSNs. The first reported study of developing functional networks studied sedated children between 3 months and 10 years of age, and found that rsfMRI can detect stable visual networks in children as young as 3 months of age (Kiviniemi et al., 2000). More stable networks were found by Fransson et al. (2007) in sedated sleeping infants under 1 year of age. Five distinct networks were discovered, and they include the following regions: (1) primary visual regions, (2) bilateral somatosensory and motor cortices, (3) bilateral temporal/inferior parietal cortex, (4) posterior lateral and medial parts of the parietal cortex and lateral aspects of the cerebellum, and (5) medial and lateral sections of the anterior prefrontal cortex. These regions comprise many of the functional networks found in adults, but one important network was missing: the default mode network (DMN).

The DMN is primarily thought to contribute to internally-directed thought, and the fact that this network is missing in infants corresponds with their lack of self-identity. These findings were elaborated on by Fair et al. (2008) who found that 13 nodes in the DMN were weakly connected in children, but more strongly functionally connected in adults.

The documented relationship between the development of RSNs and the development of aspects of cognition raises the question of how far this relationship extends, and how many aspects of cognition might be related to RSN FC.

Purpose

The present study explores the possible existence of a RSN whose FC is associated with individual differences in mental imagery vividness. We examine the rs-FC of two groups of healthy controls and relate it to measures of visual and auditory imagery vividness in the same individuals. The aim of the current project is to identify functional connections related to mental imagery vividness in two modalities: visual and auditory. We hypothesize that the overall functional network connectivity will be similar across groups, and that there will be a relationship between pairwise-connectivities and scores on assessments of visual and auditory imagery vividness that will replicate across groups as well. These findings would provide evidence for the existence of a resting-state network that underlies the vividness of mental imagery.

Materials and Methods

Participants

The joint Georgia Tech/Georgia State Institutional Review Board approved the protocol for this study. All procedures involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Two groups of healthy subjects were recruited from the undergraduate population at Georgia State University. Group A consisted of 26 participants (10 males, 16 females) with ages ranging from 18 to 34 (mean = 21.23, SD = 3.22). Group B consisted of 24 participants (12 males, 12 females) with ages ranging from 19 to 39 (mean = 24.62, SD = 6.36). Participants were excluded if they had a history of extended loss of consciousness, severe head injury, or were physically incapable of undergoing an MRI scan. Informed consent was obtained from all participants included in the study.

Imagery Assessments

VVIQ: The Vividness of Visual Imagery Questionnaire (VVIQ) is a reliable measure of visual imagery vividness, with a Cronbach's alpha 0.87 (Borst & Kosslyn, 2010). This questionnaire consists of 16 items (e.g. a rising sun into a clear blue sky, then clouds appear and a storm erupts, and finally a rainbow appears.) which participants are asked to imagine and then rate the vividness of their mental image on a scale of 1 to 5 (Marks, 1973). The total scores on the VVIQ are calculated by adding the vividness ratings for all 16 items and range from a minimum score of 16 to a maximum score of 80.

BAIS: The Bucknell Auditory Imagery Scale (BAIS) is a reliable measure of auditory imagery vividness, with a Cronbach's alpha 0.91 (Pfordrescher & Halpern, 2013). This assessment consists of 14 items (e.g. the sound of a cheering crowd when a baseball player hits the ball) which participants are asked to imagine and the rate the vividness of their mental image on a scale of 1 to 7 (Halpern, 2015). The total scores on the BAIS are calculated by adding the vividness rating for all 14 items and range from a minimum score of 14 to a maximum score of 98.

Imaging Protocol

Both groups of participants were scanned at the GSU/GA Tech Center for Advanced Brain Imaging.

Before the resting-state scans, both groups participated in visual and auditory tasks in the scanner. Details of the imagery tasks can be found in a previous publication (Kleider-Offutt et al., 2019). After completing the task-based trials, the participants underwent the resting-state scan. The data from the task-based trials are being analyzed separately from the resting-state trial.

Group A was scanned using a 3T Siemens TIM Trio scanner. Group A's functional images were acquired with a single-shot echoplanar gradient-echo pulse sequence with the following parameters: TR = 2.0s, TE = 30ms, flip angle = 77 deg, field of view = 220mm, 32 slices, slice thickness = 4.0mm, voxel size = 3.4x3.4x4.0mm. Scans lasted 6 minutes, 6 seconds.

Group B was scanned using a 3T Siemens Prisma Fit scanner. Group B's functional images were acquired with the following parameters: TR = 750ms, TE = 32.00ms, flip angle = 52 deg, field of view = 220mm, 50 slices, slice thickness = 2.50mm, voxel size = 2.5x2.5x2.5mm. Scans lasted 7 minutes, 38 seconds.

Participants in both groups were instructed to lie still in the scanner with their eyes open for the duration of the scan.

Quality Controls

Scanning data were screened for excessive head movement above 3 mm. All participants in both groups passed this criteria. Three participants in Group A did not complete the VVIQ, leaving 23 suitable datasets for comparison of resting-state data with VVIQ scores. All 26 participants in Group A completed the BAIS. Four participants in Group B did not complete the VVIQ, and three participants did not complete the BAIS, leaving 20 and 21 suitable datasets for comparison of resting-state data with VVIQ and BAIS scores, respectively.

Preprocessing

The DICOM data were preprocessed with DPARSF software (Yan, 2010), advanced edition. The preprocessing pipeline included removal of the first four timepoints, slice timing, motion correction, segmentation and normalization to the MNI template by using the T1 image-unified segmentation method, as well as nuisance covariance regression, reslicing to 2x2x2, and smoothing by FWHM of 6 mm.

All region of interest (ROI) masks were made using the WFU PickAtlas (Maldjian et al., 2003) in SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) and were coregistered to the scans. BA 19 was represented by TD Brodmann's areas+ BA 19 dilated by 1x. The precuneus was represented by TD Brodmann's areas+ BA 7. The IFG was represented by the union of TD Brodmann's areas+ BA 44 and BA 45, each dilated by 1x. The STG was represented by the union of left and right TD label superior temporal gyrus. The hippocampus was represented by TD Brodmann area + hippocampus. The PCC was represented by the intersection of a 14x10x16 box centered at MNI (0, -48, 20) and the union of IBASPM71 cingulate region right and cingulate region left.

The masks were overlayed onto each participant's preprocessed resting-state data in DPARSF advanced edition. DPARSF performs a seed-to-seed functional connectivity analysis by extracting the average time courses from the specified ROIs and correlating them with each other. The resultant connectivity values are a measure of BOLD signal correlation, such that positive connectivity values indicate synchronous activity between two regions and negative connectivity values indicate asynchronous activity between two regions.

Statistical Analyses

Functional network connectivity was calculated for each participant in DPARSF advanced edition. The connectivity of each ROI to all other ROIs was represented in a matrix of Fisher Z correlations. For each group, the matrices of all participants were combined and averaged to obtain the group's average functional network connectivity. These average connectivities were compared across groups to determine the typical FC of this RSN.

The average connectivity strength between each pair of regions in the network was then correlated with each group's average scores on the VVIQ and BAIS to determine if there was a relationship between the FC of a pair of regions and the vividness of imagery in either sensory modality.

Results

Imagery Assessments

For the VVIQ (see Figure 1), Group A's scores ranged from 29 to 76 (M = 57.48, SD = 13.66) and Group B's scores ranged from 38 to 75 (M = 61.57, SD = 10.62). For the BAIS (see Figure 2), Group A's scores ranged from 29 to 96 (M = 62.46, SD = 19.78) and Group B's scores ranged from 31 to 93 (M = 62.33, SD = 15.57).

Group Average FNC

The average FNC for each group was very similar, and is shown in Figure 3 and Table 2. For both groups, the strongest FC was found between the precuneus and BA 19, and the weakest FC was found between the PCC and IFG.

Pairwise FC vs. Imagery Scores

VVIQ Scores

For Group A, VVIQ scores had the strongest positive correlation with FC between the precuneus and hippocampus (R = .265). For Group B, VVIQ scores had the strongest correlation with FC between the STG and IFG (R = .363), the PCC and IFG (R = .362), and the PCC and BA 19 (R = .361). These results are depicted in Table 3.

BAIS Scores

For Group A, BAIS scores has the strongest positive correlation with FC between the hippocampus and BA 19 (R = .324). For Group B, BAIS scores had the strongest correlation with FC between the precuneus and PCC (R = -.275). These results are depicted in Table 4.

Discussion

The aim for this exploratory study was to determine whether rs-FC within the specified network was associated with visual and/or auditory imagery vividness. We explored the relationship between rs-FC and scores on assessments of mental imagery in Group A and then looked to see if we found the same results in Group B. By examining these relationships, we hoped to provide evidence for a RSN whose FC contributed to imagery vividness.

We hypothesized that the overall FNC would be similar across the two groups, and we found this to be true. These results are depicted in Figure 3, and demonstrate that the average baseline FC of a GSU undergraduate is consistent.

We also hypothesized that there would be a relationship between the pairwise FC of regions in the network and imagery vividness in either modality, and that these relationships would be replicated across groups. While we did find relationships between pairwise FC and scores on both assessments, none of the correlations were strong. Additionally, the correlations between pairwise FC and scores on either assessment were not replicated across groups. As seen in Figures 4 and 5, the pairwise connectivities associated with scores on either imagery assessment were completely different across groups.

One explanation for the lack of replication may be the regions chosen to comprise the RSN of this study. McNorgan (2012) highlighted the recruitment of bilateral parietal regions in the general imagery network, but most other regions in the network were left-lateralized. This study did not include any parietal regions, nor were the other regions left-lateralized, so this may contribute to the lack of group-wise replication. Kleider-Offutt et al. (2019) also found that the supplementary motor area was important in imagery, regardless of modality, and this region was also not included in this analysis.

The complexity and subjectivity of mental imagery vividness make it difficult to capture in self-report assessments. McKelvie (1995) published a critical review of the VVIQ and claimed that the VVIQ may not accurately capture the entirety of visual mental imagery. Questions were raised about the validity of the test instructions, items, rating scale, and distribution of scores and it was concluded that there were a number of issues that challenged content validity of the questionnaire.

Another notable feature in the correlations between pairwise FC and scores on the imagery assessments is the centering of correlations around the FC of the hippocampus for Group A, and the FC of the PCC for Group B. During the task-based trials, which were completed prior to the resting-state scans, Group B was asked about the vividness of their imagery after every trial while Group A was not. Given the role that the PCC plays in internally-directed thought, asking participants about the vividness of their imagery during the task-based trials may have primed them to be in a more self-referential state of mind during the resting-state scan, which could explain the correlation between PCC rs-FC and scores on the imagery assessments for Group B.

The effects of completing the task-based imagery trials before conducting the resting-state scans likely influenced the rs-FC, and numerous studies have demonstrated that cognitive training can in fact have an effect on rs-FC. Cao et al. (2016) found alterations in rs-FC within and between the default mode network (DMN), salience network (SN), and central executive network (CEN) in healthy older adults after one year of cognitive training. Although the long-term nature of this study is not consistent with the time frame of the present study, other studies have found similar changes with short-term training. Marins et al. (2019) demonstrated that one hour of neurofeedback training while completing motor imagery tasks resulted in increased FC of the sensorimotor RSN as well as the DMN. These studies provide evidence that prior training can influence rs-FC, and although there was no prescribed training in this study, the effects of the task-based imagery trials on the subsequent rs-FC must be considered.

The results of this study add to the understanding of mental imagery ability by investigating the contribution of rs-FC to the vividness of mental imagery. Our study could not provide evidence for a relationship between rs-FC and scores on assessments of visual and auditory imagery, and this may be due to a variety of factors that were previously discussed.

Appendix

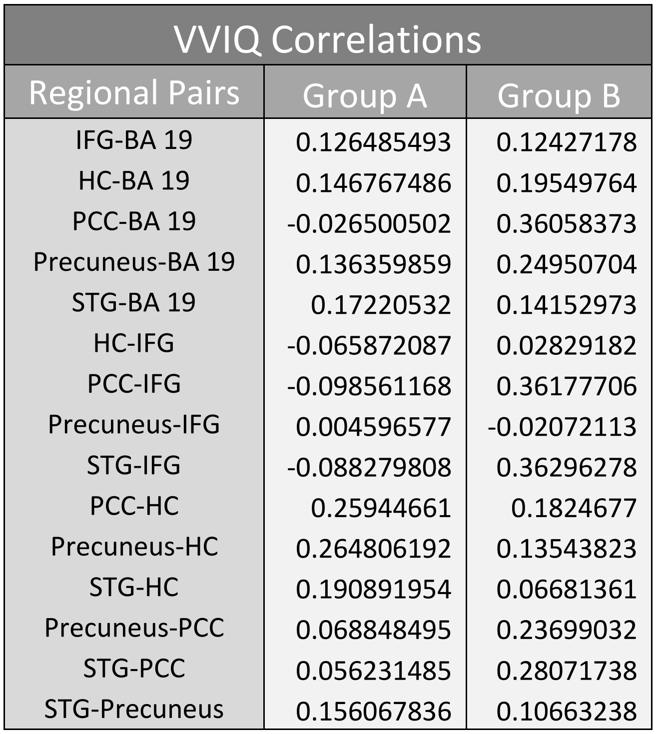
Table 1. Participant Characteristics

	Participant Characteristics					
	Group A			Group B		
	Age	VVIQ Score	BAIS Score	Age	VVIQ Score	BAIS Score
Mean	21.2308	57.4783	62.4615	24.9545	61.5714	62.3333
SD	3.2163	13.6577	19.7752	6.5500	10.6234	15.5703

Table 2. Average Functional Network Connectivity

	Average FNC					
	Group A			Group B		
Regional Pairs	Mean	SD	SEM	Mean	SD	SEM
IFG-BA19	0.68125	0.3183	0.06242	0.7135	0.26037	0.05315
HC-BA19	0.96142	0.32975	0.06467	0.89723	0.34601	0.07063
PCC-BA19	0.70648	0.36408	0.0714	0.61416	0.35645	0.07276
Precuneus-BA19	1.39145	0.32299	0.06334	1.26911	0.40941	0.08357
STG-BA19	0.96411	0.36096	0.07079	0.91043	0.29767	0.06076
HC-IFG	0.59926	0.2995	0.05874	0.62575	0.301	0.06144
PCC-IFG	0.31341	0.35738	0.07009	0.33612	0.23864	0.04871
Precuneus-IFG	0.61874	0.31032	0.06086	0.62076	0.21928	0.04476
STG-IFG	1.015	0.31703	0.06218	1.03683	0.25525	0.0521
PCC-HC	0.89648	0.30005	0.05884	0.92114	0.23493	0.04796
Precuneus-HC	1.01889	0.37165	0.07289	0.97658	0.20912	0.04269
STG-HC	0.9868	0.33531	0.06576	1.0038	0.26273	0.05363
Precuneus-PCC	0.94128	0.40348	0.07913	0.92866	0.33268	0.06791
STG-PCC	0.652	0.35443	0.06951	0.6787	0.23376	0.04772
STG-Precuneus	0.9468	0.34455	0.06757	0.88642	0.2294	0.04683

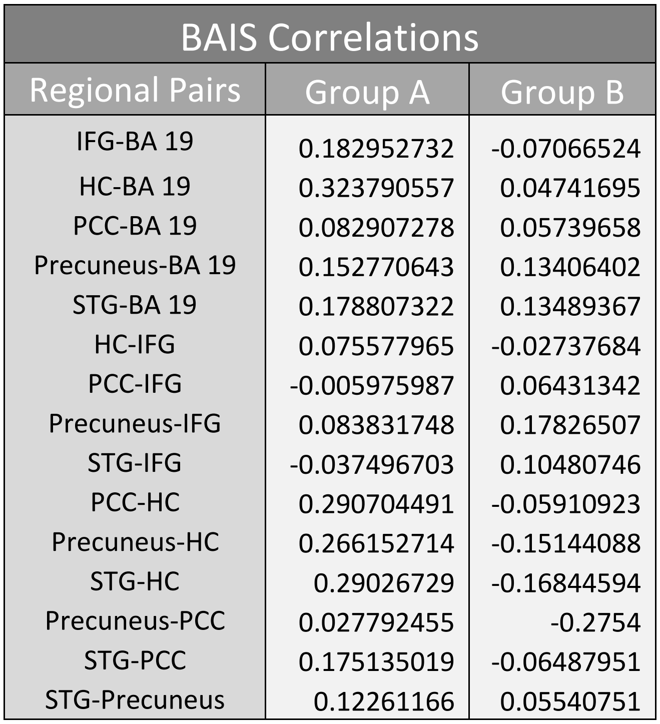
Table 3. Average FNC-VVIQ Scores Correlations



VVIQ Correlations

Regional Pairs	Group A	Group B
IFG-BA 19	0.126485493	0.12427178
HC-BA 19	0.146767486	0.19549764
PCC-BA 19	-0.026500502	0.36058373
Precuneus-BA 19	0.136359859	0.24950704
STG-BA 19	0.17220532	0.14152973
HC-IFG	-0.065872087	0.02829182
PCC-IFG	-0.098561168	0.36177706
Precuneus-IFG	0.004596577	-0.02072113
STG-IFG	-0.088279808	0.36296278
PCC-HC	0.25944661	0.1824677
Precuneus-HC	0.264806192	0.13543823
STG-HC	0.190891954	0.06681361
Precuneus-PCC	0.068848495	0.23699032
STG-PCC	0.056231485	0.28071738
STG-Precuneus	0.156067836	0.10663238

Table 4. Average FNC-BAIS Scores Correlations



BAIS Correlations

Regional Pairs	Group A	Group B
IFG-BA 19	0.182952732	-0.07066524
HC-BA 19	0.323790557	0.04741695
PCC-BA 19	0.082907278	0.05739658
Precuneus-BA 19	0.152770643	0.13406402
STG-BA 19	0.178807322	0.13489367
HC-IFG	0.075577965	-0.02737684
PCC-IFG	-0.005975987	0.06431342
Precuneus-IFG	0.083831748	0.17826507
STG-IFG	-0.037496703	0.10480746
PCC-HC	0.290704491	-0.05910923
Precuneus-HC	0.266152714	-0.15144088
STG-HC	0.29026729	-0.16844594
Precuneus-PCC	0.027792455	-0.2754
STG-PCC	0.175135019	-0.06487951
STG-Precuneus	0.12261166	0.05540751

Figure 1. VVIQ Score Distributions

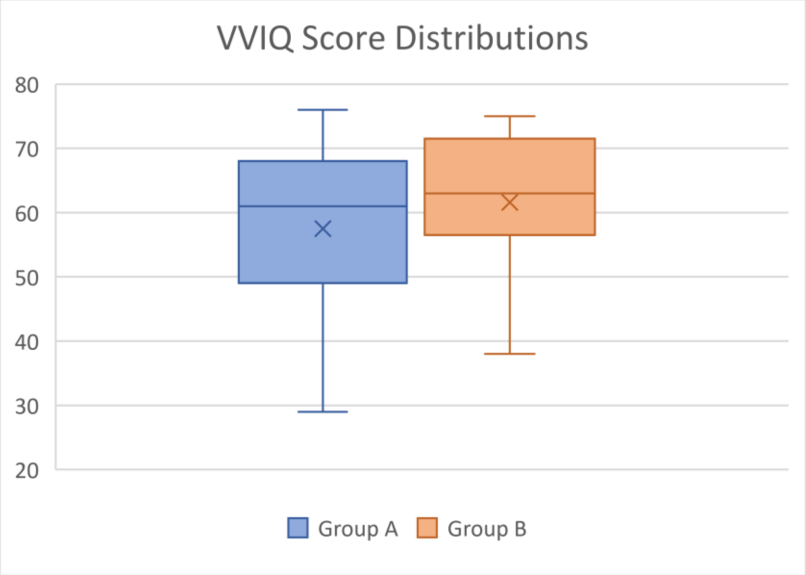


Figure 2. BAIS Score Distributions

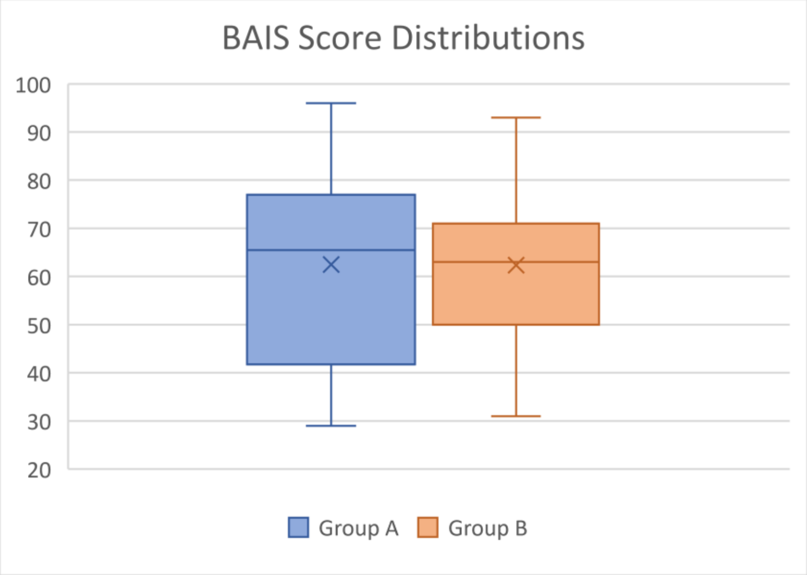


Figure 3. Average Functional Network Connectivity

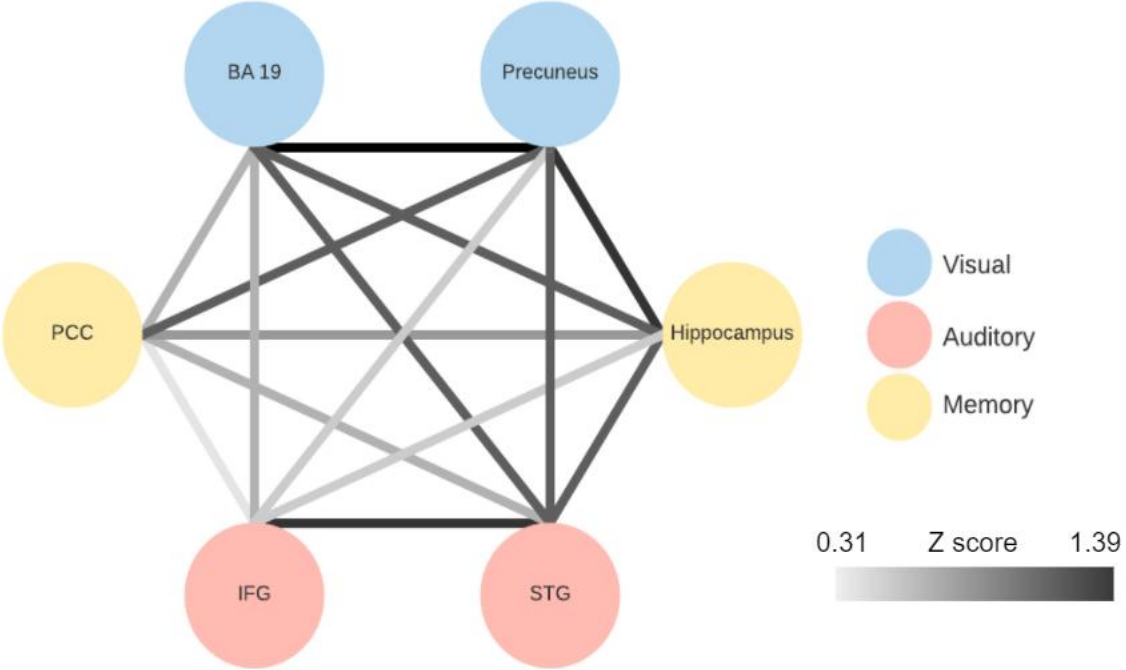


Figure 4. Group A Correlations

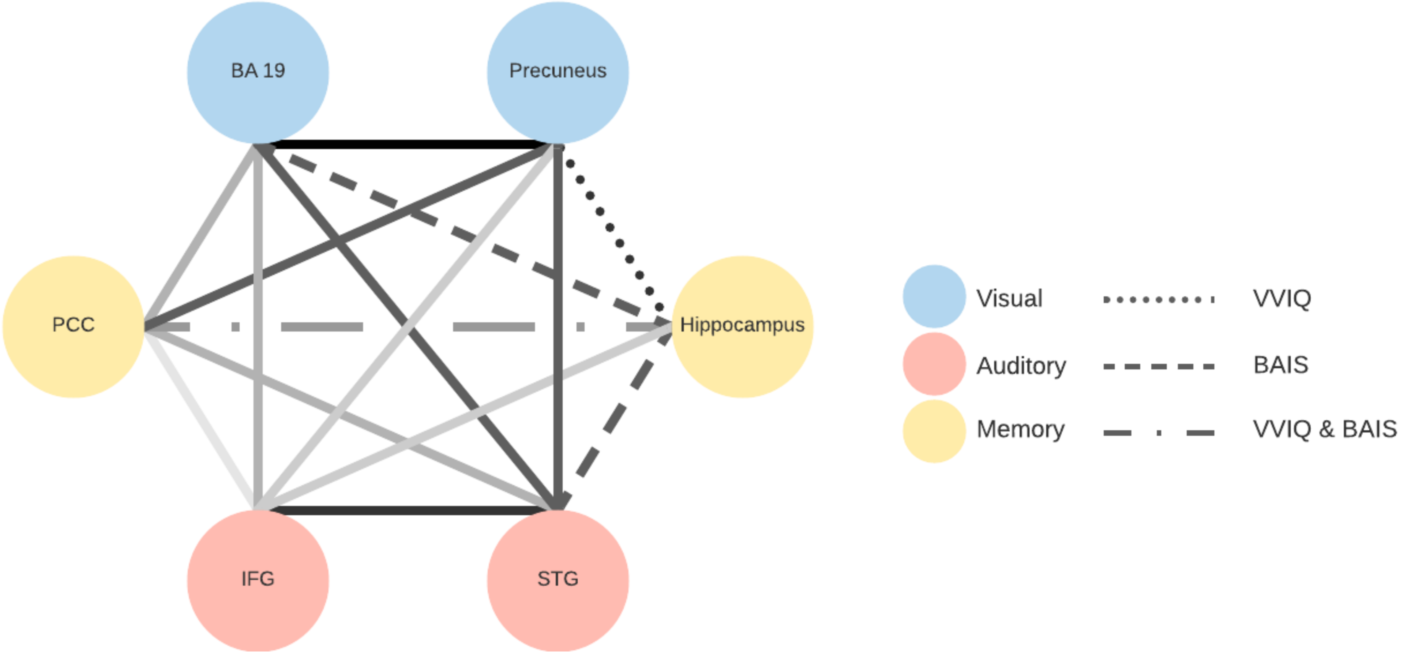
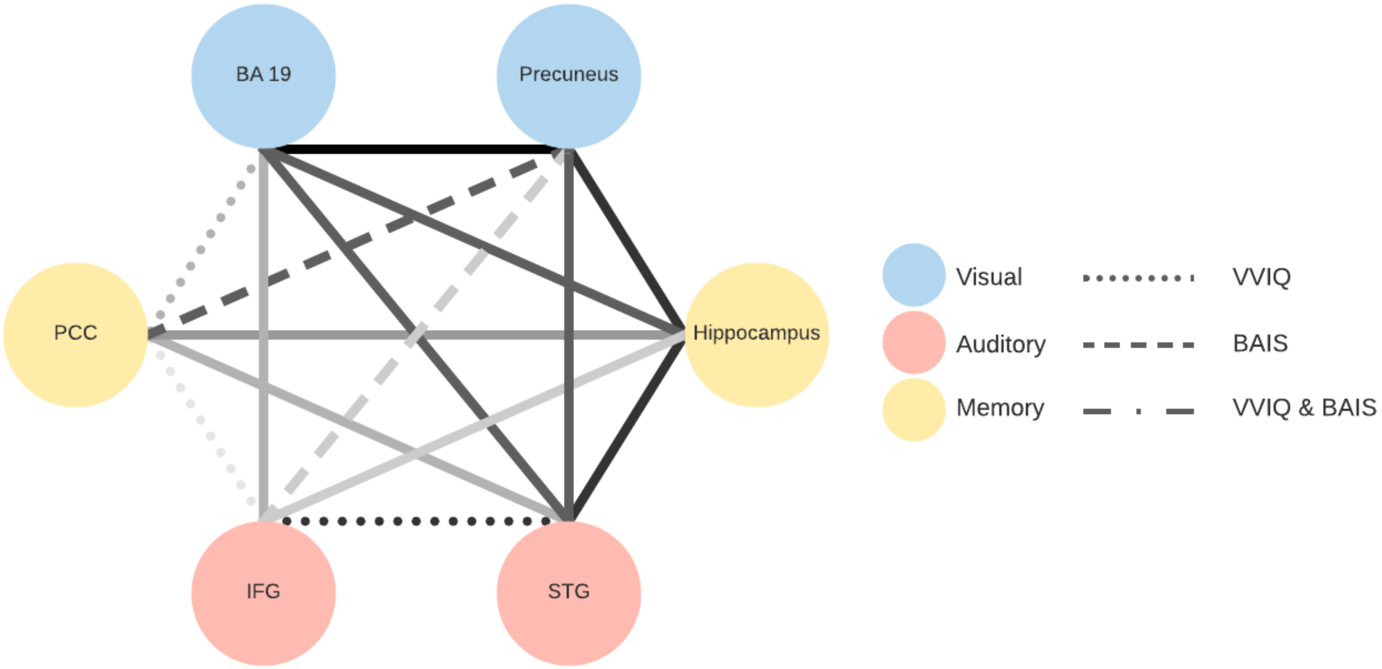


Figure 5. Group B Correlations



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