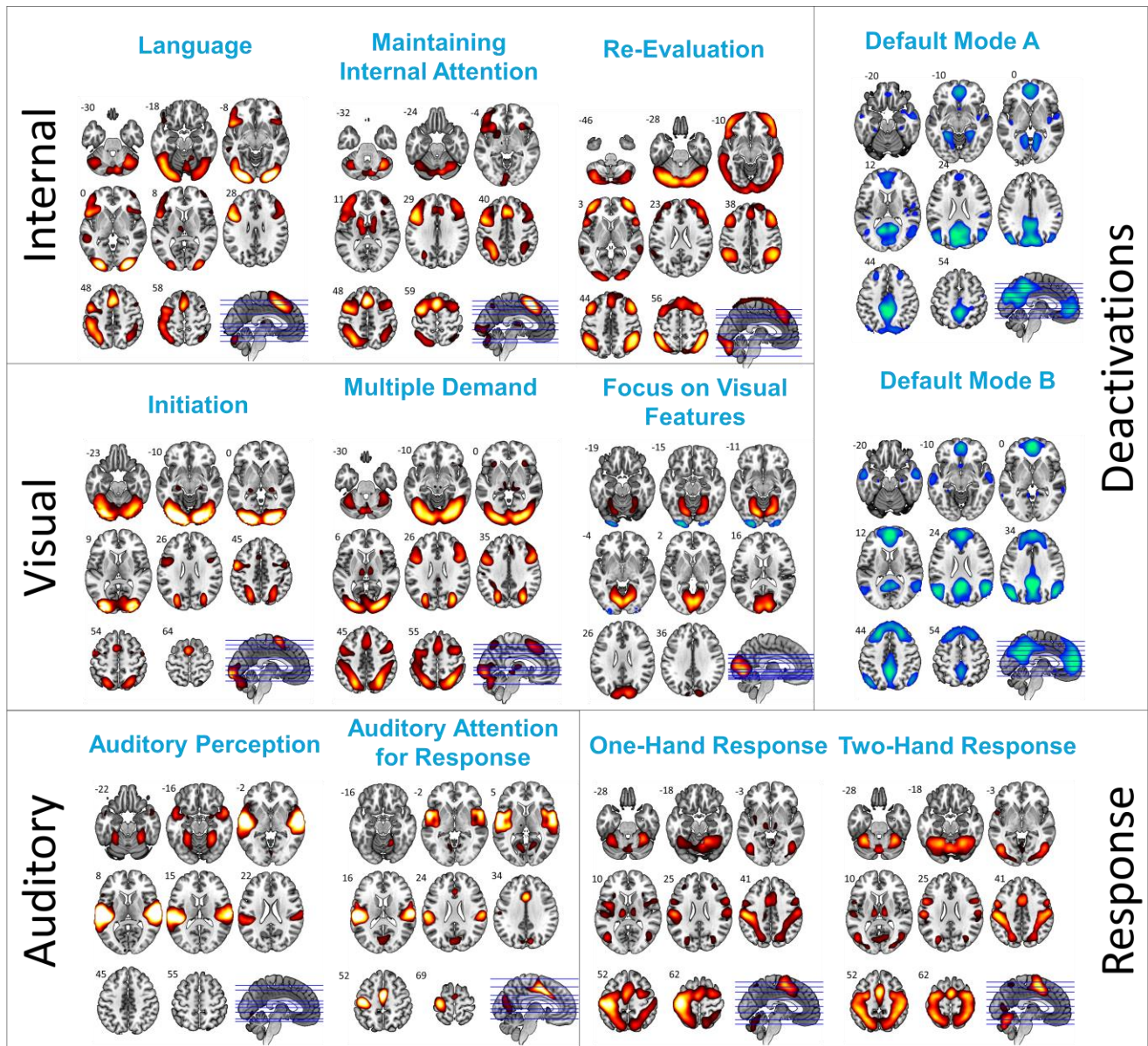


**Task-Based Brain Networks Detectable with fMRI**  
**Chantal M. Percival, Linda Chen, Hafsa B. Zahid & Todd S. Woodward**  
**Department of Psychiatry, University of British Columbia, Canada**



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The goal of this work was to observe replicability of task-based brain networks over a range of tasks using patterns (as opposed to coordinates), and to propose a preliminary cognitive mode associated with each by way of inspection of the task-induced BOLD signal changes over a range of cognitive tasks. This pattern-based anatomical methodology is an alternative to the traditional coordinate-based methodology (Lancaster et al., 2000), and provides an efficient way to communicate the configuration of hundreds or thousands of voxels with one pattern. The functional cognitive-mode approach involves evidence-based determination of a network-specific cognitive mode based on observation of the task-induced BOLD changes over a wide range of tasks and task conditions. These anatomical and functional goals were achieved by re-analysis of fMRI data collected in our laboratory and others', from both published and unpublished studies, and working towards definition of a cognitive mode associated with each network by observing BOLD signal change associated with a set of anatomical patterns over a range of tasks and task conditions.

### **fMRI-CPCA Overview**

Constrained principal component analysis for functional magnetic resonance imaging (fMRI-CPCA) was employed to extract the task-based functional brain networks on which the 12 prototypical networks are based. fMRI-CPCA follows four fundamental principles used to analyze task-based fMRI data: (1) variance in the BOLD data submitted to dimension reduction is constrained to that related to task timing, (2) an assumed model of the hemodynamic response (HDR) is not used, (3) multivariate analysis of eigenvalue-based patterns across voxels is used, and (4) no parcellations, regions of interest (ROI), or pre-determined network masks are imposed, allowing genuine whole-brain analysis.

The theory and proofs of CPCA are detailed in previously published work (Hunter & Takane, 2002; Lavigne, Rapin, et al., 2015; Metzak et al., 2011; Metzak et al., 2012; Takane & Hunter, 2001; Whitman et al., 2013; Woodward et al., 2013) and comparisons with other multivariate methods are described in Metzak et al. (2011). A general overview of the mathematical steps for fMRI data is provided on the subsequent page, and the software code is freely available online at <https://www.nitrc.org/projects/fmricpca>.

Conceptually, fMRI-CPCA combines multivariate multiple regression analysis and principal component analysis (PCA) into a unified framework. Multivariate multiple regression isolates variance in BOLD signal predictable from the independent variables that are the design matrix. Then PCA is performed on the matrix of predicted scores

The PCA component loadings are interpreted spatially, depicting the brain networks (systems of inter-correlated voxels), and temporally through component scores. The component scores provide a value indexing the activity of each brain network for every brain scan (TR). They are regressed onto the Finite Impulse Response (FIR) model matrix to obtain predictor weights for every participant in each condition in each component. Then, the predictor weights are plotted to produce task-induced hemodynamic response (HDR) changes. Thus, through fMRI-CPCA, we are able to (1) identify multiple functional brain networks that are simultaneously involved in a cognitive task, (2) estimate the HDR shape following stimulus presentation for each network

separately for each participant and condition, and (3) statistically test the effect of task conditions on estimated HDR shapes for each functional brain network using ANOVAs.

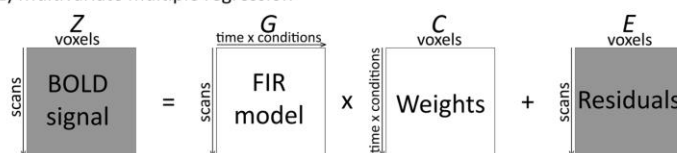
### Mathematical steps of fMRI-CPCA.

**Step 1:** Multivariate least-squares regression of blood oxygen level-dependent (BOLD) intensity values,  $Z$ , onto finite impulse response (FIR) basis set,  $G$  (performed for each participant). The value 1 is placed in cells of  $G$  for which BOLD signal is to be estimated, and the value 0 in all other cells. The  $C$  matrix, where  $C = (G'G)^{-1}G'Z$ , comprises condition-specific regression weights.  $GC$  represents the variability in  $Z$  that is predictable from  $G$  (i.e., the task-related variability in BOLD signal). Individual participant  $GC$  matrices are concatenated to create the resulting  $GC$  matrix in the following step.

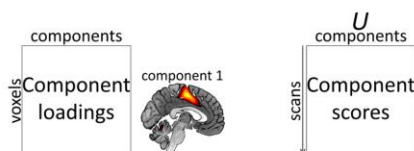
**Step 2:** Singular value decomposition (of which PCA is a special case) is used to extract components in  $GC$  that represent temporally orthogonal functional brain networks in which coordinated BOLD activity is directly related to the task timing. This also produces a matrix,  $U$ , containing the component scores for each participant. Anatomical regions are visualized by overlaying thresholded component loadings onto a brain template.

**Step 3:** For each participant, component scores ( $U$ ) are regressed onto  $G$  to produce predictor weights ( $P$ ) estimating the intensity of the component at each time bin coded in  $G$ . When successfully detecting the BOLD response, predictor weights will take the shape of a hemodynamic response (HDR) when plotted over post-stimulus time, and may be input to conventional statistical analyses such as repeated-measures ANOVA, since there is a separate HDR shape for each subject, condition and component.

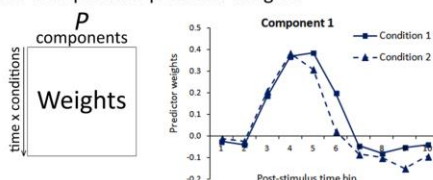
(1) Multivariate multiple regression



(2) PCA on  $GC$



(3) Regress  $U$  onto  $G$  to produce predictor weights

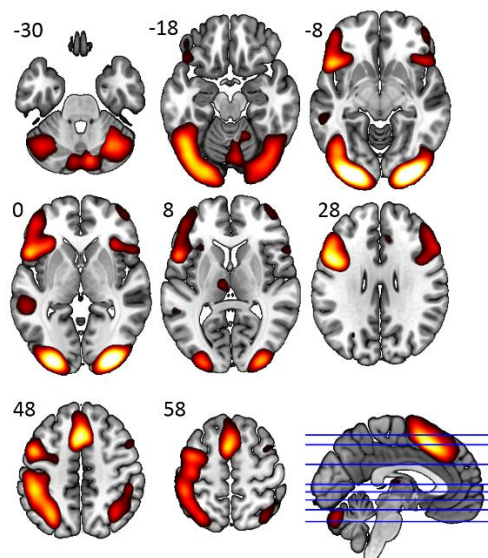


### *fMRI Measures of Cognitive Functions*

These brain image templates were created by averaging over exemplars of each network. Publications containing these networks are listed below. Any fMRI-CPCA derived network can be automatically classified into those depicted in Figure 1 by a MATLAB-based algorithm. This involved digitizing 20-30 brain slices prototypical of each of the networks, and correlating newly derived networks with those prototype slices, and classifying based on the magnitude of the correlations. Activation in these networks is thought to be capturing the neural correlates of the multiple modular cognitive processes that create an **fMRI-specific, emergent, cognitive mode**. The functions of these cognitive modes are determined by cross-interpreting HDR shapes over the range of tasks eliciting each network.

Networks	Images	Examples
<i>Cognitive processes involved in attending to internal representations</i>		
There are three networks which focus on cognitive modes primarily involved in attending to internal representations.		
The first is the <i>Language Network (LN)</i> . This network is well established (Fedorenko et al., 2024; Lipkin et al., 2022). This network was previously reported by our group in a number of publications, labelled the Linguistic Processing Network (LPN) (Kusi et al., 2022; Wong et al., 2020), and the Semantic Integration Network (SIN) (Woodward et al., 2015). However, in our most recent publication eliciting this networks (Besso et al., 2024), we adapted the LN terminology as suggested by the Fedorenko group (Fedorenko et al., 2024; Lipkin et al., 2022), to avoid numerous labels for the same general anatomical network configuration (Uddin et al., 2022; Uddin et al., 2019).		
The second is <i>Maintaining Internal Attention (MAIN)</i> , which was referred to previously as the <i>Internal Attention Network</i> (Sanford et al., 2020b; Sanford & Woodward, 2021) and the <i>Saliency Network</i> (Larivière et al., 2017). This network shows load-dependence for items in verbal and spatial working memory (Chen et al., 2024; Sanford et al., 2020b; Sanford & Woodward, 2021), and increased activity when imagine the past or future relative to episodic recall (Momeni et al., 2024).		
The third is <i>Re-Evaluation (RE-EV)</i> . Our group has previously reported the RE-EV network in several publications, though it has been referred to by other names; namely, the Evaluation Network (Sanford, 2019), the Cognitive Evaluation Network (Lavigne, 2018; Lavigne et al., 2020; Lavigne et al., 2020), and the Integration Network (Lavigne et al., 2015). A review of these task-induced BOLD changes over 6 tasks showing the RE-EV patterns was associated with the RE-EV network configuration converged on a cognitive mode involving re-evaluating, re-considering, or regulating mental states (Redway et al., 2024). It is more active when disconfirming evidence is presented relative to confirming (Lavigne et al., 2020; Lavigne et al., 2020), and this is decreased in delusions (fixed false beliefs) in schizophrenia (Lavigne et al., 2020), and delusional ideation in healthy people (Lavigne et al., 2020),. It is also more active during incongruent relative to neutral Stroop task performance (Sanford, 2019, Chapter 4.4), increased in conditions involving enhancing or suppress responses to negative stimuli.		





### Summary

Zeng, E., Shahki, J., Woodward, T. S. (2024). The pattern-based anatomy and cognitive mode associated with the language network in fMRI. *PsyArXiv*. May 28. [osf.io/preprints/psyarxiv/c83d7](https://osf.io/preprints/psyarxiv/c83d7). DOI:10.31234/osf.io/c83d7.

### Component 2

Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. & Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. *Psychiatry Research: Neuroimaging*. <https://doi.org/10.1016/j.psychresns.2024.111824>

### Component 2

Roes, M.M., Chinchani, A.M., & Woodward, T.S. (2023). Reduced functional connectivity in brain networks underlying paired associates memory encoding in schizophrenia. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, 8(1), 61-70. <https://doi.org/10.1016/j.bpsc.2021.07.003>

### Component 2

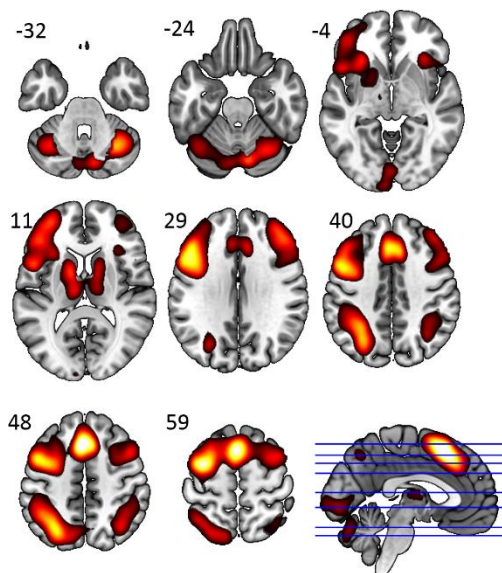
Kusi, M., Wong, S.T.S., Percival, C.M., Zurrin, R., Roes, M.M., Woodward, T.S., & Goghari, V.M. (2022). Altered activity in functional brain networks involved in lexical decision making in bipolar disorder: an fMRI case-control study. *Journal of Affective Disorders*, 317, 59-71. <https://doi.org/10.1016/j.jad.2022.08.040>

### Component 3

Wong, S.T.S., Goghari, V.M., Sanford, N., Lim, R., Clark, C., Metzrak, P.D., Rossell, S.L., Menon, M., & Woodward, T.S. (2020). Functional brain networks involved in lexical decision. *Brain and Cognition*, 138, Article 103631. <https://doi.org/10.1016/j.bandc.2019.103631>

### Component 3

Goghari, V.M., Sanford, N., Spilka, M.J. & Woodward, T.S. (2017). Task-related functional connectivity analysis of emotion discrimination in a family study of schizophrenia. *Schizophrenia Bulletin*, 43(6), 1348–1362. <https://doi.org/10.1093/schbul/sbx004>



### Component 2

Sanford, N., & Woodward, T.S. (2021). Functional delineation of prefrontal networks underlying working memory in schizophrenia: a cross-data-set examination. *Journal of Cognitive Neuroscience*, 33(9), 1880-1908. [https://doi.org/10.1162/jocn\\_a\\_01726](https://doi.org/10.1162/jocn_a_01726)

### Component 3- Multi-Experiment

Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-merging for finer separation of functional brain networks in working memory. *Cortex*, 125, 246-271. <https://doi.org/10.1016/j.cortex.2019.12.014>

### Component 2- Chapter 5

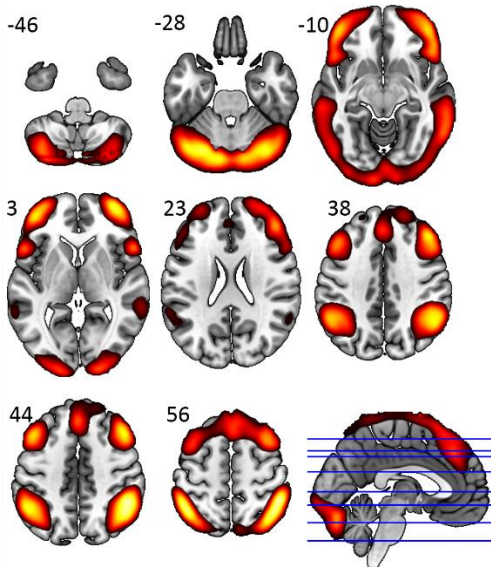
Sanford, N.A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library. <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

### Component 2

Larivière, S., Lavigne, K.M., Woodward, T.S., Gerretsen, P., Graff-Guerrero, A., & Menon, M. (2017). Altered functional connectivity in brain networks underlying self-referential processing in delusions of reference in schizophrenia. *Psychiatry Research: Neuroimaging*, 263, 32–43. <https://doi.org/10.1016/j.psychresns.2017.03.005>

### Component 3

Metzak, P.D., Riley, J., Wang, L., Whitman, J.C., Ngan, E.T.C. & Woodward, T.S. (2012). Decreased efficiency of task-positive and task-negative networks during working memory in schizophrenia. *Schizophrenia Bulletin*, 38(4), 803-813. <https://doi.org/10.1093/schbul/sbq154>



### Summary

Redway, S., Arreaza, L., Shahki, J., Zeng, E., & Woodward, T. (2024). The Pattern-Based Anatomy and Cognitive Mode associated with the Re-Evaluation (RE-EV) Network in fMRI. PsyArXiv. June 27.

<https://doi.org/10.31234/osf.io/y7pv2>

### Component 3- Chapter 4 Analysis 3 TSI

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.

<https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

### Component 3- Study 2

### Component 3- Study 3

Lavigne, K. M. (2018). *Cognitive biases and functional brain networks underlying delusions in schizophrenia* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.

<https://open.library.ubc.ca/collections/ubctheses/24/items/1.0364055>

### Component 1

Lavigne, K.M., Metzak, P.D., & Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. *NeuroImage*, 112, 138-151.

<https://doi.org/10.1016/j.neuroimage.2015.02.043>

### ***Cognitive processes involved in attending to visually presented stimuli.***

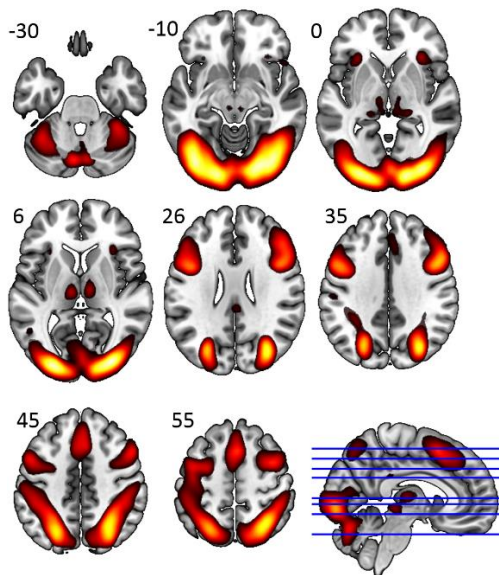
There are three networks which focus on cognitive modes primarily involved in attending to visual representations.

The first is *Initiation (INIT)*, which has been referred to previously as the *Energizing Network* (Sanford & Woodward, 2021), *Visual Attention Network* (Sanford et al., 2020a, 2020b), *Visual Network*, and *Encoding/Probe* (Woodward et al., 2013). This network involves restarting cognitive processing after a break of a few seconds after a set of operations, and peaks very early in the trial (Sanford et al., 2020a, 2020b).

The second is the *Multiple Demand Network (MDN)*, which has been published previously by our group with different nomenclature as the *External Attention Network* (Sanford et al., 2020b), *Visual Attention Network* (Fouladirad et al., 2022; Lavigne et al., 2020), and *Saliency Network* (Lavigne et al., 2020). This network is activated when maintaining attention to rapidly presented stimuli (Lavigne, 2018; Lavigne et al., 2020; Whitman et al., 2013), and shows increased activity under conditions of more difficult decision making (Fouladirad et al., 2022).

The third is *Focus on Visual Features (FoVF)*, which has been referred to previously as the *Occipital Network* (Sanford et al., 2020b) and *Undershoot* (Woodward et al., 2013). This network is activated when details of a scene are important as in spatial working memory, but suppressed when it is better to ignore them, for example, when they could impede performance in the Stroop task (Sanford et al., 2020b).





### Component 1

Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. & Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. *Psychiatry Research: Neuroimaging*.

### Component 3

Zurrin, R., Wong, S.T.S., Roes, M.M., Percival, C.M., Chinchani, A., Arreaza, L., Kusi, M., Momeni, A., Rasheed, M., Mo, Z., Goghari, V.M., & Woodward, T.S. (2024). Functional brain networks involved in the Raven's Standard Progressive Matrices task and their relation to theories of fluid intelligence. *Intelligence*, 103, Article 101807. <https://doi.org/10.1016/j.intell.2024.101807>

### Component 1

### Component 4

Fouladirad, S., Chen, L.V., Roes, M., Chinchani, A., Percival, C., Khangura, J., Zahid, H., Moscovitz, A., Arreaza, L., Wun, C., Sanford, N., Balzan, R., Moritz, S., Menon, M., & Woodward, T.S. (2022). Functional brain networks underlying probabilistic reasoning and delusions in schizophrenia. *Psychiatry Research: Neuroimaging*, 323, Article 111472. <https://doi.org/10.1016/j.psychresns.2022.111472>

### Component 3

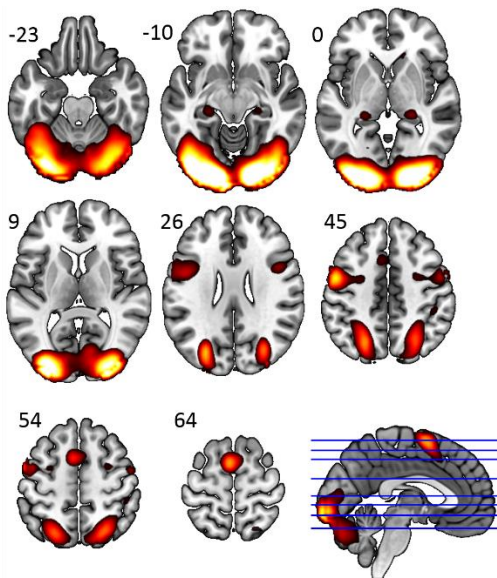
Lavigne, K.M., Menon, M., Moritz, S., & Woodward, T.S. (2020). Functional brain networks underlying evidence integration and delusional ideation. *Schizophrenia Research*, 216, 302-309. <https://doi.org/10.1016/j.schres.2019.11.038>

### Component 5

Lavigne, K.M., Metzak, P.D., & Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. *NeuroImage*, 112, 138-151. <https://doi.org/10.1016/j.neuroimage.2015.02.043>

### Component 1

Woodward, T.S., Tipper, C.M., Leung, A., Lavigne, K.M., Sanford, N., Metzak, P.D. (2015). Reduced functional connectivity during controlled semantic integration in schizophrenia: A multivariate approach. *Human Brain Mapping*, 36(8), 2948-2964. <https://doi.org/10.1002/hbm.22820>



### Component 5

Sanford, N., & Woodward, T.S. (2021). Functional delineation of prefrontal networks underlying working memory in schizophrenia: a cross-data-set examination. *Journal of Cognitive Neuroscience*, 33(9), 1880-1908. [https://doi.org/10.1162/jocn\\_a\\_01726](https://doi.org/10.1162/jocn_a_01726)

### Component 2- Single-Experiment

### Component 2- Multi-Experiment

Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. *Cortex*, 125, 246-271.

<https://doi.org/10.1016/j.cortex.2019.12.014>

### Component 2

Lavigne, K.M., Metzack, P.D., & Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. *NeuroImage*, 112, 138-151.

<https://doi.org/10.1016/j.neuroimage.2015.02.043>

### Component 1

Lavigne, K.M., Rapin, L.A., Metzack, P.D., Whitman, J.C., Jung, K., Dohen, M., Loevenbruck, H., & Woodward, T.S. (2015). Left-dominant temporal-frontal hypercoupling in schizophrenia patients with hallucinations during speech perception. *Schizophrenia Bulletin*, 41(1), 259-267. <https://doi.org/10.1093/schbul/sbu004>

### Component 1

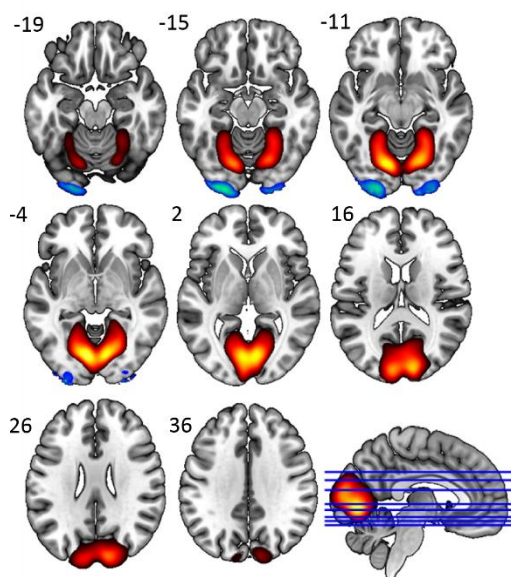
Woodward, T.S., Feredoes, E., Metzack, P.D., Takane, Y., & Manoach, D.S. (2013). Epoch-specific functional networks involved in working memory. *NeuroImage*, 65, 529-539.

<https://doi.org/10.1016/j.neuroimage.2012.09.070>

### Component 2

Metzack, P.D., Riley, J., Wang, L., Whitman, J.C., Ngan, E.T.C. & Woodward, T.S. (2012). Decreased efficiency of task-positive and task-negative networks during working memory in schizophrenia. *Schizophrenia Bulletin*, 38(4), 803-813.

<https://doi.org/10.1093/schbul/sbq154>



### Component 6- Multi-Experiment

Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. *Cortex*, 125, 246-271.

<https://doi.org/10.1016/j.cortex.2019.12.014>

### Component 1- Chapter 4 Analysis 3 TSI

### Component 7- Chapter 5

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.

<https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

### Component 3

Lavigne, K.M., Metzak, P.D., & Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. *NeuroImage*, 112, 138-151.

<https://doi.org/10.1016/j.neuroimage.2015.02.043>

### Component 4

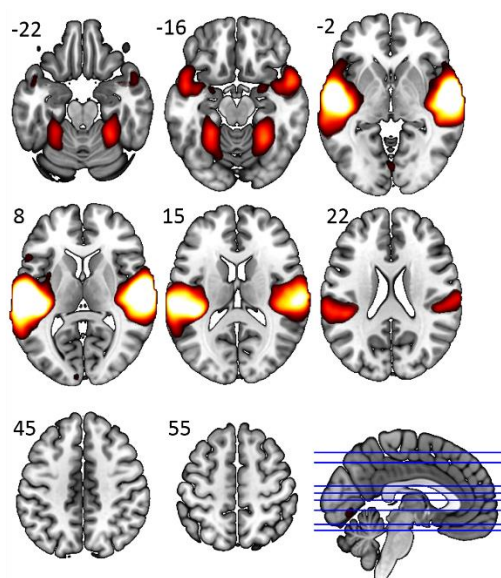
Woodward, T.S., Feredoes, E., Metzak, P.D., Takane, Y., & Manoach, D.S. (2013). Epoch-specific functional networks involved in working memory. *NeuroImage*, 65, 529-539.

<https://doi.org/10.1016/j.neuroimage.2012.09.070>

***Cognitive processes involved in attending to auditorily presented stimuli.***

There are two networks which measure cognitive processes involved in attending to auditory stimuli in different ways. The first is *Auditory Perception* (AUD), which has been referred to previously as the *Auditory Network* (Sanford et al., 2020a, 2020b). This network is active when listening to speech, and is hyperactive in hallucinations in schizophrenia (Lavigne & Woodward, 2018).

The second is the *Auditory Attention for Response* (AAR) network, which has been referred to previous as the *Auditory-Motor Attention Network* (Sanford & Woodward, 2021), *Sensorimotor Network* (Sanford et al., 2020b), *Auditory-Motor Network* (Lavigne & Woodward, 2018), and *(Auditory-Motor) Response Activation Network* (Lavigne et al., 2016). This network is activated when auditory stimuli is being monitored when a response is required, but deactivated during intensive monitoring of visual details (Lavigne et al., 2016; Lavigne & Woodward, 2018; Sanford et al., 2020b; Sanford & Woodward, 2021), analogous to the familiar situation where someone is visually monitoring their phone, they are less likely to hear what you're saying to them.



#### Component 2- Melbourne Patient/Control Radio Speech (Short/Medium/Long) Analysis

Gill, K., Percival, C., Roes, M., Arreaza, L., Chinchani, A., Sanford, N., Sena, W., Mohammadsadeghi, H., Menon, M., Hughes, M., Carruthers, S., Sumner, P., Woods, W., Jardri, R., Sommer, I.E., Rossell, S.L., & Woodward, T.S. (2022). Real-time symptom capture of hallucinations in schizophrenia with fMRI: absence of duration-dependent activity. *Schizophrenia Bulletin Open*, 3(1), Article sgac050. <https://doi.org/10.1093/schizbullopen/sgac050>

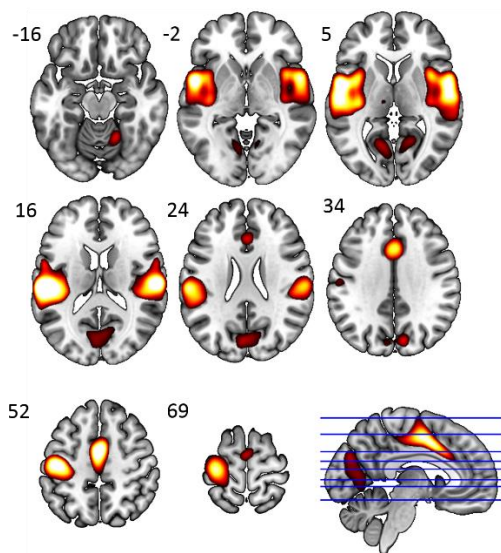
#### Component 7- Multi-Experiment

Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. *Cortex*, 125, 246-271. <https://doi.org/10.1016/j.cortex.2019.12.014>

#### Component 4- Chapter 4 Analysis 4 TGT

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library. <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>





### Component 3

Fouladirad, S., Chen, L.V., Roes, M., Chinchani, A., Percival, C., Khangura, J., Zahid, H., Moscovitz, A., Arreaza, L., Wun, C., Sanford, N., Balzan, R., Moritz, S., Menon, M., & Woodward, T.S. (2022). Functional brain networks underlying probabilistic reasoning and delusions in schizophrenia. *Psychiatry Research: Neuroimaging*, 323, Article 111472.

<https://doi.org/10.1016/j.psychresns.2022.111472>

### Component 3

Sanford, N., & Woodward, T.S. (2021). Functional delineation of prefrontal networks underlying working memory in schizophrenia: a cross-data-set examination. *Journal of Cognitive Neuroscience*, 33(9), 1880-1908. [https://doi.org/10.1162/jocn\\_a\\_01726](https://doi.org/10.1162/jocn_a_01726)

### Component 3- Chapter 5

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.

<https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

### Component 1

Lavigne, K.M., & Woodward, T.S. (2018). Hallucination- and speech-specific h Auditory Attention for Response ypercoupling in frontotemporal auditory and language networks in schizophrenia using combined task-based fMRI data: An fBIRN study. *Human Brain Mapping*, 39(4), 1582–1595.

<https://doi.org/10.1002/hbm.23934>

### Component 2

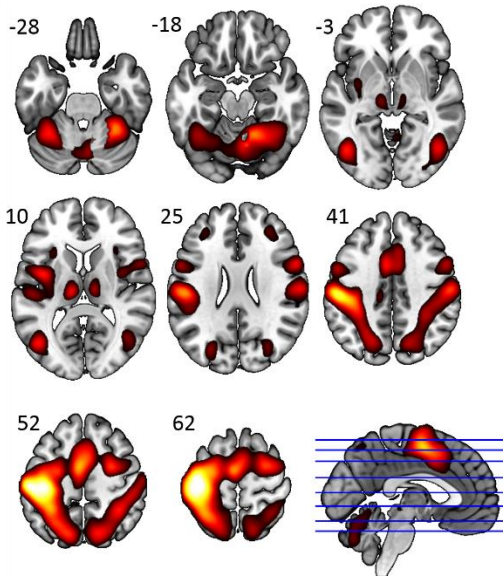
Lavigne, K.M., Menon, M., & Woodward, T.S. (2016). Impairment in subcortical suppression in schizophrenia: Evidence from the fBIRN oddball task. *Human Brain Mapping*, 37(12), 4640-4653.

<https://doi.org/10.1002/hbm.23334>

Sensorimotor Processes.

The *Motor Response* (RESP) network is involved in responding, with a HDR that peaks late in the trial, but it is lateralized for one-handed response (Sanford et al., 2020b), and bilateral for a two-handed response (Goghari et al., 2017). This network has been referred to previously in our published work as the *Responding Network* (Roes et al., 2023), *Sensorimotor (Response) Network* (Gill et al., 2022), *Posterior Cortical Midline Structure Network* (Larivière et al., 2017), *Dorsal Attention Network/Frontoparietal Network* (Woodward et al., 2016), *Dorsal Anterior Cingulate Cortex-Based Network* (Whitman et al., 2013), and *Probe* (Woodward et al., 2013).

One-Handed Response



Component 3

Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. & Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. *Psychiatry Research: Neuroimaging*.

Component 2

Zurrin, R., Wong, S.T.S., Roes, M.M., Percival, C.M., Chinchani, A., Arreaza, L., Kusi, M., Momeni, A., Rasheed, M., Mo, Z., Goghari, V.M., & Woodward, T.S. (2024). Functional brain networks involved in the Raven's Standard Progressive Matrices task and their relation to theories of fluid intelligence. *Intelligence*, 103, Article 101807. <https://doi.org/10.1016/j.intell.2024.101807>

Component 1

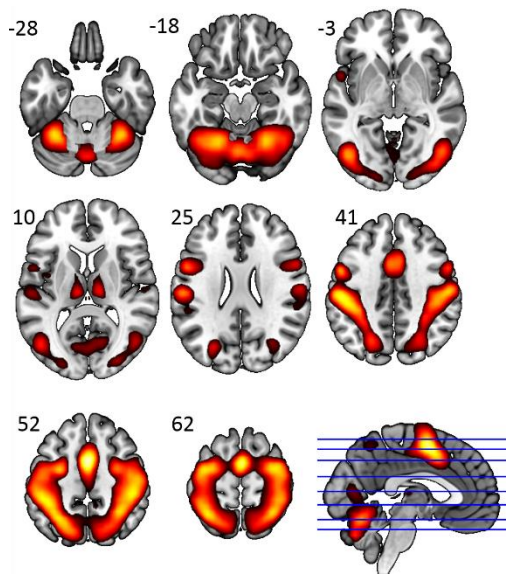
Roes, M.M., Chinchani, A.M., & Woodward, T.S. (2023). Reduced functional connectivity in brain networks underlying paired associates memory encoding in schizophrenia. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, 8(1), 61-70. <https://doi.org/10.1016/j.bpsc.2021.07.003>

Component 2

Fouladirad, S., Chen, L.V., Roes, M., Chinchani, A., Percival, C., Khangura, J., Zahid, H., Moscovitz, A., Arreaza, L., Wun, C., Sanford, N., Balzan, R., Moritz, S., Menon, M., & Woodward, T.S. (2022). Functional brain networks underlying probabilistic reasoning and delusions in schizophrenia. *Psychiatry Research: Neuroimaging*, 323, Article 111472. <https://doi.org/10.1016/j.psychresns.2022.111472>

Component 2- Melbourne and Utrecht Patient Hallucinations Merged Analysis

	<p>Gill, K., Percival, C., Roes, M., Arreaza, L., Chinchani, A., Sanford, N., Sena, W., Mohammadsadeghi, H., Menon, M., Hughes, M., Carruthers, S., Sumner, P., Woods, W., Jardri, R., Sommer, I.E., Rossell, S.L., &amp; Woodward, T.S. (2022). Real-time symptom capture of hallucinations in schizophrenia with fMRI: absence of duration-dependent activity. <i>Schizophrenia Bulletin Open</i>, 3(1), Article sgac050. <a href="https://doi.org/10.1093/schizbullopen/sgac050">https://doi.org/10.1093/schizbullopen/sgac050</a></p> <p><u>Component 3</u>  Kusi, M., Wong, S.T.S., Percival, C.M., Zurrin, R., Roes, M.M., Woodward, T.S., &amp; Goghari, V.M. (2022). Altered activity in functional brain networks involved in lexical decision making in bipolar disorder: an fMRI case-control study. <i>Journal of Affective Disorders</i>, 317, 59-71. <a href="https://doi.org/10.1016/j.jad.2022.08.040">https://doi.org/10.1016/j.jad.2022.08.040</a></p> <p><u>Component 3</u>  Lavigne, K.M., Menon, M., Moritz, S., &amp; Woodward, T.S. (2020). Functional brain networks underlying evidence integration and delusional ideation. <i>Schizophrenia Research</i>, 216, 302-309. <a href="https://doi.org/10.1016/j.schres.2019.11.038">https://doi.org/10.1016/j.schres.2019.11.038</a></p> <p><u>Component 1- Single-Experiment</u>  <u>Component 1- Multi-Experiment</u>  Sanford, N., Whitman, J.C., &amp; Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. <i>Cortex</i>, 125, 246-271. <a href="https://doi.org/10.1016/j.cortex.2019.12.014">https://doi.org/10.1016/j.cortex.2019.12.014</a></p> <p><u>Component 1</u>  Larivière, S., Lavigne, K.M., Woodward, T.S., Gerretsen, P., Graff-Guerrero, A., &amp; Menon, M. (2017). Altered functional connectivity in brain networks underlying self-referential processing in delusions of reference in schizophrenia. <i>Psychiatry Research: Neuroimaging</i>, 263, 32–43. <a href="https://doi.org/10.1016/j.psychresns.2017.03.005">https://doi.org/10.1016/j.psychresns.2017.03.005</a></p> <p><u>Component 4</u>  Lavigne, K.M., Metzak, P.D., &amp; Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. <i>NeuroImage</i>, 112, 138-151. <a href="https://doi.org/10.1016/j.neuroimage.2015.02.043">https://doi.org/10.1016/j.neuroimage.2015.02.043</a></p>
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### Component 2

Wong, S.T.S., Goghari, V.M., Sanford, N., Lim, R., Clark, C., Metzak, P.D., Rossell, S.L., Menon, M. & Woodward, T.S. (2020).

Functional brain networks involved in lexical decision. *Brain and Cognition*, 138, Article 103631.

<https://doi.org/10.1016/j.bandc.2019.103631>

### Component 1- Chapter 4 Analysis 2 SCAP

### Component 2- Chapter 4 Analysis 3 TSI

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.

<https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

### Component 1

Goghari, V.M., Sanford, N., Spilka, M.J. & Woodward, T.S. (2017).

Task-related functional connectivity analysis of emotion discrimination in a family study of schizophrenia. *Schizophrenia Bulletin*, 43(6), 1348–1362. <https://doi.org/10.1093/schbul/sbx004>

### Component 1

Woodward, T.S., Leong, K., Sanford, N., Tipper, C.M., & Lavigne, K.M. (2016). Altered balance of functional brain networks in schizophrenia. *Psychiatry Research: Neuroimaging*, 248, 94-104.

<https://doi.org/10.1016/j.psychresns.2016.01.003>

### Component 1

Metzak, P.D., Lavigne, K.M., & Woodward, T.S. (2015). Functional brain networks involved in reality monitoring. *Neuropsychologia*, 75, 50-60. <https://doi.org/10.1016/j.neuropsychologia.2015.05.014>

### Component 1

Whitman, J.C., Metzak, P.D., Lavigne, K.M., & Woodward, T.S.

(2013). Functional connectivity in a frontoparietal network involving the dorsal anterior cingulate cortex underlies decisions to accept a hypothesis. *Neuropsychologia*, 51(6), 1132–1141.

<https://doi.org/10.1016/j.neuropsychologia.2013.02.016>

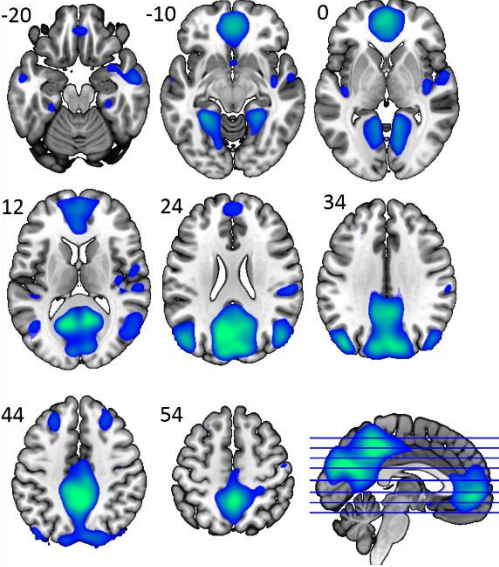
### Component 2

Woodward, T.S., Feredoes, E., Metzak, P.D., Takane, Y., & Manoach, D.S. (2013). Epoch-specific functional networks involved in working memory. *NeuroImage*, 65, 529-539.

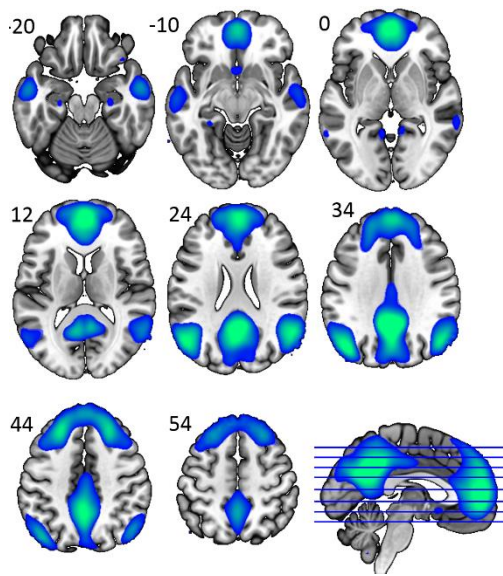
<https://doi.org/10.1016/j.neuroimage.2012.09.070>

Deactivations.

There are two deactivating networks. There is evidence that DMN-B is involved in *taking the self as a reference point* . They both decrease activity when carrying out a task, unless that task is imagining a past of future event (Momeni et al., 2024). These networks are known as the *Default Mode Network A* (DMNA; previously referred to by our group as the *Novel Default Mode Network*) and *Default Mode Network B* (DMNB; previously referred to by our group as the *Traditional Default Mode Network*). DMN-B is more commonly found in resting state research.

Default Mode Network A		<p><u>Component 2</u> Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. &amp; Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. <i>Psychiatry Research: Neuroimaging</i>.</p> <p><u>Component 1</u> Kusi, M., Wong, S.T.S., Percival, C.M., Zurrin, R., Roes, M.M., Woodward, T.S., &amp; Goghari, V.M. (2022). Altered activity in functional brain networks involved in lexical decision making in bipolar disorder: an fMRI case-control study. <i>Journal of Affective Disorders</i>, 317, 59-71. <a href="https://doi.org/10.1016/j.jad.2022.08.040">https://doi.org/10.1016/j.jad.2022.08.040</a></p> <p><u>Component 3</u> Wong, S.T.S., Goghari, V.M., Sanford, N., Lim, R., Clark, C., Metzack, P.D., Rossell, S.L., Menon, M. &amp; Woodward, T.S. (2020). Functional brain networks involved in lexical decision. <i>Brain and Cognition</i>, 138, Article 103631. <a href="https://doi.org/10.1016/j.bandc.2019.103631">https://doi.org/10.1016/j.bandc.2019.103631</a></p> <p><u>Component 3</u> Metzack, P.D., Riley, J., Wang, L., Whitman, J.C., Ngan, E.T.C. &amp; Woodward, T.S. (2012). Decreased efficiency of task-positive and task-negative networks during working memory in schizophrenia. <i>Schizophrenia Bulletin</i>, 38(4), 803-813. <a href="https://doi.org/10.1093/schbul/sbq154">https://doi.org/10.1093/schbul/sbq154</a></p>
Default Mode Network B		<p><u>Component 3</u> Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. &amp; Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. <i>Psychiatry Research: Neuroimaging</i>. <a href="https://doi.org/10.1016/j.psychresns.2024.111824">https://doi.org/10.1016/j.psychresns.2024.111824</a></p> <p><u>Component 1</u></p>





Zurrin, R., Wong, S.T.S., Roes, M.M., Percival, C.M., Chinchani, A., Arreaza, L., Kusi, M., Momeni, A., Rasheed, M., Mo, Z., Goghari, V.M., & Woodward, T.S. (2024). Functional brain networks involved in the Raven's Standard Progressive Matrices task and their relation to theories of fluid intelligence. *Intelligence*, 103, Article 101807. <https://doi.org/10.1016/j.intell.2024.101807>

#### Component 3

Roes, M.M., Chinchani, A.M., & Woodward, T.S. (2023). Reduced functional connectivity in brain networks underlying paired associates memory encoding in schizophrenia. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, 8(1), 61-70. <https://doi.org/10.1016/j.bpsc.2021.07.003>

#### Component 1

Lavigne, K.M., Menon, M., Moritz, S., & Woodward, T.S. (2020). Functional brain networks underlying evidence integration and delusional ideation. *Schizophrenia Research*, 216, 302-309. <https://doi.org/10.1016/j.schres.2019.11.038>

#### Component 3- Single-Experiment

#### Component 4- Multi-Experiment

Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. *Cortex*, 125, 246-271. <https://doi.org/10.1016/j.cortex.2019.12.014>

#### Component 1

Wong, S.T.S., Goghari, V.M., Sanford, N., Lim, R., Clark, C., Metzack, P.D., Rossell, S.L., Menon, M. & Woodward, T.S. (2020). Functional brain networks involved in lexical decision. *Brain and Cognition*, 138, Article 103631. <https://doi.org/10.1016/j.bandc.2019.103631>

#### Component 3- Chapter 4 Analysis 1 WM

#### Component 2- Chapter 4 Analysis 2 SCAP

#### Component 1- Chapter 5

Sanford, N. A. (2019). *Functional brain networks underlying working memory performance in schizophrenia : a multi-experiment approach* [Doctoral dissertation, University of British Columbia]. University of British Columbia Library. <https://open.library.ubc.ca/collections/ubctheses/24/items/1.0387449>

#### Component 2- Study 2

#### Component 2- Study 3

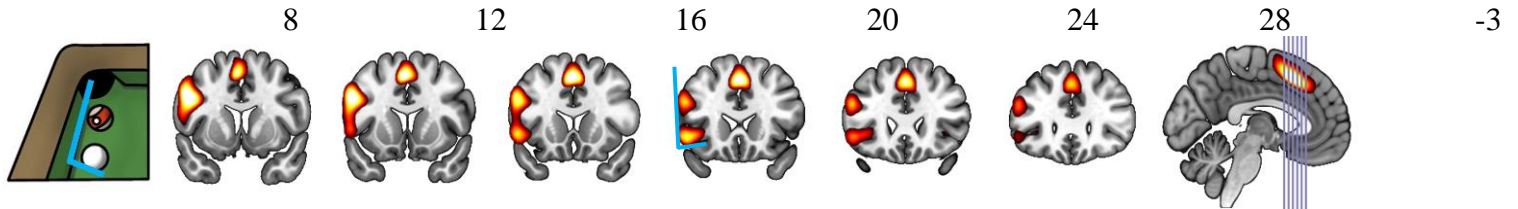
	<p>Lavigne, K. M. (2018). <i>Cognitive biases and functional brain networks underlying delusions in schizophrenia</i> [Doctoral dissertation, University of British Columbia]. University of British Columbia Library.  <a href="https://open.library.ubc.ca/collections/ubctheses/24/items/1.0364055">https://open.library.ubc.ca/collections/ubctheses/24/items/1.0364055</a></p> <p><u>Component 2</u></p> <p>Goghari, V.M., Sanford, N., Spilka, M.J. &amp; Woodward, T.S. (2017). Task-related functional connectivity analysis of emotion discrimination in a family study of schizophrenia. <i>Schizophrenia Bulletin</i>, 43(6), 1348–1362. <a href="https://doi.org/10.1093/schbul/sbx004">https://doi.org/10.1093/schbul/sbx004</a></p> <p><u>Component 2</u></p> <p>Woodward, T.S., Leong, K., Sanford, N., Tipper, C.M., &amp; Lavigne, K.M. (2016). Altered balance of functional brain networks in schizophrenia. <i>Psychiatry Research: Neuroimaging</i>, 248, 94-104. <a href="https://doi.org/10.1016/j.psychresns.2016.01.003">https://doi.org/10.1016/j.psychresns.2016.01.003</a></p> <p><u>Component 4</u></p> <p>Lavigne, K.M., Metzak, P.D., &amp; Woodward, T.S. (2015). Functional brain networks underlying detection and integration of disconfirmatory evidence. <i>NeuroImage</i>, 112, 138-151. <a href="https://doi.org/10.1016/j.neuroimage.2015.02.043">https://doi.org/10.1016/j.neuroimage.2015.02.043</a></p> <p><u>Component 2</u></p> <p>Woodward, T.S., Tipper, C.M., Leung, A., Lavigne, K.M., Sanford, N., Metzak, P.D. (2015). Reduced functional connectivity during controlled semantic integration in schizophrenia: A multivariate approach. <i>Human Brain Mapping</i>, 36(8), 2948-2964. <a href="https://doi.org/10.1002/hbm.22820">https://doi.org/10.1002/hbm.22820</a></p> <p><u>Component 2</u></p> <p>Whitman, J.C., Metzak, P.D., Lavigne, K.M., &amp; Woodward, T.S. (2013). Functional connectivity in a frontoparietal network involving the dorsal anterior cingulate cortex underlies decisions to accept a hypothesis. <i>Neuropsychologia</i>, 51(6), 1132–1141. <a href="https://doi.org/10.1016/j.neuropsychologia.2013.02.016">https://doi.org/10.1016/j.neuropsychologia.2013.02.016</a></p>
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### Characteristic Anatomical Patterns of the Proposed Prototypical Networks

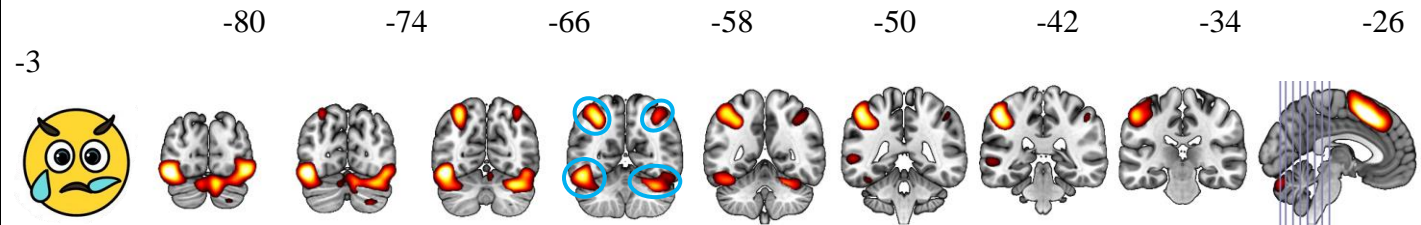
Each of the twelve task-based brain networks described above were identified through replicable and characteristic anatomical activation patterns. The characteristic activation patterns for each network are detailed below.

#### **Language Network**

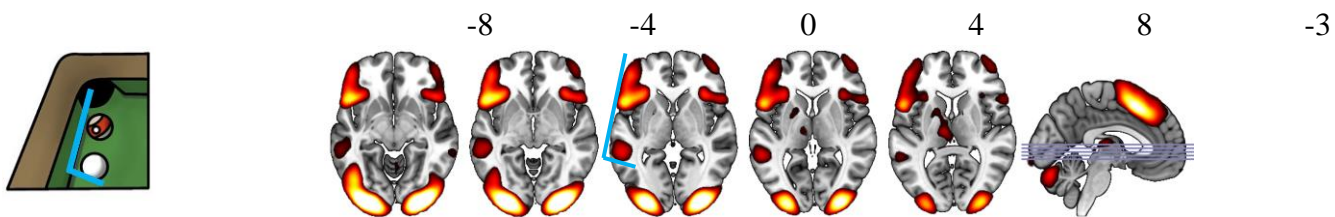
##### Pattern 1: Rail Shot Coronal



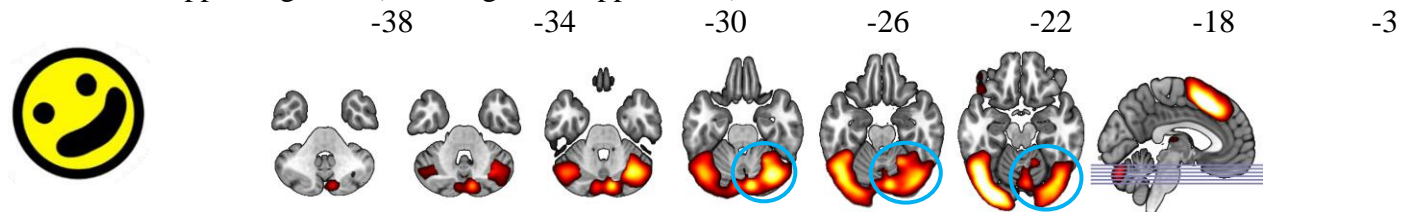
##### Pattern 2: Tears Blown Leftwards and Eyebrows



##### Pattern 3: Rail Shot Axial

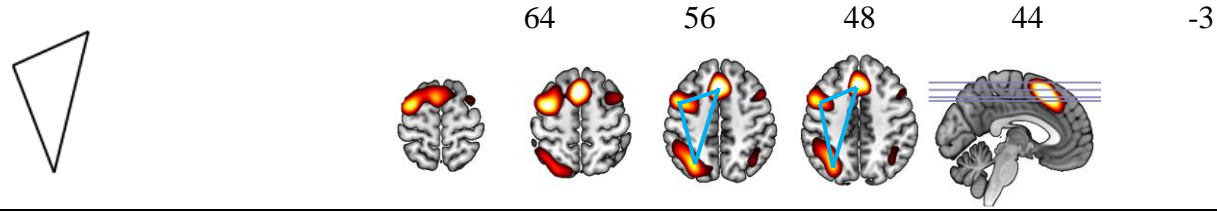


##### Pattern 4: Disappearing Face (Start Right, Disappear Left)

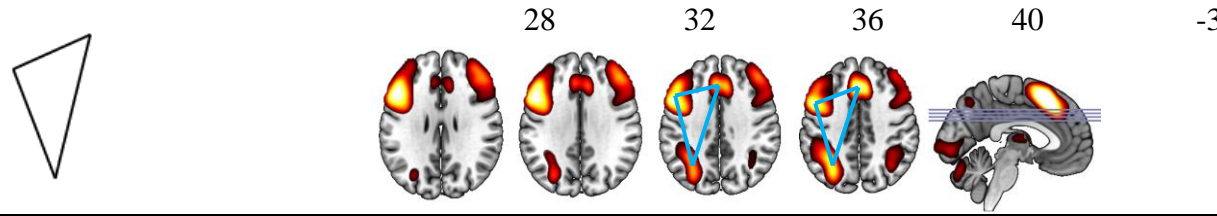


*Maintaining Internal Attention*

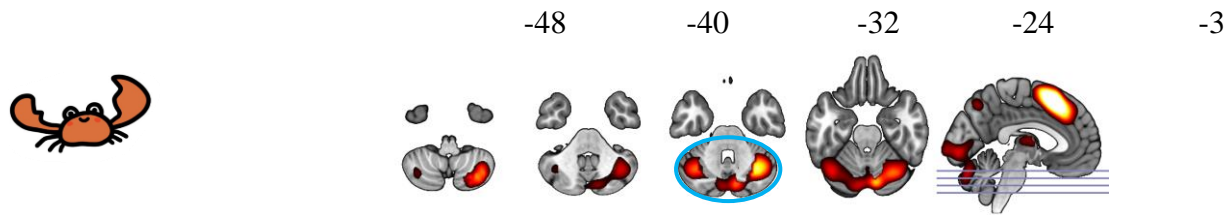
Pattern 1: Left-Lateralized Upper Triangle



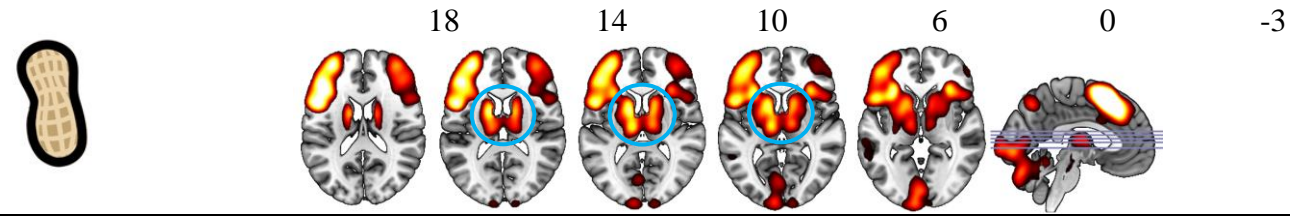
Pattern 2: Left-Lateralized Lower Triangle



Pattern 3: Right-Sided Crab Claw



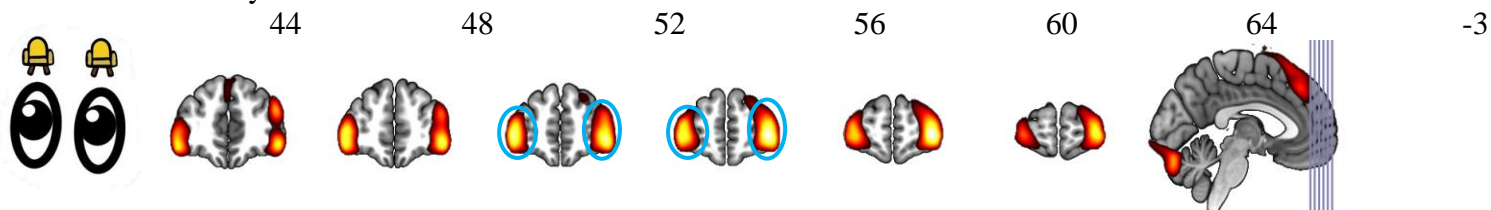
Pattern 4: Found a Peanut



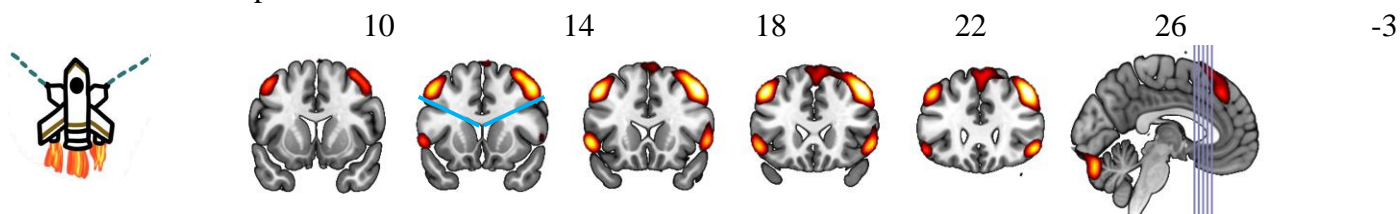


## Re-Evaluation

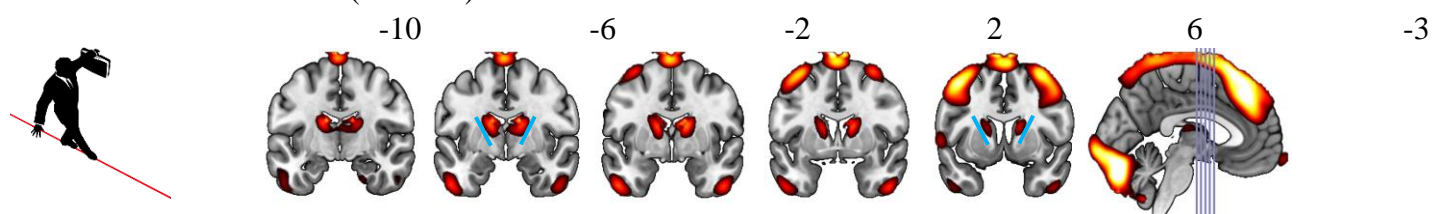
Pattern 1: Bilateral Eyeball Sitters



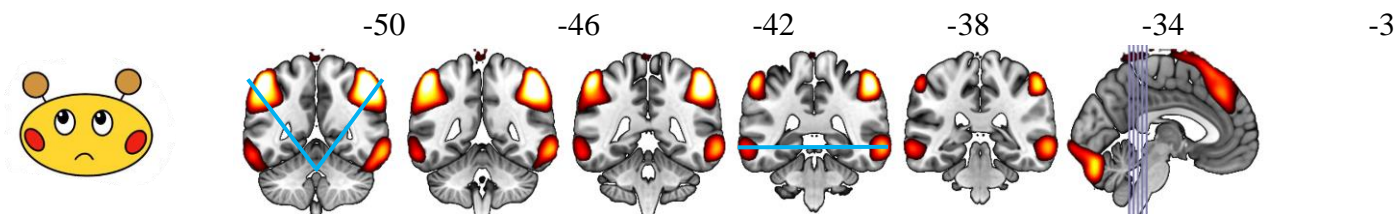
Pattern 2: Bilateral Space Invader Shooters



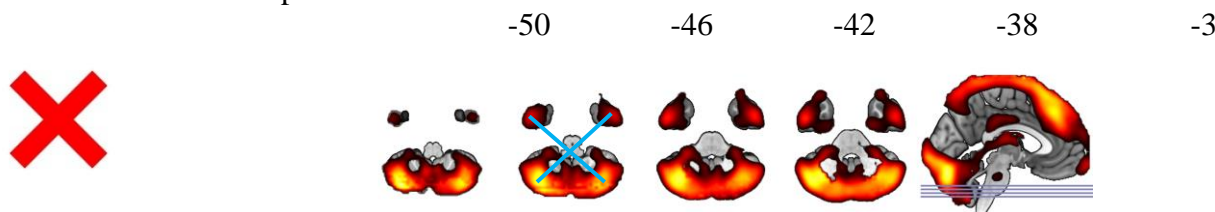
Pattern 3: Above the Line (Caudate)



Pattern 4: Sad Face Antennae and Flushed Cheeks



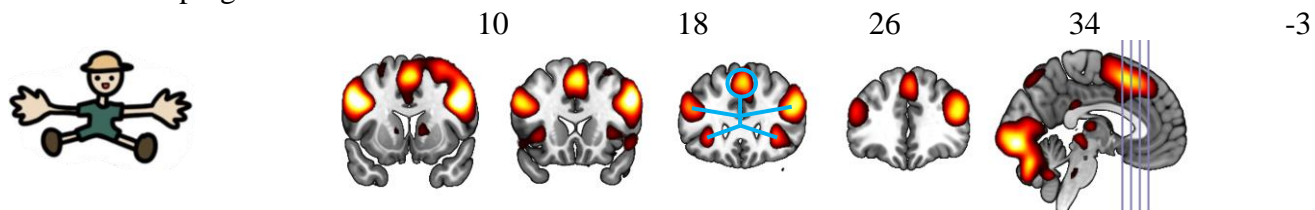
Pattern 5: X Marks the Spot



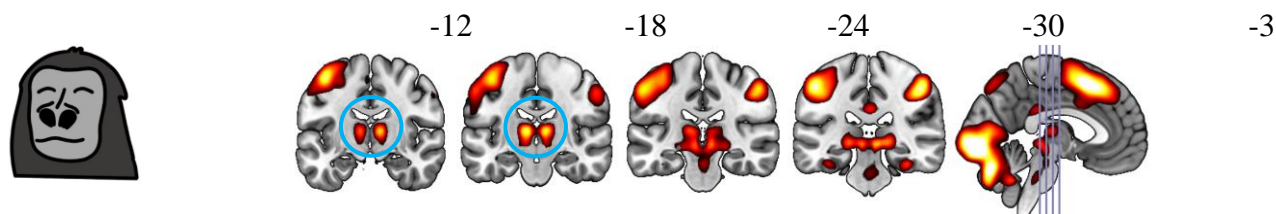


## Multiple Demand Network

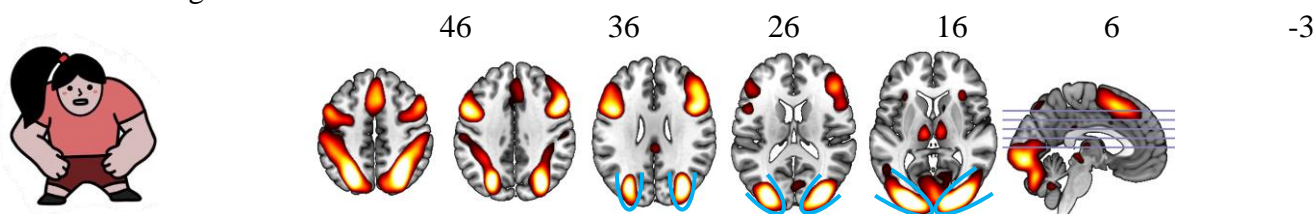
Pattern 1: Jumping Jack Flash



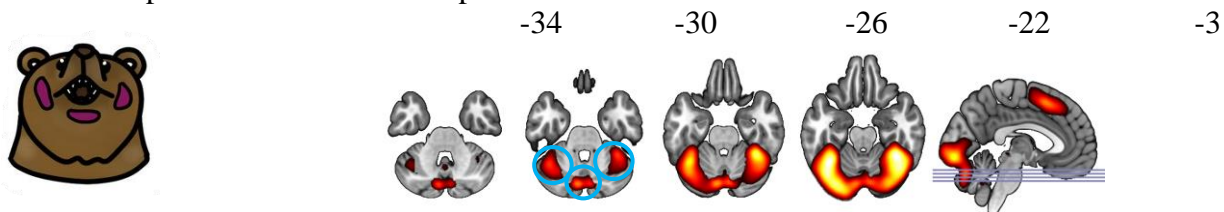
Pattern 2: Gorilla Nostrils



Pattern 3: Flexing Hands

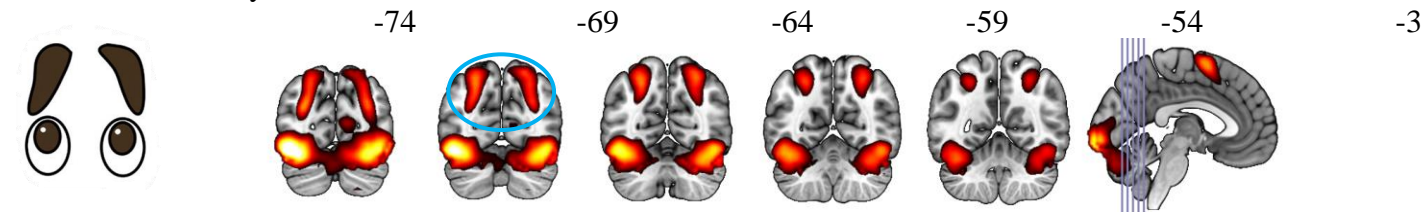


Pattern 4: Wipe Your Mouth Bear Triple Jam

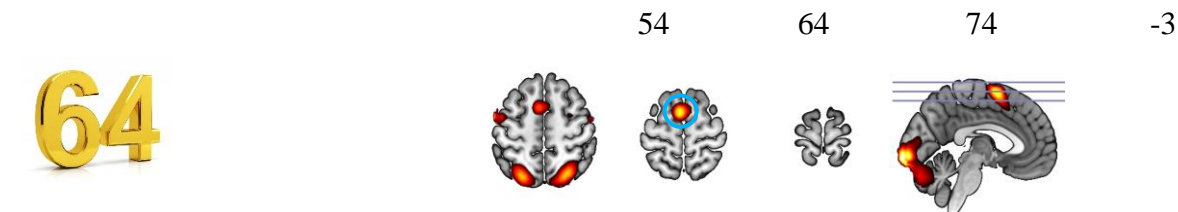


*Initiation*

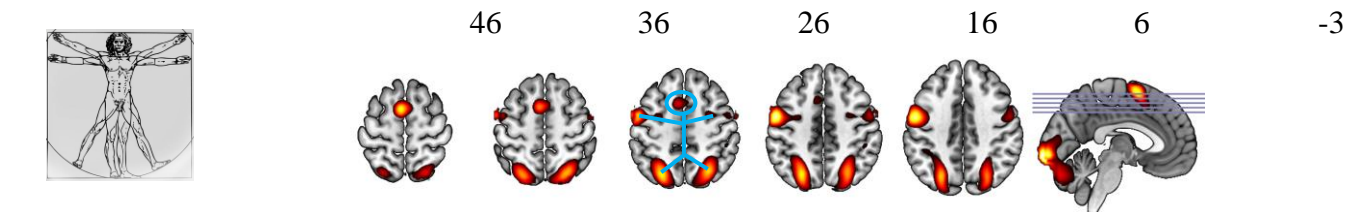
Pattern 1: Raised Eyebrows



Pattern 2: When I'm 64



Pattern 3: De Divina Proportione Front Guy



*Focus on Visual Features*

Pattern 1: Stay Puft



-89



-84



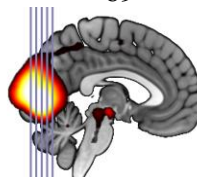
-79



-74



-69



-3

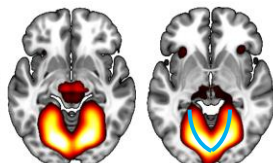
Pattern 2: Wishbone



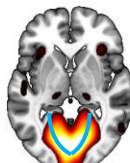
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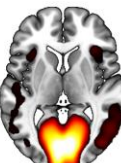
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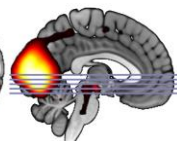
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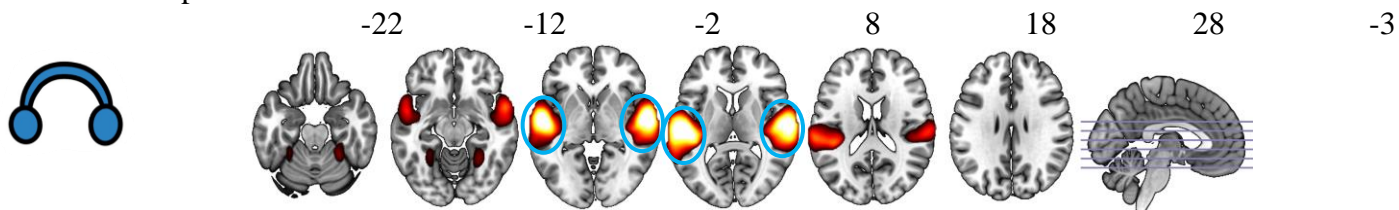
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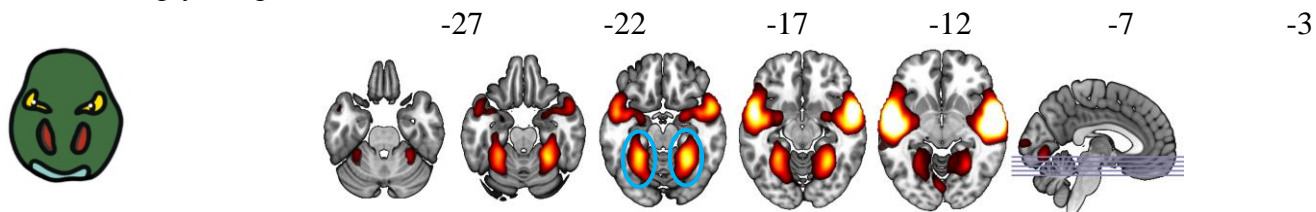
-3

## Auditory Perception

Pattern 1: Headphones

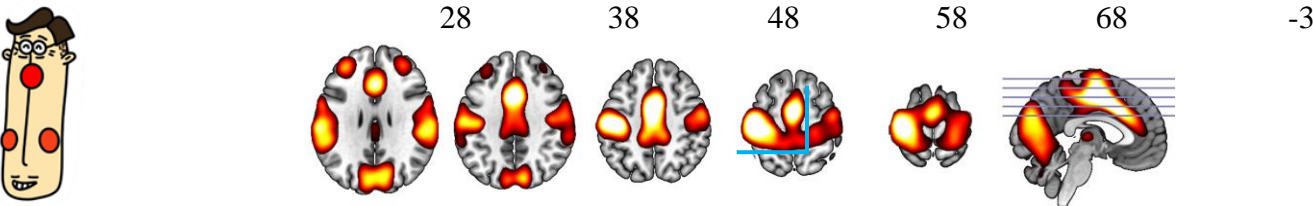


Pattern 2: Angry Dragon

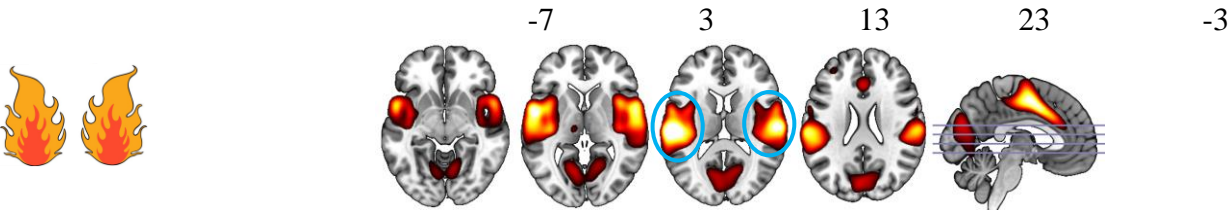


*Auditory Attention for Response*

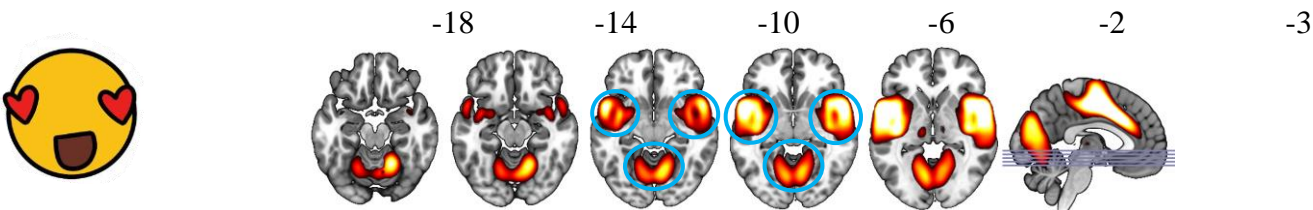
Pattern 1: Happy 28th Birthday Long Face/Right Angle



Pattern 2: On Fire



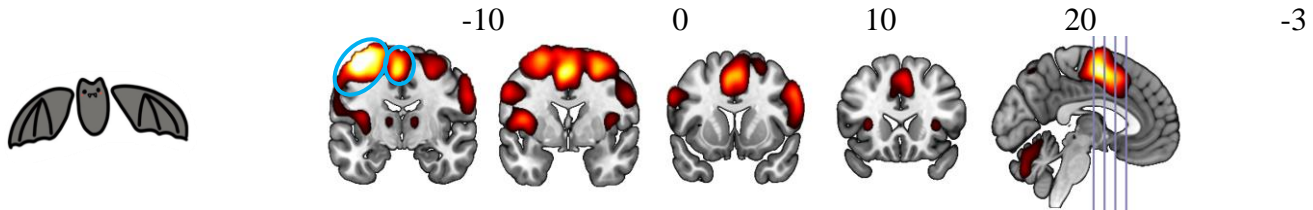
Pattern 3: Small Smile



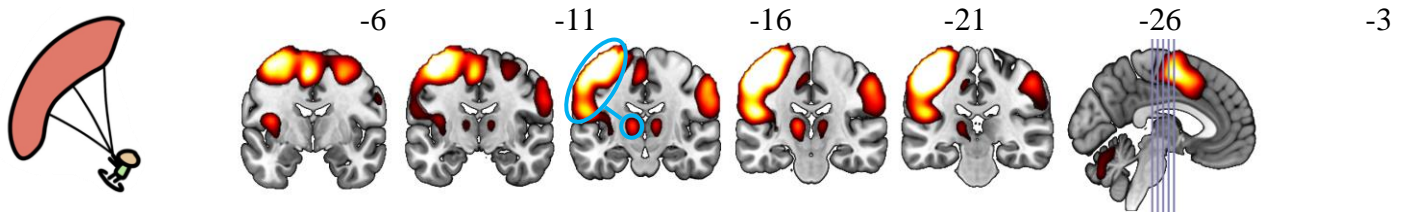


## One-Handed Response

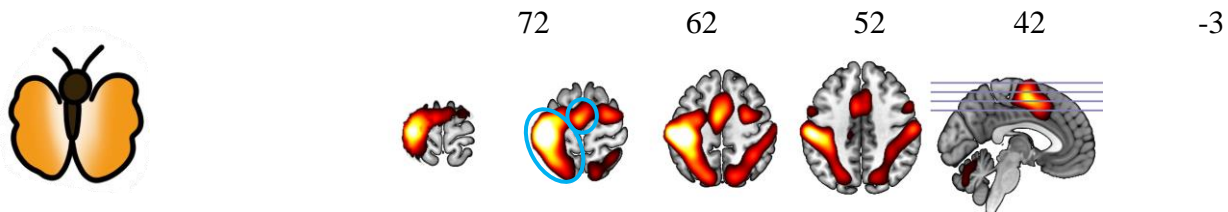
Pattern 1: Bat (Left Wing)



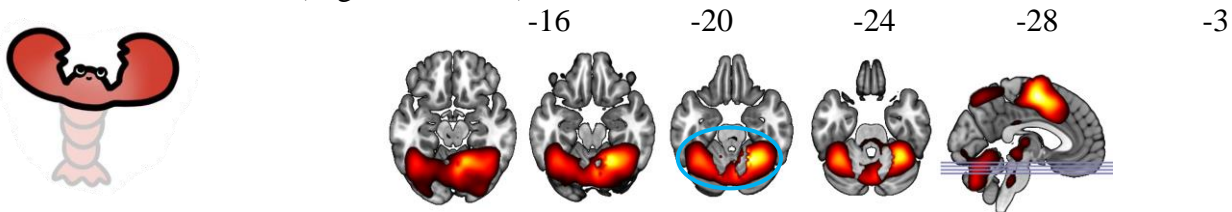
Pattern 2: Thalamus Kite Surfer (Left-Lateralized)



Pattern 3: Butterfly (Left-Dominant)

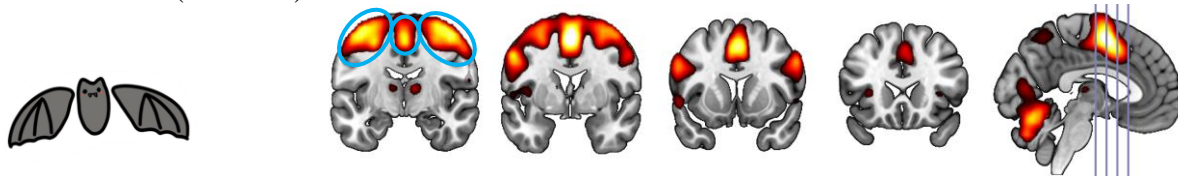


Pattern 4: Lobster Claw (Right-Dominant)

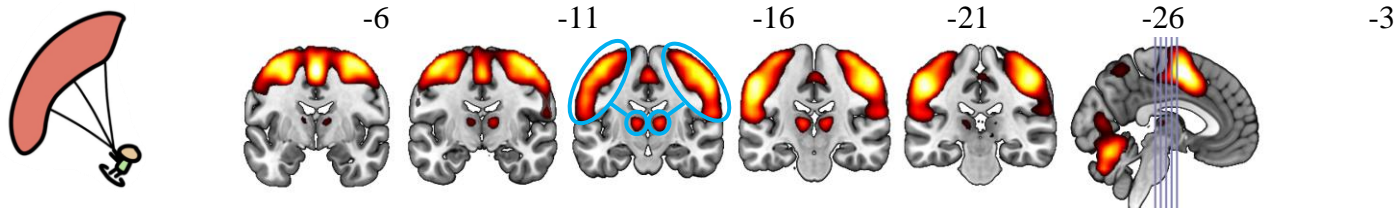


## Two-Handed Response

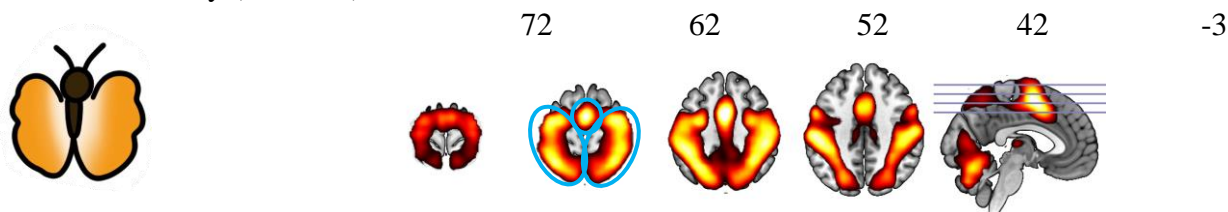
Pattern 1: Bat (Bilateral)



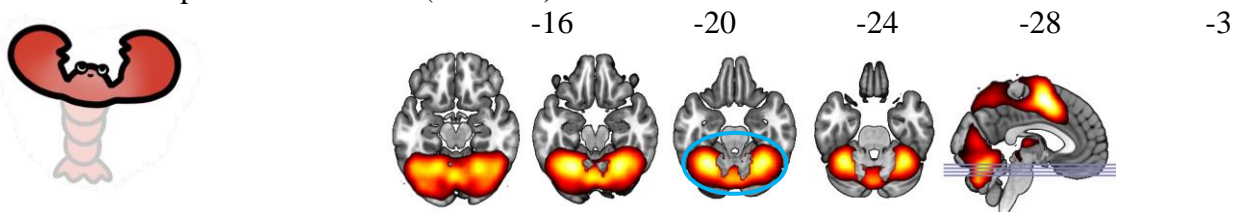
Pattern 2: Thalamus Kite Surfer (Bilateral)



Pattern 3: Butterfly (Bilateral)

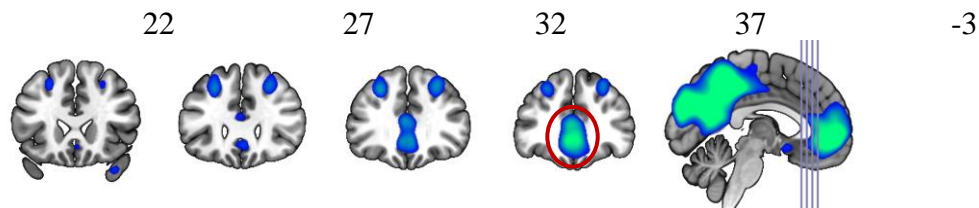


Pattern 4: Compact Lobster Claw (Bilateral)

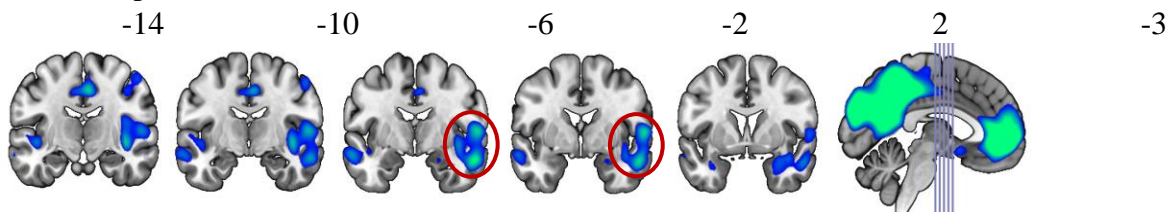


## Default Mode Network A

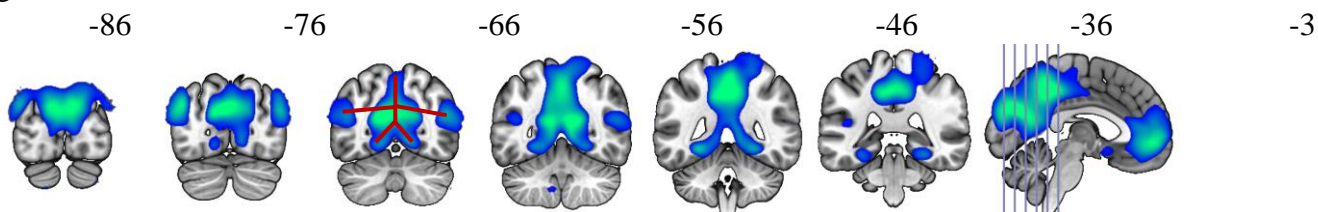
Pattern 1: Snowman Mouth



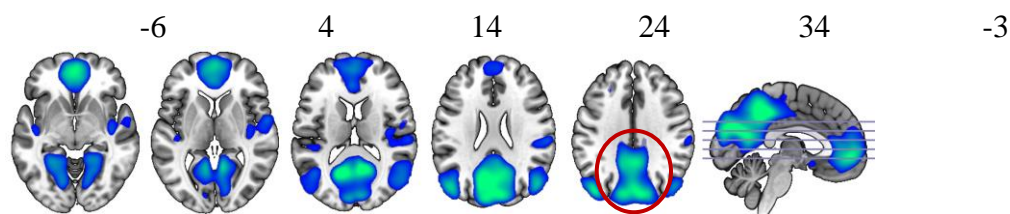
Pattern 2: Muted Medial Temporal Dots



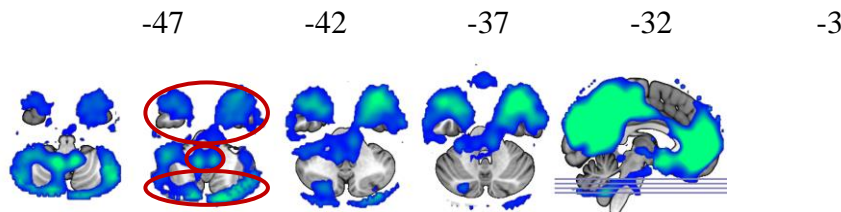
Pattern 3: Penguin



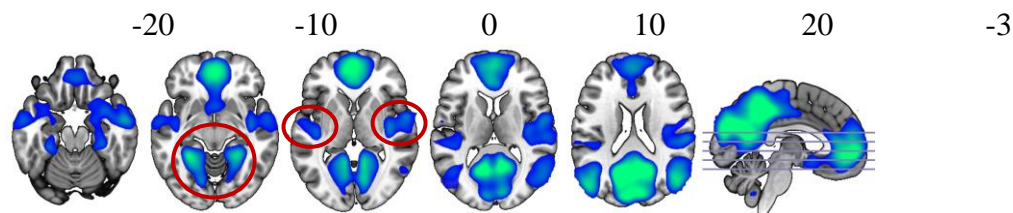
Pattern 4: Kitten



Pattern 5: Laughing Clown



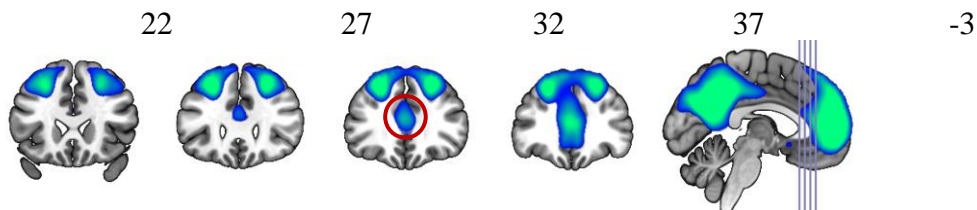
Pattern 6: You're In Trouble



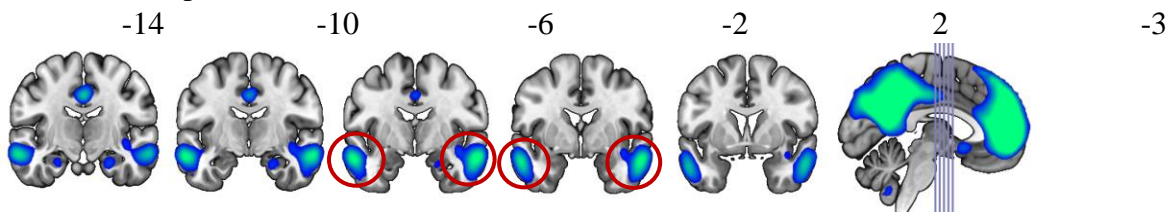


## Default Mode Network B

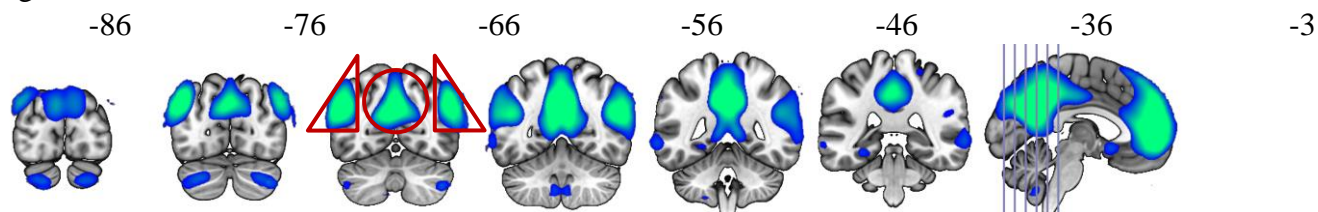
Pattern 1: Snowman Nose



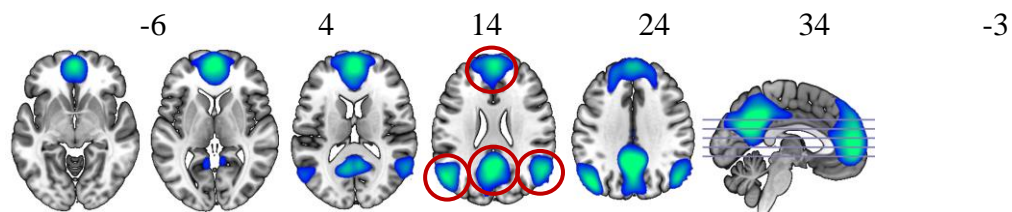
Pattern 2: Prominent Medial Temporal Dots



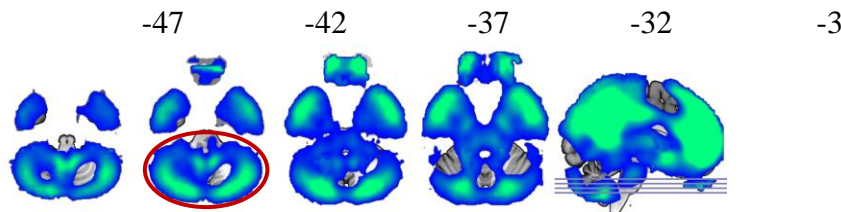
Pattern 3: In Flight



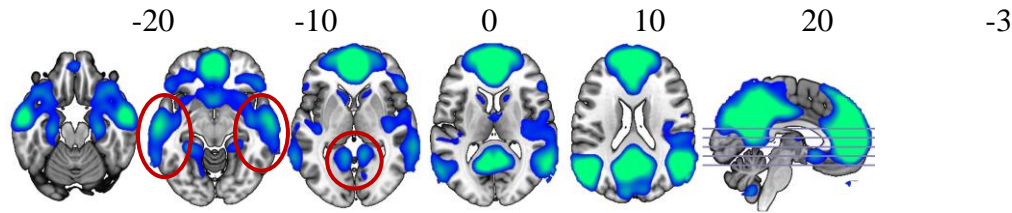
Pattern 4: Tripod



Pattern 5: Mandibles



Pattern 6: Angel Wings



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