Task-Based Brain Networks Detectable with fMRI

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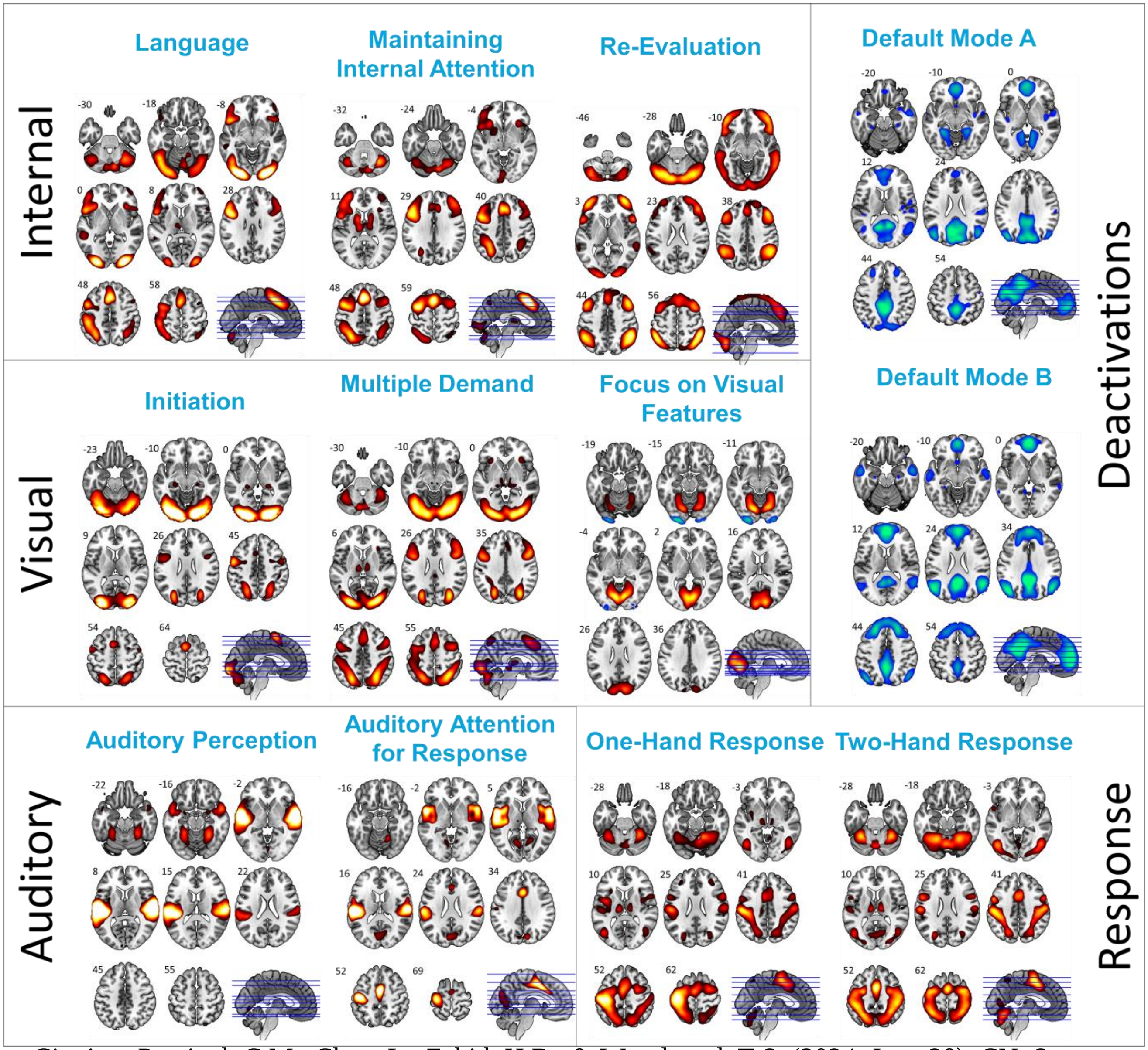

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The goal of this work was to observe replicability of task-based brain networks over a range of tasks using patterns (as opposed to coordinates), and to propose a preliminary cognitive mode associated with each by way of inspection of the task-induced 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goals were achieved by re-analysis of fMRI data collected in our laboratory and others', from both published and unpublished studies, and working towards definition of a cognitive mode associated with each network by observing BOLD signal change associated with a set of anatomical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 predicable from the independent variables that are the design matrix. Then PCA is performed on the matrix of predicted scores

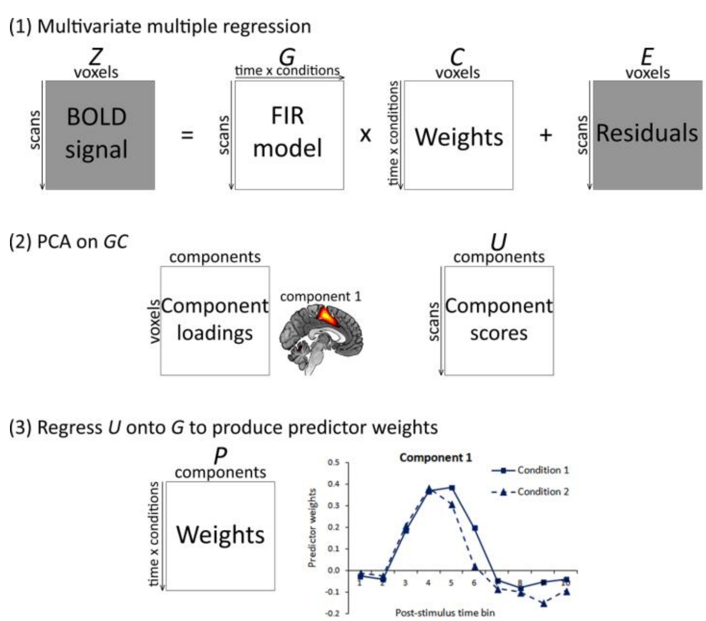
The PCA component loadings are interpreted spatially, depicting the brain networks (systems of inter-correlated voxels), and temporally through component scores. The component scores provide a value indexing the activity of each brain network for every brain scan (TR). They are regressed onto the Finite 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.

<u>Mathematical steps of fMRI-CPCA</u>.

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.



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**

Cognitive processes involved in attending to internal representations

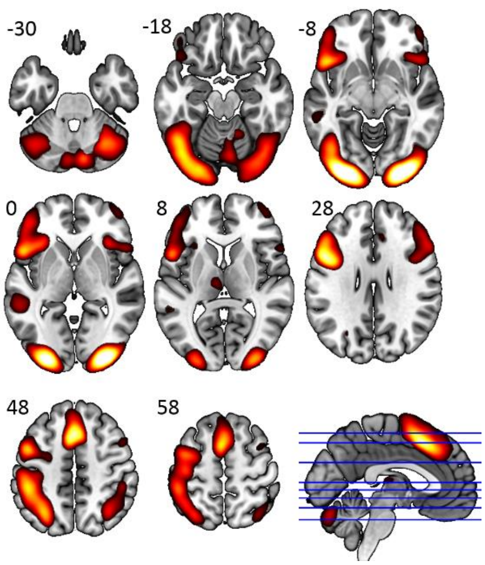
There are three networks which focus on cognitive modes primarily involved in attending to internal representations.

The first is the *Language Network (LN)*. 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 *Maintaining Internal Attention (MAIN)*, which was referred to previously as the *Internal Attention Network* (Sanford et al., 2020b; Sanford & Woodward, 2021) and the *Salience Network* (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 *Re-Evaluation (RE-EV).* 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.

Language Network



<u>Summary</u>

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. DOI:10.31234/osf.io/c83d7.

<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. & 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.pscychresns.2024.111824

<u>Component 2</u>

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

<u>Component 2</u>

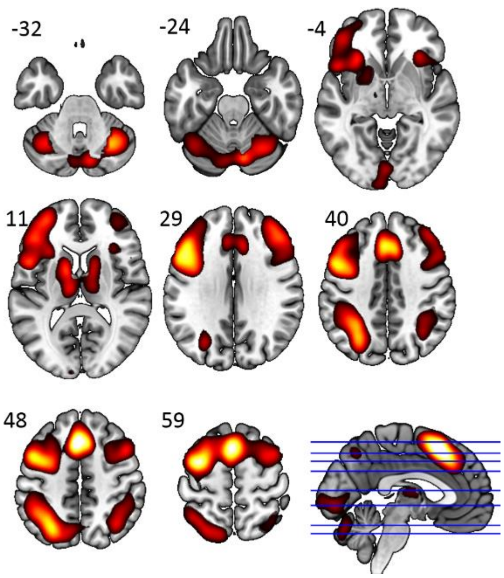
Kusi, M., Wong, S.T.S., Percival, C.M., Zurrin, R., Roes, M.M., Woodward, T.S., & Goghari, V.M. (2022). Altered activity in functional brain networks involved in lexical decision making in bipolar disorder: an fMRI case-control study. *Journal of Affective Disorders*, *317*, 59-71. https://doi.org/10.1016/j.jad.2022.08.040

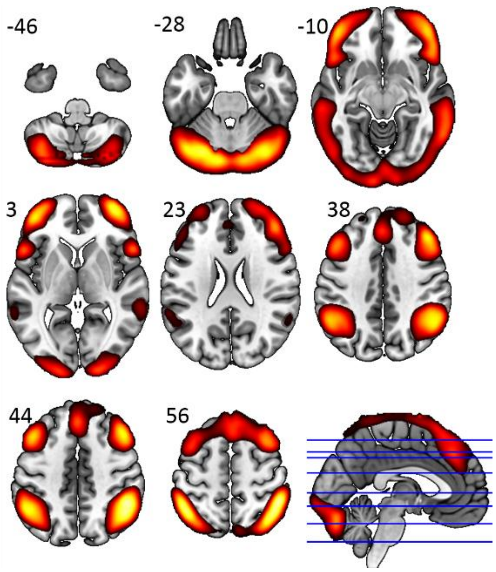
<u>Component 3</u>

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

<u>Component 3</u>

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

Maintaining Internal Attention		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 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.pscychresns.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

Re-Evaluation		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

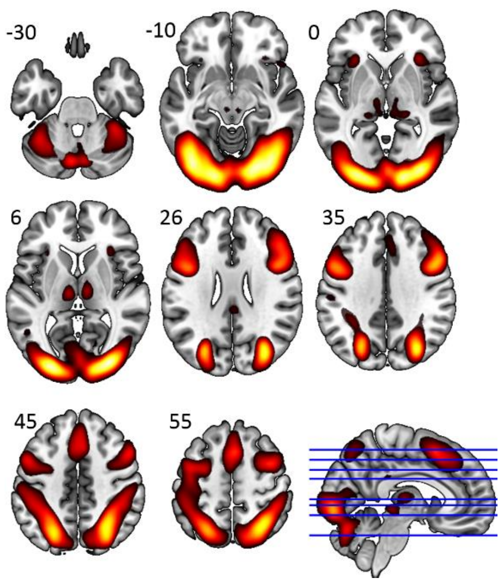
***Cognitive processes involved in attending to visually presented stimuli*.**

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

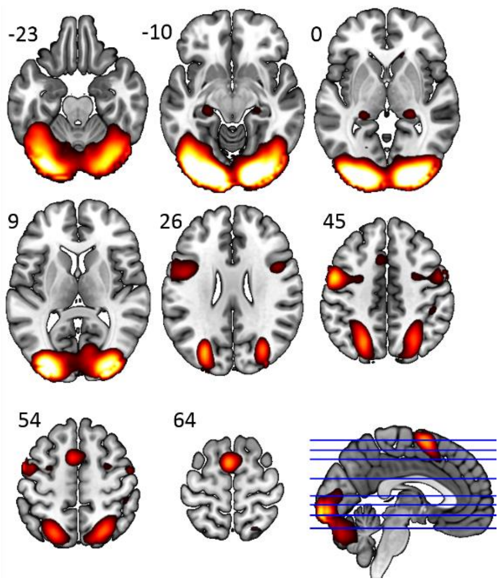
The first is *Initiation (INIT)*, which has been referred to previously as the *Energizing Network* (Sanford & Woodward, 2021), *Visual Attention Network* (Sanford et al., 2020a, 2020b), *Visual Network* , and *Encoding/Probe* (Woodward et al., 2013). This network involves restarting cognitive processing 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 *Salience 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).

Multiple Demand Network		<u>Component 1</u> 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. <u>Component 3</u> 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 <u>Component 1</u> <u>Component 4</u> 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.pscychresns.2022.111472 <u>Component 3</u> 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 <u>Component 5</u> 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 <u>Component 1</u> 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

Initiation



<u>Component 5</u>

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

<u>Component 2- Single-Experiment</u>
<u>Component 2- Multi-Experiment</u>

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

<u>Component 2</u>

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

<u>Component 1</u>

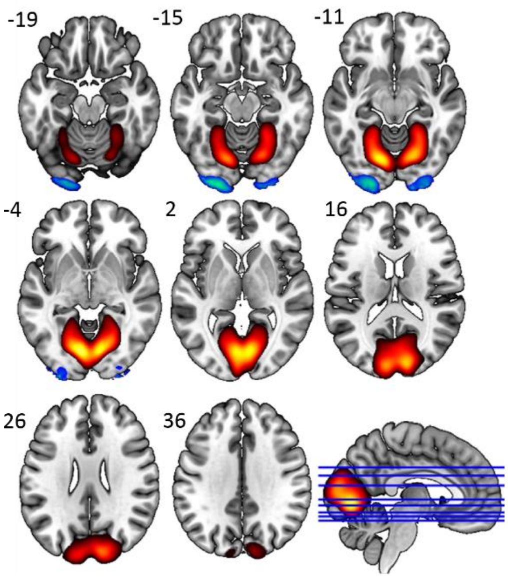
Lavigne, K.M., Rapin, L.A., Metzak, P.D., Whitman, J.C., Jung, K., Dohen, M., Loevenbruck, H., & Woodward, T.S. (2015). Left-dominant temporal-frontal hypercoupling in schizophrenia patients with hallucinations during speech perception. *Schizophrenia Bulletin*, *41*(1), 259-267. https://doi.org/10.1093/schbul/sbu004

<u>Component 1</u>

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

<u>Component 2</u>

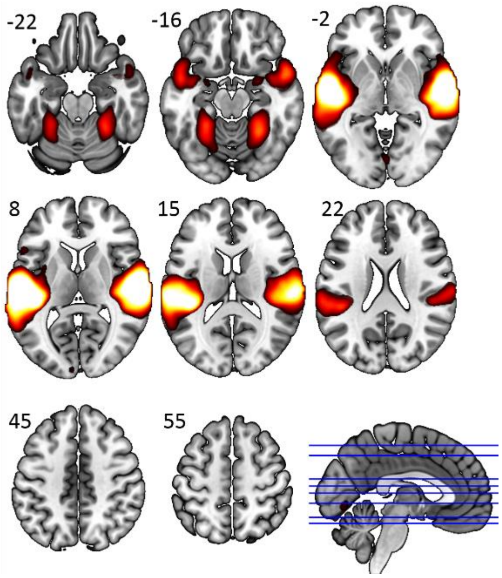
Metzak, P.D., Riley, J., Wang, L., Whitman, J.C., Ngan, E.T.C. & Woodward, T.S. (2012). Decreased efficiency of task-positive and task-negative networks during working memory in schizophrenia. *Schizophrenia Bulletin*, *38*(4), 803-813. https://doi.org/10.1093/schbul/sbq154

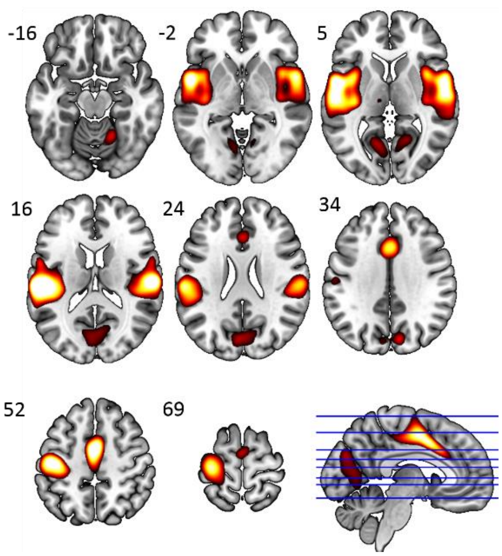
Focus on Visual Features		Component 6- Multi-Experiment Sanford, N., Whitman, J.C., & Woodward, T.S. (2020). Task-Merging for finer separation of functional brain networks in working memory. *Cortex, 125*, 246-271. https://doi.org/10.1016/j.cortex.2019.12.014 Component 1- Chapter 4 Analysis 3 TSI Component 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).

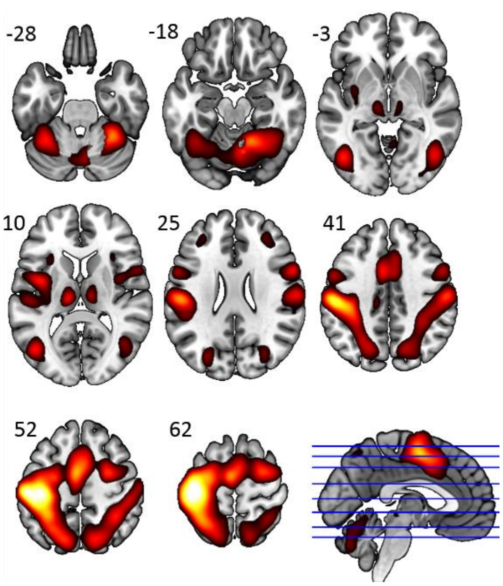
The second is the *Auditory Attention for Response* (AAR) network, which has been referred to previous as the *Auditory-Motor Attention Network* (Sanford & Woodward, 2021), *Sensorimotor Network* (Sanford et al., 2020b), *Auditory-Motor Network* (Lavigne & Woodward, 2018), and *(Auditory-Motor) Response 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.

Auditory Perception		<u>Component 2- Melbourne Patient/Control Radio Speech (Short/Medium/Long) Analysis</u> 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 <u>Component 7- Multi-Experiment</u> 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 <u>Component 4- Chapter 4 Analysis 4 TGT</u> 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

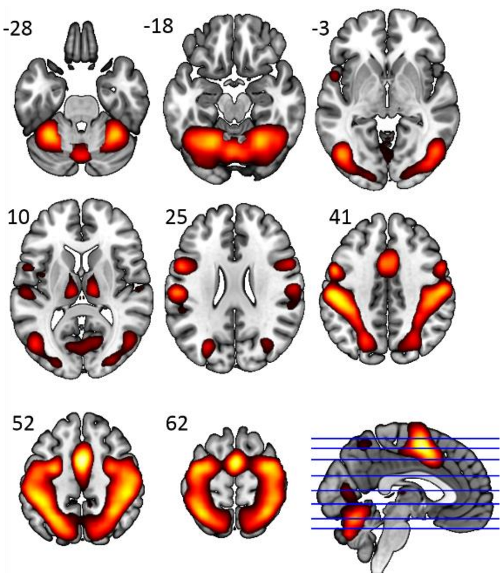
Auditory Attention for Response		<u>Component 3</u> Fouladirad, S., Chen, L.V., Roes, M., Chinchani, A., Percival, C., Khangura, J., Zahid, H., Moscovitz, A., Arreaza, L., Wun, C., Sanford, N., Balzan, R., Moritz, S., Menon, M., & Woodward, T.S. (2022). Functional brain networks underlying probabilistic reasoning and delusions in schizophrenia. *Psychiatry Research: Neuroimaging*, *323*, Article 111472. https://doi.org/10.1016/j.pscychresns.2022.111472 <u>Component 3</u> 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 <u>Component 3- Chapter 5</u> 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 <u>Component 1</u> 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 <u>Component 2</u> 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).

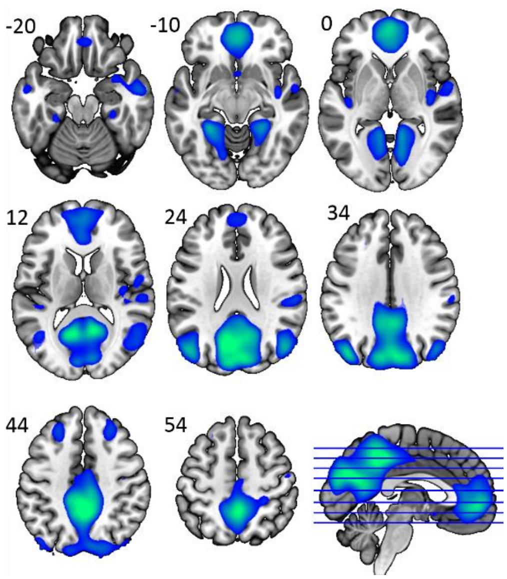
One-Handed Response		<u>Component 3</u> Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. & Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. Psychiatry Research: Neuroimaging. <u>Component 2</u> 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 <u>Component 1</u> 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 <u>Component 2</u> 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.pscychresns.2022.111472 <u>Component 2- Melbourne and Utrecht Patient Hallucinations Merged Analysis</u>

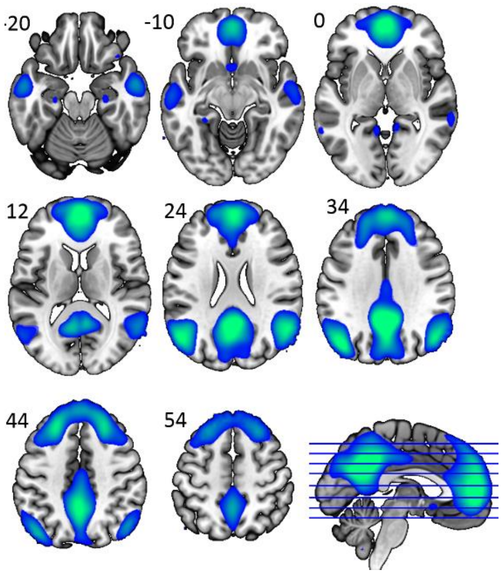
		Gill, K., Percival, C., Roes, M., Arreaza, L., Chinchani, A., Sanford, N., Sena, W., Mohammadsadeghi, H., Menon, M., Hughes, M., Carruthers, S., Sumner, P., Woods, W., Jardri, R., Sommer, I.E., Rossell, S.L., & Woodward, T.S. (2022). Real-time symptom capture of hallucinations in schizophrenia with fMRI: absence of duration-dependent activity. *Schizophrenia Bulletin Open*, *3*(1), Article sgac050. https://doi.org/10.1093/schizbullopen/sgac050 Component 3 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 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 1- Single-Experiment Component 1- 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 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.pscychresns.2017.03.005 Component 4 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

Two-Handed Response		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.pscychresns.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.

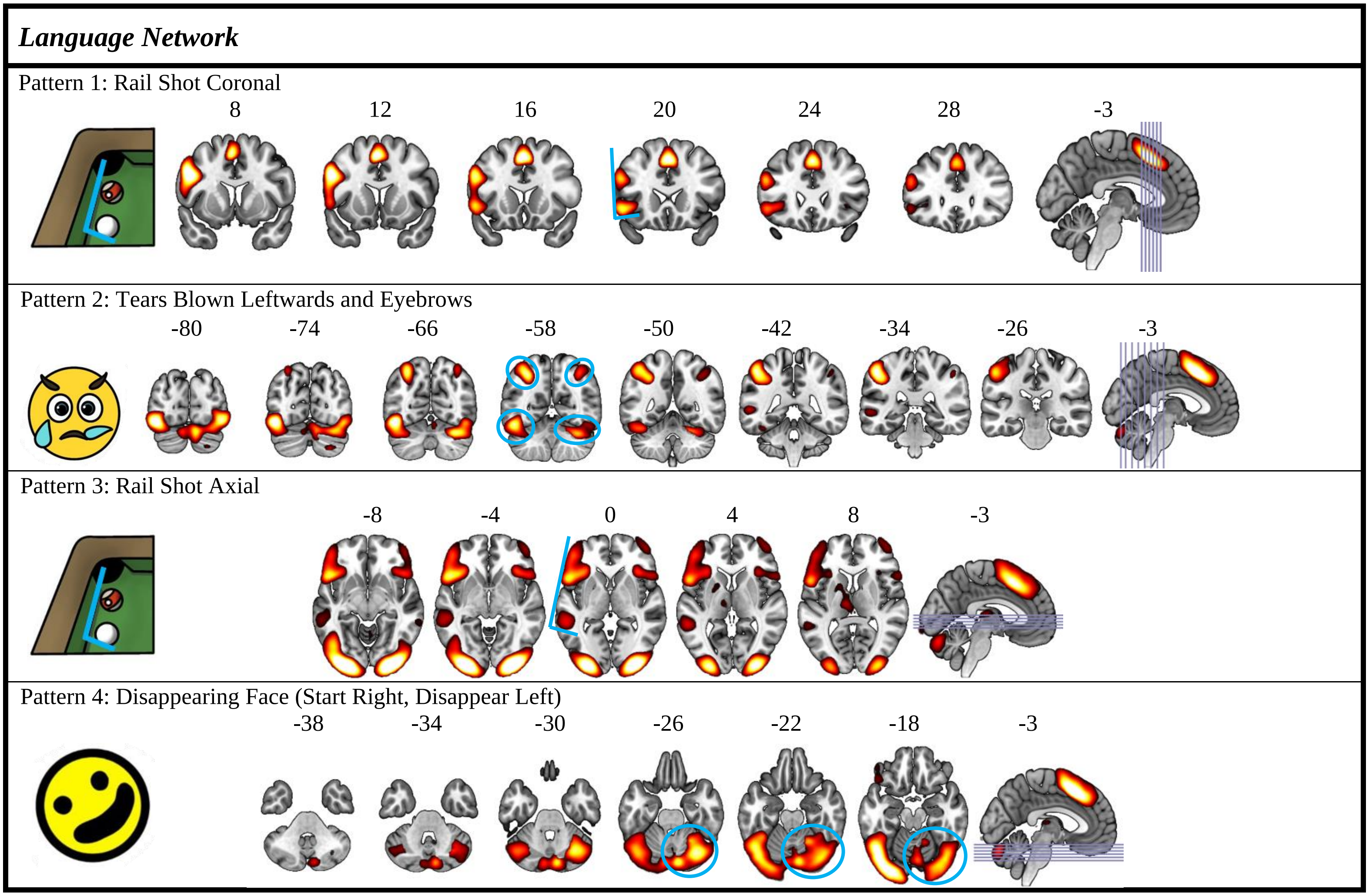
Default Mode Network A		<u>Component 2</u> Besso, L., Larivière, S., Roes, M., Sanford, N., Percival, C., Damascelli, M., Momeni, A., Lavigne, K., Menon, M., Aleman, A., Ćurčić-Blake, B. & Woodward, T. S. (2024) Hypoactivation of a Linguistic Processing Brain Network During Auditory Imagery Contributes to Hallucinations in Schizophrenia. Psychiatry Research: Neuroimaging. <u>Component 1</u> 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 <u>Component 3</u> 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 <u>Component 3</u> 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
Default Mode Network B		<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. & 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.pscychresns.2024.111824 <u>Component 1</u>

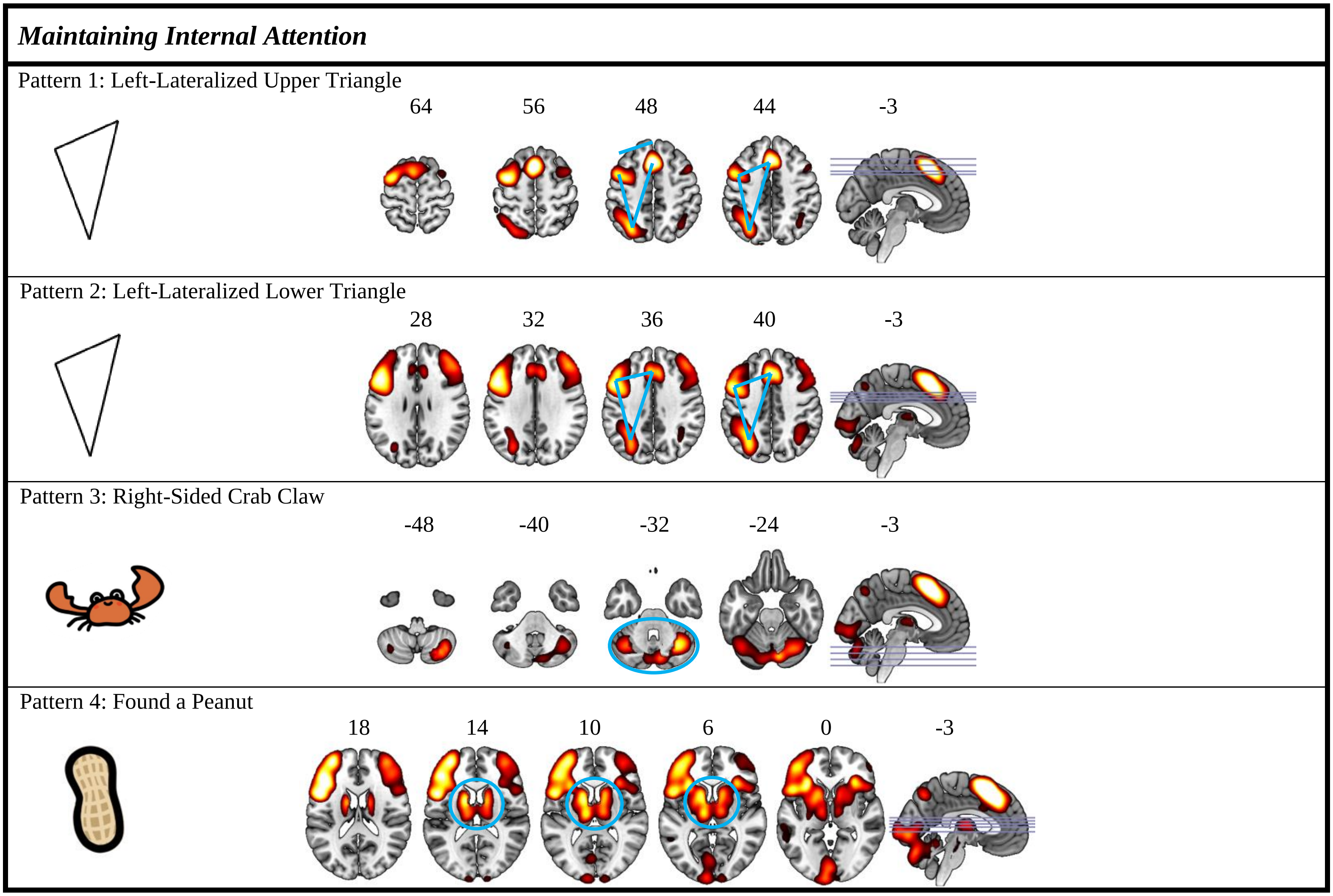
		Zurrin, R., Wong, S.T.S., Roes, M.M., Percival, C.M., Chinchani, A., Arreaza, L., Kusi, M., Momeni, A., Rasheed, M., Mo, Z., Goghari, V.M., & Woodward, T.S. (2024). Functional brain networks involved in the Raven's Standard Progressive Matrices task and their relation to theories of fluid intelligence. *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., 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 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

		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 2 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 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.pscychresns.2016.01.003 Component 4 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 2 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 2 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

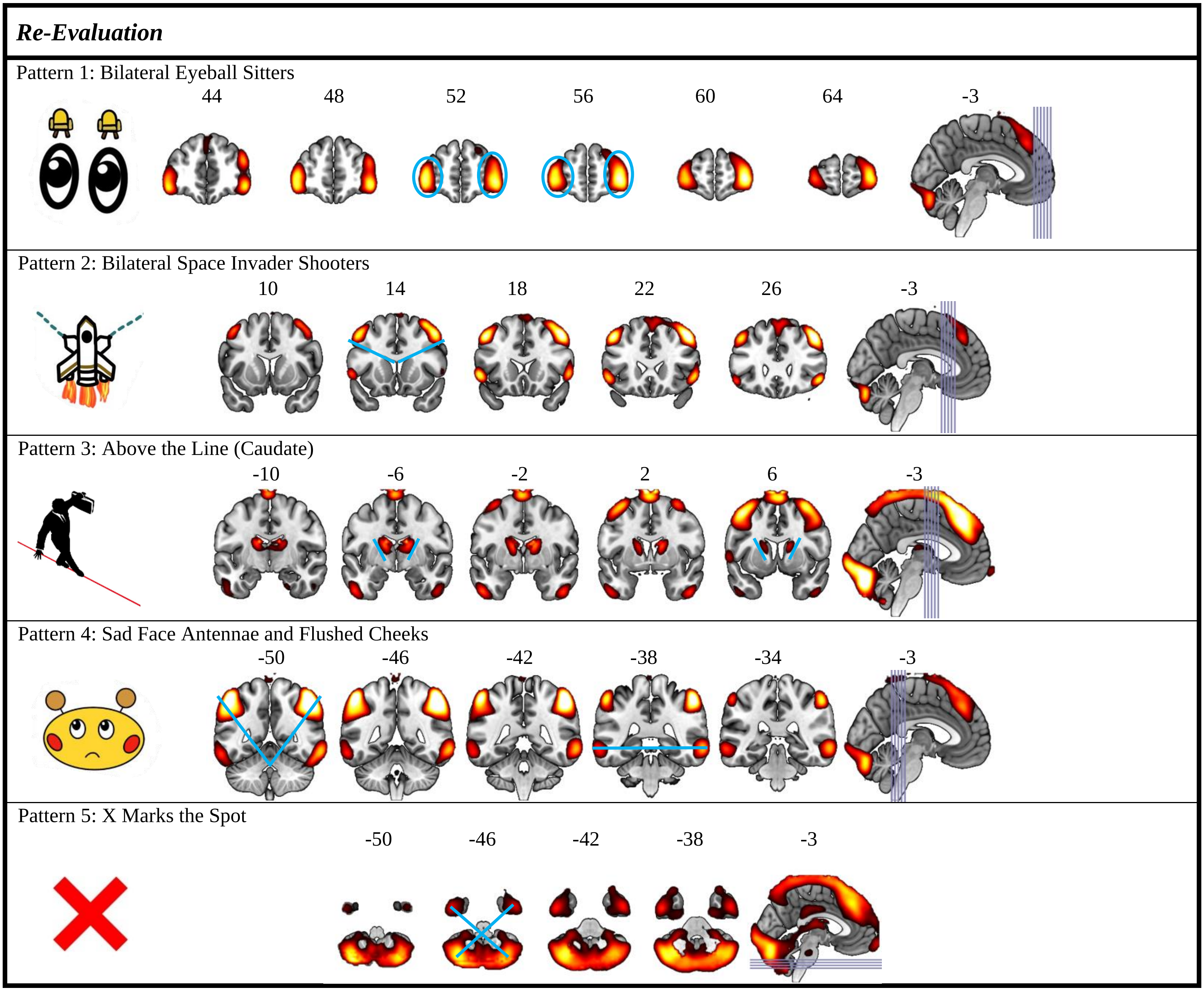
Characteristic Anatomical Patterns of the Proposed Prototypical Networks

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.

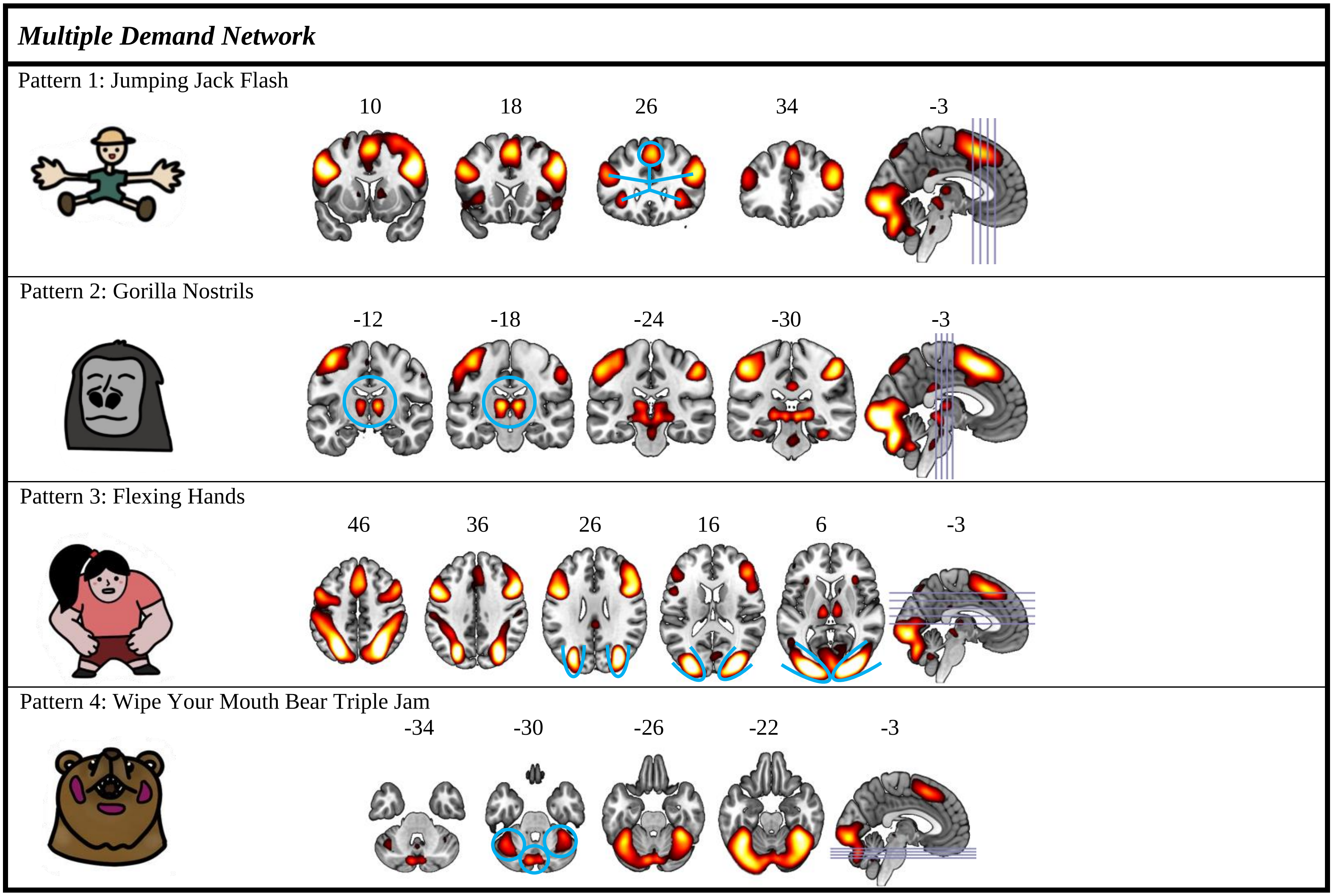




Maintaining Internal Attention
Pattern 1: Left-Lateralized Upper Triangle
64 56 48 44 -3
Pattern 2: Left-Lateralized Lower Triangle
28 32 36 40 -3
Pattern 3: Right-Sided Crab Claw
-48 -40 -32 -24 -3
Pattern 4: Found a Peanut
18 14 10 6 0 -3



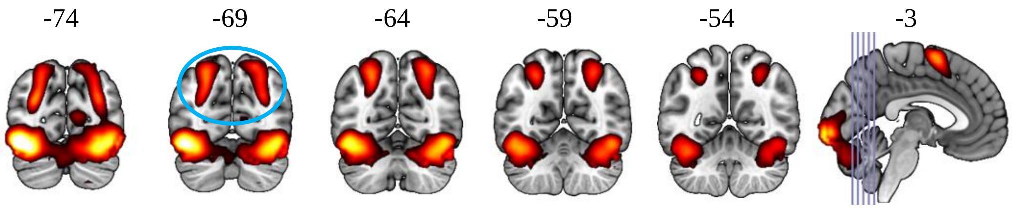
Re-Evaluation
Pattern 1: Bilateral Eyeball Sitters
44 48 52 56 60 64 -3
Pattern 2: Bilateral Space Invader Shooters
10 14 18 22 26 -3
Pattern 3: Above the Line (Caudate)
-10 -6 -2 2 6 -3
Pattern 4: Sad Face Antennae and Flushed Cheeks
-50 -46 -42 -38 -34 -3
Pattern 5: X Marks the Spot
-50 -46 -42 -38 -3



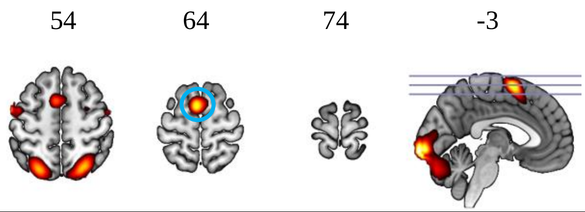
Multiple Demand Network
Pattern 1: Jumping Jack Flash
10
18
26
34
-3
Pattern 2: Gorilla Nostrils
-12
-18
-24
-30
-3
Pattern 3: Flexing Hands
46
36
26
16
6
-3
Pattern 4: Wipe Your Mouth Bear Triple Jam
-34
-30
-26
-22
-3

Initiation

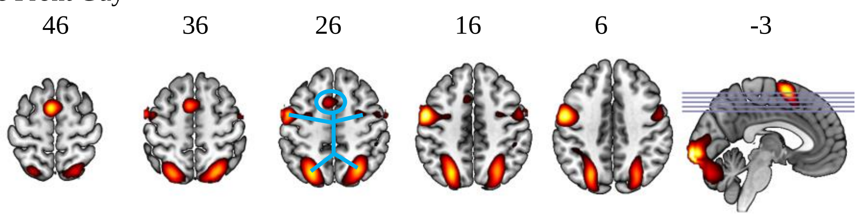
Pattern 1: Raised Eyebrows

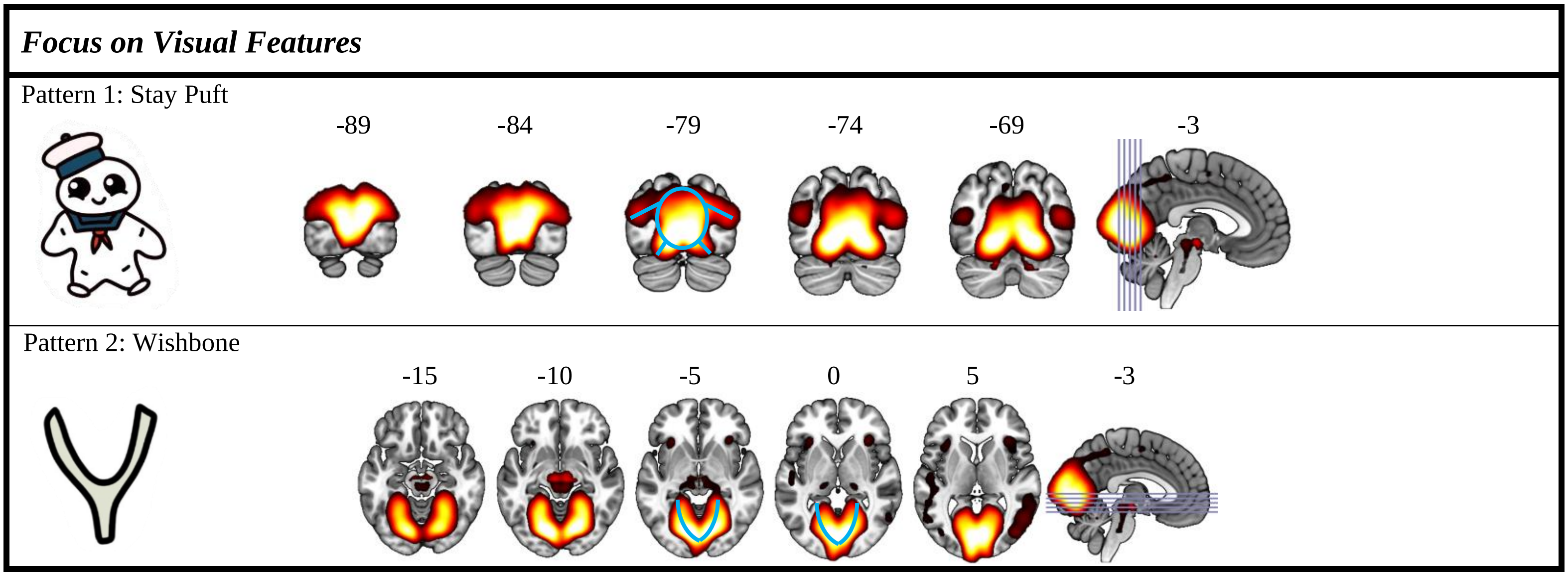


Pattern 2: When I’m 64

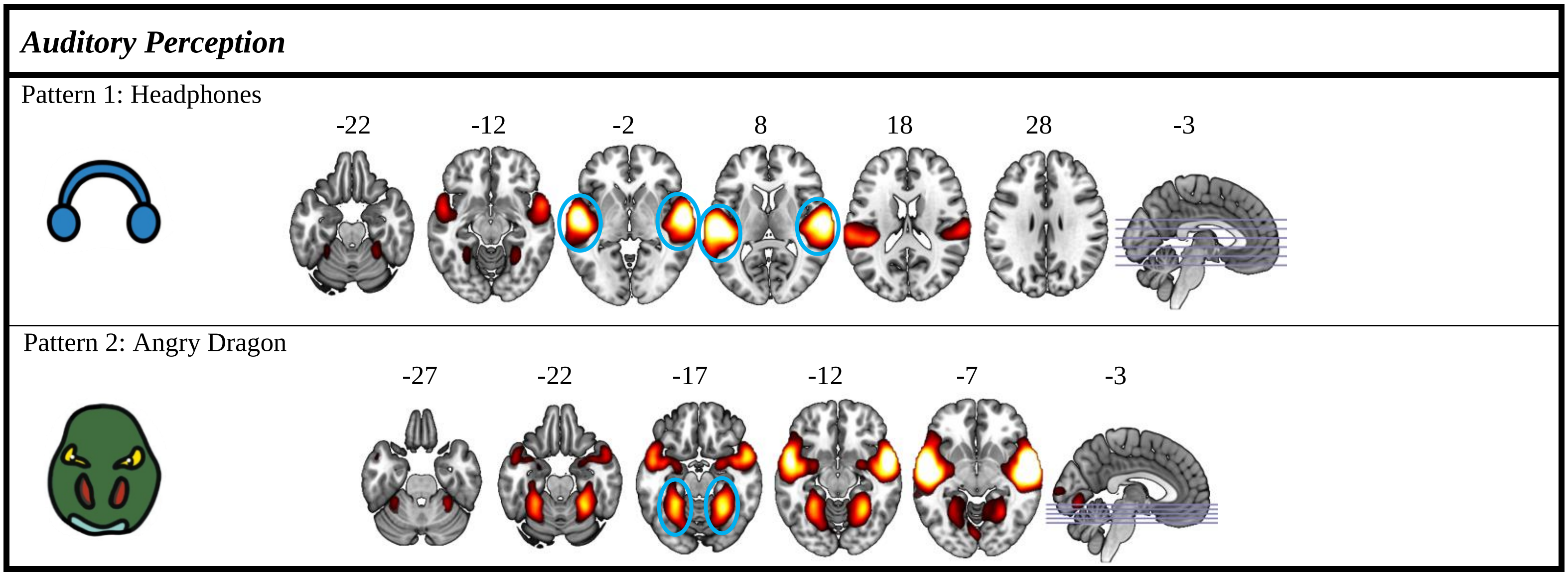


Pattern 3: De Divina Proportione Front Guy

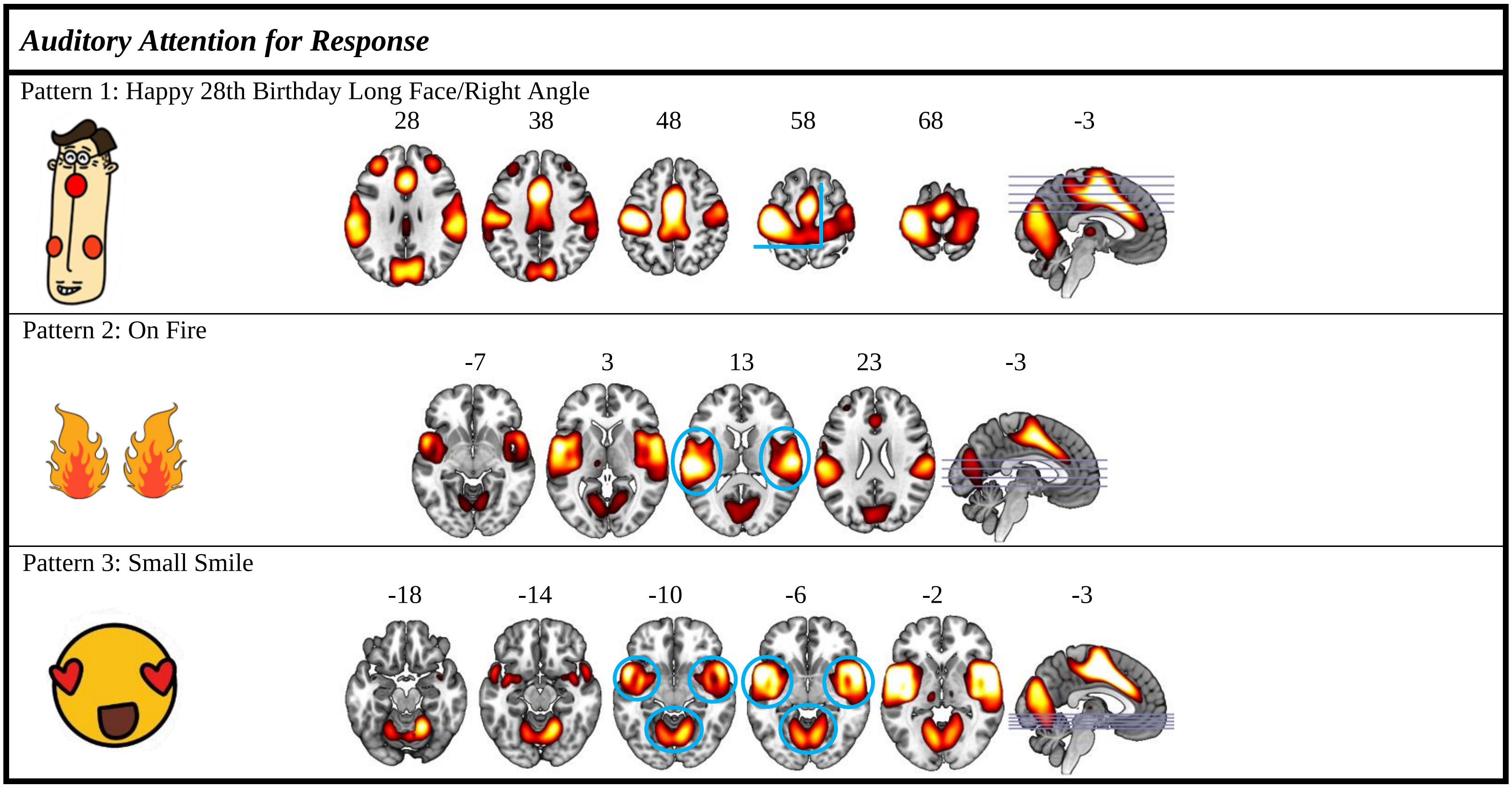




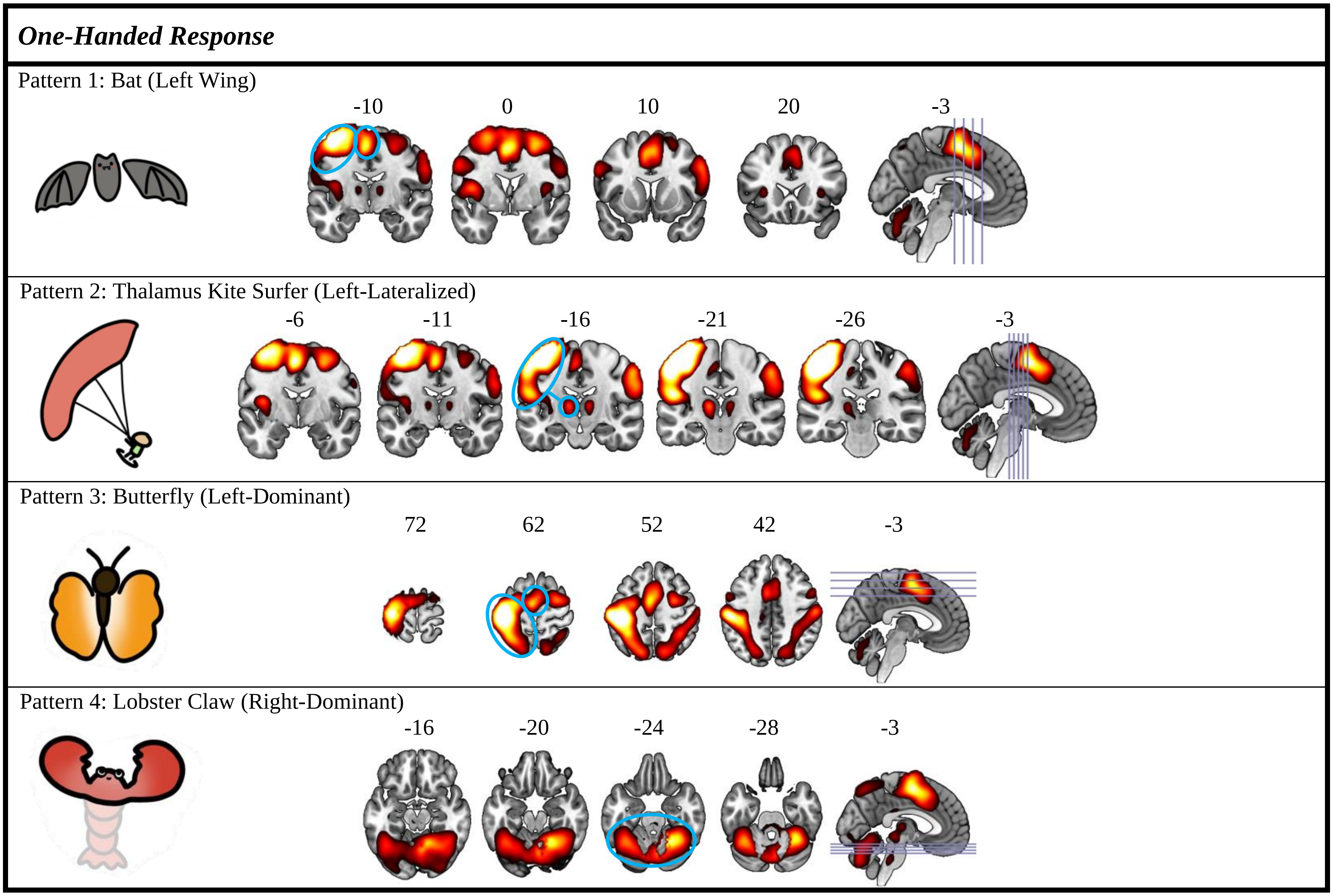
Focus on Visual Features
Pattern 1: Stay Puft
-89
-84
-79
-74
-69
-3
Pattern 2: Wishbone
-15
-10
-5
0
5
-3

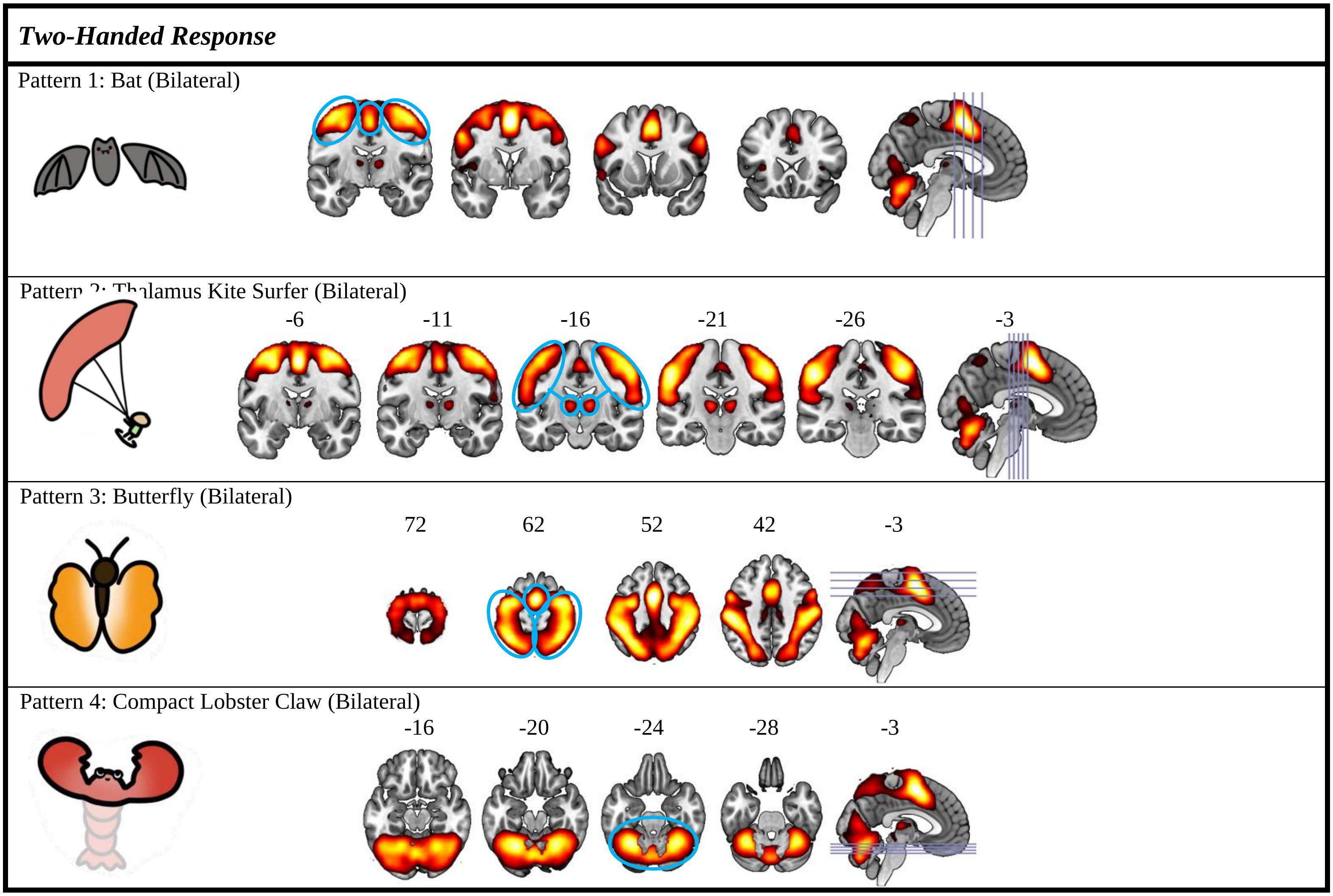


Auditory Perception
Pattern 1: Headphones
-22
-12
-2
8
18
28
-3
Pattern 2: Angry Dragon
-27
-22
-17
-12
-7
-3



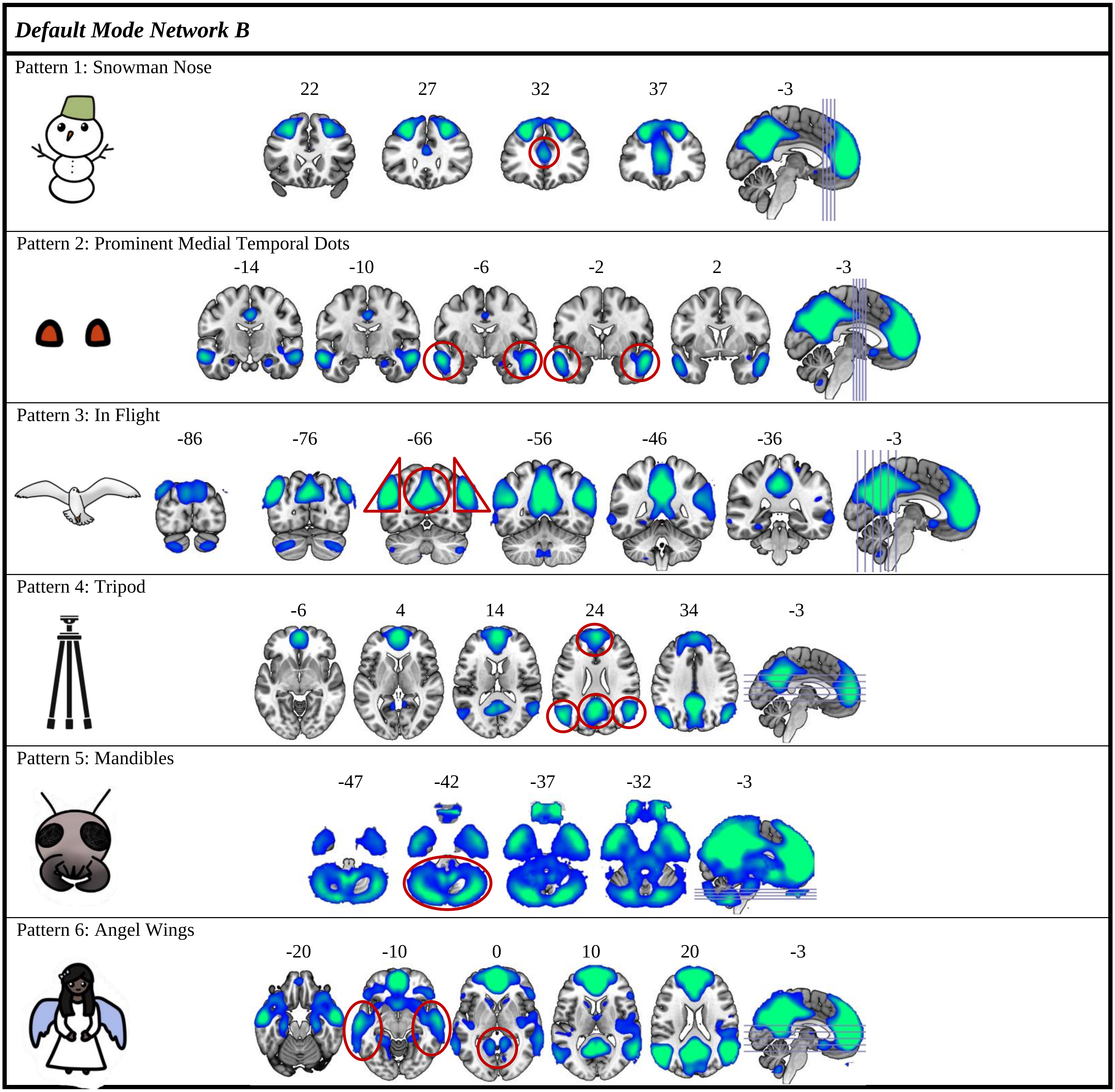
Auditory Attention for Response
Pattern 1: Happy 28th Birthday Long Face/Right Angle
28
38
48
58
68
-3
Pattern 2: On Fire
-7
3
13
23
-3
Pattern 3: Small Smile
-18
-14
-10
-6
-2
-3


One-Handed Response
Pattern 1: Bat (Left Wing)
-10
0
10
20
-3
Pattern 2: Thalamus Kite Surfer (Left-Lateralized)
-6
-11
-16
-21
-26
-3
Pattern 3: Butterfly (Left-Dominant)
72
62
52
42
-3
Pattern 4: Lobster Claw (Right-Dominant)
-16
-20
-24
-28
-3



Two-Handed Response
Pattern 1: Bat (Bilateral)
Pattern 2: Thalamus Kite Surfer (Bilateral)
-6
-11
-16
-21
-26
-3
Pattern 3: Butterfly (Bilateral)
72
62
52
42
-3
Pattern 4: Compact Lobster Claw (Bilateral)
-16
-20
-24
-28
-3


Default Mode Network A
Pattern 1: Snowman Mouth
22 27 32 37 -3
Pattern 2: Muted Medial Temporal Dots
-14 -10 -6 -2 2 -3
Pattern 3: Penguin
-86 -76 -66 -56 -46 -36 -3
Pattern 4: Kitten
-6 4 14 24 34 -3
Pattern 5: Laughing Clown
-47 -42 -37 -32 -3
Pattern 6: You're In Trouble
-20 -10 0 10 20 -3



Default Mode Network B
Pattern 1: Snowman Nose
22
27
32
37
-3
Pattern 2: Prominent Medial Temporal Dots
-14
-10
-6
-2
2
-3
Pattern 3: In Flight
-86
-76
-66
-56
-46
-36
-3
Pattern 4: Tripod
-6
4
14
24
34
-3
Pattern 5: Mandibles
-47
-42
-37
-32
-3
Pattern 6: Angel Wings
-20
-10
0
10
20
-3

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Lavigne, K., 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/https://doi.org/10.1016/j.schres.2019.11.038

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