Cortical contributions to cognitive control of language and beyond: evidence from functional connectivity profiles of the inferior parietal cortex and cognitive control-related resting state networks

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Chapter 6

Distinct connectivity patterns in clusters of inferior parietal cortex

This chapter is based on:

Tabassi Mofrad, F., & Schiller, N. O. (under review). Distinct connectivity patterns in clusters of inferior parietal cortex.

Abstract

The inferior parietal cortex (IPC) is a complex brain region with the rostral, the middle and the caudal clusters, and functionally connected to several other cortical areas. Various cognitive functions are suggested to be governed by the IPC, however, due to ignoring the tripartite structure of this part of the brain, contradictory research reports abound in the literature. Here, we address the functional connectivity behaviour of the clusters of the IPC and point out that only the rostral cluster of this parietal area is involved in cognitive control and not the whole IPC. We also explicate the unique connectivity profiles of the middle and the caudal clusters of this part of the cortex which are not accommodated by the traditional classification of brain areas as either being task-based or being related to the resting-state functionality of the brain. The middle and the caudal IPC demonstrate negative functional associations with cortical areas involved in general cognitive functions, executive functions, in addition to the precuneus cortex, proportional to cognitive demand, in a modulating manner.

6.1 Introduction

The inferior parietal cortex (IPC) is usually known as being involved in executive functions, such as attention, memory, and processing language (Bareham et al., 2018; Buchsbaum & D'Esposito, 2011; Bzdok et al., 2016). However, such roles for the IPC are contrasted with some other research findings that consider this cortical area part of the default mode network (Doose et al., 2020; Mars et al., 2012; Raichle, 2015) - which decreases its activity when our brain is focused on explicit tasks (Smallwood et al., 2021) – and such contradictory findings about the functions of the IPC have remained in the literature for years.

According to the structural properties of the IPC, this part of the brain consists of three clusters, namely, the rostral, the middle and the caudal (Caspers et al., 2006; 2008). However, in investigating the functions of the IPC, previous research considered this part of the cortex as a whole, regardless of the fact that each cluster of the IPC has a different transmitter receptor-based organization and thus they might have different functions. Research on the white matter connectivity of the IPC in addition to the diffusion-weighted magnetic resonance imaging also point to the cytoarchitectonically different areas of the IPC (Caspers et al., 2013; Ruschel et al., 2014).) reflected by its clusters. Yet, until the time we mapped the functional connectivity of the clusters of the IPC, no studies had investigated the contribution of the rostral, the middle and the caudal IPC to cognitive control in a comparative manner, while that could have addressed the contradicting reports on how IPC functions.

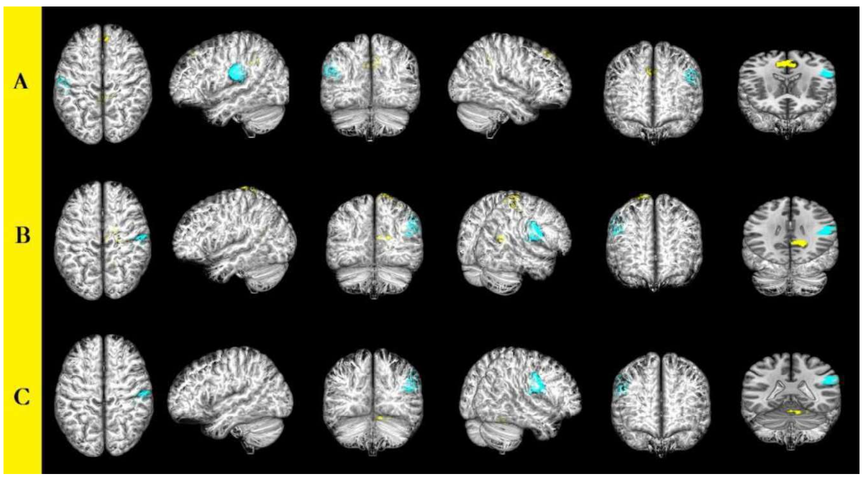
Based on the idea that the functional characteristics of the sub-regions of the IPC are underlined by their structural organization and given the inconsistent nature of research findings regarding the IPC, under the same experimental conditions we investigated the functional connectivity profiles of the clusters of this cortical area in a task which required cognitive control, with two different levels of cognitive demand. In this perspective, research findings from our comprehensive project in map the functional connectivity of the clusters of the IPC are presented and discussed, starting with the contribution of the rostral IPC to cognitive control, followed by unique connectivity profiles of the caudal and the middle IPC. The objectives are to highlight the fact that this is only the rostral IPC that contributes to cognitive control in the frontoparietal network (FPN) - not the whole IPC - and to emphasize that the connectivity patterns of the middle and the caudal IPC characteise these two parietal areas with distinctive features which are unaccommodated by traditional categorization of brain areas as either being involved in task performance or being related to the resting-state functionality of the brain.

6.2 Contributions of rostral IPC to cognitive control

The rostral IPC is the only cluster of this cortical area that is involved in cognitive control. Under the more demanding context of cognitive control, the rostral IPC has negative functional couplings with the superior frontal gyrus, the postcentral gyrus, and positive association with the cerebellum (the posterior lobe, the declive). Regarding the postcentral gyrus, the location of the primary somatosensory cortex, previous studies reported positive functional connectivity between this brain area and the FPN in individuals with better performance in executive functions during resting state fMRI (Reineberg et al., 2015). However, since we used task-based fMRI, the decreased functional connectivity between the rostral IPC and the superior frontal gyrus contributes to cognitive control. Besides, the cerebellum is known to contribute to higher order cognitive functions (Bellebaum & Daum, 2007), in addition to being part of the language control network (Green & Abutalebi, 2013; Krienen & Buckner, 2009). Thus, the positive functional connectivity of the rostral IPC and the cerebellum corroborates previous findings of the involvement of these two brain areas in cognitive control (see Figure 6.1).

Figure 6.1

Demonstration of brain areas that the rostral IPC is functionally connected with, in the more demanding context.

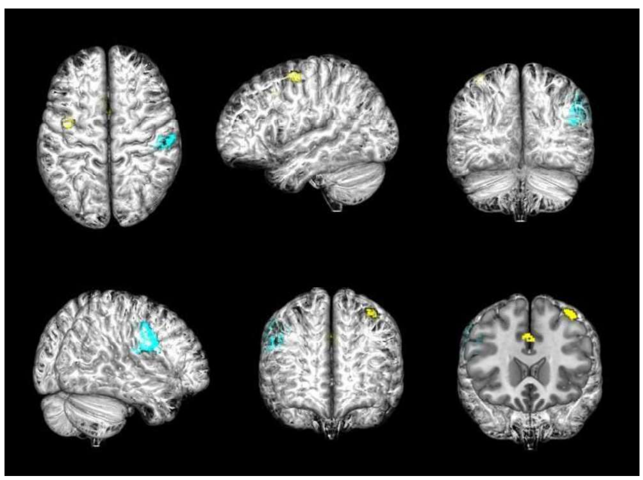


Note. The yellow color demonstrates brain areas that the rostral IPC (shown in cyan) is functionally connected with, in the more demanding context of cognitive control. The descriptions of each row are as follows: A) negative functional connectivity of the left rostral IPC with the superior frontal gyrus and the precuneus cortex, B) negative functional connectivity of the right rostral IPC with the postcentral gyrus and the precuneus cortex, C) positive functional connectivity of the right rostral IPC with the posterior lobe of the cerebellum.

Under the same experimental conditions, both the right and the left rostral IPC have negative functional connectivity with the precuneus cortex. When brain processes external stimuli, the precuneus cortex reduces its activity relative to the degree of the difficulty of the task. That is, the more difficult the task is, the more negative activity of the precuneus cortex would be observed (Dang, O'Neil & Jagust, 2013); hence, the reason the rostral IPC, as a task-related cortical area, demonstrate negative functional connectivity with this part of the brain.

Figure 6.2

Demonstration of brain areas that the rostral IPC is functionally connected with, in the less demanding context.



Note. The yellow color demonstrates brain areas (the precentral gyrus and the anterior division of the cingulate gyrus) that the right rostral IPC (shown in cyan) has positive functional connectivity with, in the less demanding context of cognitive control.

Regarding the less demanding context of the cognitive control, the right rostral IPC has positive functional connectivity with the anterior cingulate cortex (ACC) and the precentral gyrus. The ACC, as part of the control network (Abutalebi & Green, 2008, 2016), is involved in e.g. speech monitoring (Christoffels, Formisano, & Schiller, 2007) and monitoring the conflict between languages (Abutalebi et al., 2012). Therefore, the positive coupling of the rostral IPC and the ACC, by forming a strong circuit results in better task performance. Moreover, our findings elucidated that the connectivity of the rostral IPC with the precentral gyrus brings about a facilitatory function in cognitive control (see Figure 6.2).

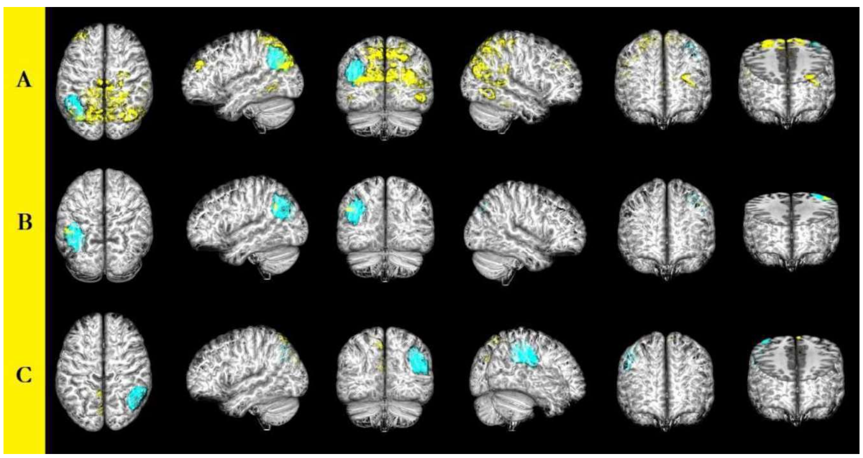
6.3 Unique connectivity profile of caudal IPC

The caudal IPC, however, is characterized with entirely different connectivity patterns from those of the rostral IPC. In fact, this part of the cortex has no similarity to a cognitive control area (Tabassi Mofrad & Schiller, 2022), in particular by having negative functional connectivity with the ACC (Tabassi Mofrad & Schiller, 2020) which is heavily involved in processing cognitive control (Braem et al., 2017; Brockett et al., 2020). Besides, regardless of degree of the cognitive demand, the left caudal IPC has negative coupling with the frontal pole, the anterior part of the prefrontal cortex, which contributes to cognitive control (Hartogsveld et al., 2018; Menon et al., 2022; Zanto & Gazzaley, 2013); such negative functional associations of the caudal IPC with cognitive control-related parts of the cortex evidence that the caudal IPC is not involved in processing cognitive control in the FPN (see Figures 6.3 & 6.4).

The caudal IPC also has negative functional connectivity with different parts of the visual cortex when the task requires cognitive control. In comparison, under the more demanding context of the cognitive control, the caudal IPC demonstrates negative functional connectivity with the fusiform gyrus, posterior division, the cuneal cortex, the lateral occipital cortex, the inferior division, and the lingual gyrus; under the less demanding context of the cognitive control, the caudal IPC has negative functional connectivity with the lateral occipital cortex, the superior division (Tabassi Mofrad & Schiller, 2022). Thus, more cognitive demand results in more negative functional connectivity of the caudal IPC with different parts of the visual cortex.

Figure 6.3

Demonstration of brain areas that the caudal IPC is functionally connected with, in the more demanding context.

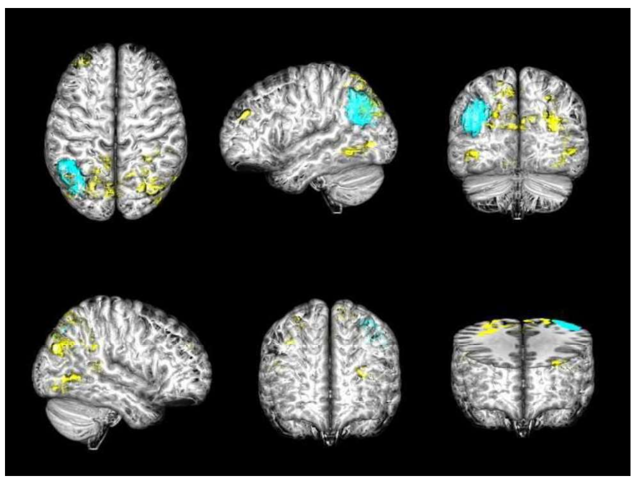


*Note***.** The yellow color demonstrates brain areas that the caudal IPC (shown in cyan) is functionally connected with, in the more demanding context of cognitive control. The descriptions of each row are as follows: A) negative functional connectivity of the left caudal IPC with the precuneus cortex, the inferior and posterior divisions of the lateral occipital cortex, the frontal pole, the anterior division of the cingulate gyrus, the posterior division of the temporal occipital fusiform and the lingual gyrus, B) positive functional connectivity of the left caudal IPC with the IPC caudal cluster left (PGa), C) negative functional connectivity of the right caudal IPC with the cuneal cortex.

While positive coupling between brain areas in the FPN and the visual cortex would result in better cognitive abilities such as word recognition (Twait & Horowitz-Kraus, 2019) and reading (Horowitz-Kraus & Holland, 2015), lack of a positive fluctuation between the caudal IPC and different parts of the visual cortex - the type of functional connectivity which is dissimilar to those of cognitive control related parts of the brain - demonstrates that this parietal area is not involved in other cognitive functions either.

Figure 6.4

Demonstration of brain areas that the caudal IPC is functionally connected with, in the less demanding context



Note. The yellow color demonstrates brain areas (the inferior and posterior divisions of the lateral occipital cortex and the frontal pole) that the left caudal IPC (shown in cyan) has negative functional connectivity with, in the less demanding context of cognitive control.

Our research findings also revealed that the caudal IPC has negative functional association with the precuneus cortex which is active when brain is not processing external stimuli. Taking into account that cortical areas that are involved in task performance decrease activity during the resting state, and those parts of the cortex that are active in the absence of external stimuli decrease activity when doing a task, the negative functional connectivity of the caudal IPC with the precuneus cortex indicates that this parietal area is not resting state related. Likewise, the negative couplings of the caudal IPC with cognitive control areas evidence that this part of the cortex does not contribute to cognitive control in the FPN. Furthermore, the negative functional connectivity of the caudal IPC with different parts of the visual cortex demonstrates that this brain area is not involved in general cognitive functions. Thus, the caudal IPC is not a task-related part of the brain.

Having negative connectivity patterns with both the resting state and the task based-related cortical areas characterize the caudal IPC with distinctive features, highlighting that the traditional categorization of different cortical areas into resting state and task related does not accommodate the functions of this parietal area. This part of the brain functions in a modulating manner, in the sense that the deactivations of the caudal IPC, relative to cognitive demand, contributes to task performance. The more difficult the task is or rather the higher the cognitive demand is, the more the number of negative functional connectivity of the caudal IPC with both task and resting state-related parts of the cortex would be observed.

6.4 Connectivity profile of middle IPC

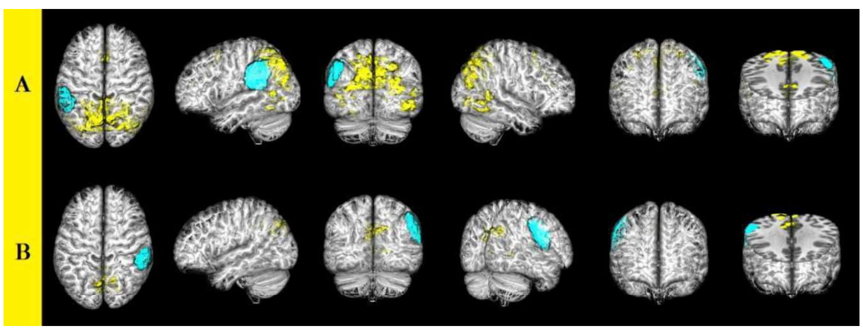
According to our findings, the connectivity patterns of the middle IPC are very similar to those of the caudal IPC (Tabassi Mofrad & Schiller, 2023), by having negative couplings with different parts of the visual cortex, the precuneus cortex, in addition to the anterior division of the cingulate gyrus, and the paracingulate gyrus, which are cognitive control-related parts of the brain (Jobson et al., 2021; Kragel et al., 2018).

In previous studies, the functions of the cingulate gyrus anterior division, in different executive functions such as decision making, task monitoring, error prediction (Khamassi et al., 2015; Shenhav et al., 2016;

Silvetti et al., 2013) and the involvement of the paracingulate gyrus in cognitive control (Kragel et al., 2018) have been elaborated on. The negative functional connectivity of the middle IPC with such brain areas underline that the middle IPC does not contribute to cognitive control either.

Figure 6.5

Demonstration of brain areas that the middle IPC is functionally connected with, in the more demanding context.

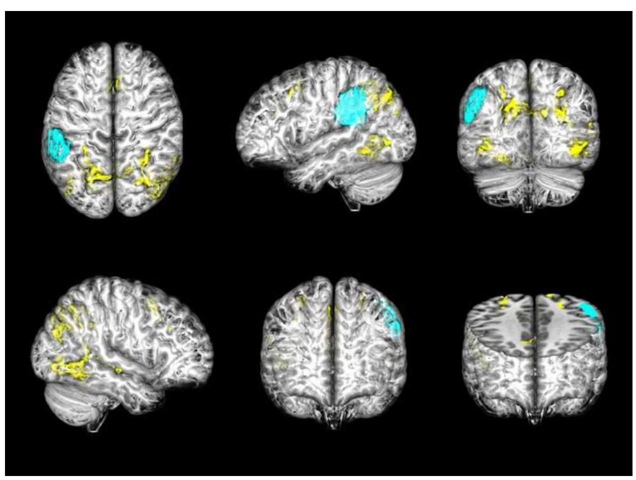


Note. The yellow color demonstrates brain areas that the middle IPC (shown in cyan) is functionally connected with, in the more demanding context of cognitive control. The descriptions of each row are as follows: A) negative functional connectivity of the left middle IPC with the precuneus cortex, the inferior division of the lateral occipital cortex, the anterior division of the cingulate gyrus, the occipital fusiform gyrus, and the lingual gyrus, B) negative functional connectivity of the right middle IPC with the precuneus cortex and the intracalcarine cortex.

The negative functional associations of the middle IPC is influenced by cognitive demand, with the more cognitively demanding condition, resulting in more negative functional couplings with other parts of the brain (see Figures 6.5 & 6.6). Besides, the negative functional associations of the middle IPC do not indicate that this part of the brain is resting state-related because of its negative coupling with the precuneus cortex – a brain area with reduced activity when performing a task. Furthermore, the middle IPC has negative connectivity with different parts of the visual cortex; improving cognitive performance, by better visualizing the stimuli, is the result of positive functional coupling of brain areas involved in cognitive control with the visual cortex. The absence of such positive functional associations of the middle IPC with e.g. the lateral occipital cortex, the occipital fusiform gyrus, and the lingual gyrus emphasize that this parietal area does not contribute to general cognitive functions and is not a task-related part of the cortex.

Figure 6.6

Demonstration of brain areas that the middle IPC is functionally connected with, in the less demanding context.



Note. The yellow color demonstrates brain areas (the inferior and posterior divisions of the lateral occipital cortex, the paracingulate gyrus and the anterior division of the cingulate gyrus) that the left middle IPC (shown in cyan) has negative functional connectivity with, in the less demanding context of cognitive control.

The connectivity profile of the middle IPC has highlighted the distinctive functions of this part of the cortex, characterized with deactivations in functionally coupling with other brain areas, in a modulating manner, proportional to the level of cognitive demand. In fact, the connectivity patterns of the middle IPC, similar to those of the caudal IPC, are not explained by the classic categorization of brain areas as resting-state and task-related, which advanced our hypothesis about modulating cortical areas.

6.5 Conclusion

The connectivity profiles of the clusters of the IPC elucidate that it is not the whole IPC that is involved in cognitive control but only the rostral cluster of this brain area (Tabassi Mofrad & Schiller, 2020) - with the middle and the caudal IPC demonstrating negative associations with parts of the brain that are engaged in executive functions (Tabassi Mofrad & Schiller, 2022; 2023). In previous studies, by ignoring the tripartite structure of the IPC, if the experimental conditions necessitated cognitive control, the functions of the rostral IPC were generalized to the whole IPC. However, if the experiment was conducted during the resting state or in the absence of an explicit task, the negative functional associations of the middle and the caudal IPC were considered representative of the whole IPC; hence, the contradictory research results on how this part of the brain functions.

Given the unique connectivity profiles of the middle and the caudal IPC, we considered modulating roles for these parietal areas, which demonstrate negative functional couplings with different parts of the visual cortex, cognitive control-related parts of the brain and with the precuneus cortex (Tabassi Mofrad & Schiller, 2022; 2023); the more difficult the task is, the more negative functional associations of these clusters of the IPC with other brain areas would be observed, while their connectivity profiles make them dissimilar to task-related and resting state-related parts of the cortex. In fact, the functional connectivity patterns of the middle and the caudal IPC evidence that the traditional categorization of brain areas does not accommodate the functions of such clusters of the IPC; the functional associations of the middle and the caudal IPC have highlighted another brain functional category beyond the classic definitions, as modulating cortical areas, the functional connectivity of which are disparate from parts of the cortex involved in task performance and brain areas related to the resting state functionality of the brain.

References

Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., Lazeyras, F., Cappa, S., & Khateb, A. (2008). Language control and lexical competition in bilinguals: an event-related fMRI study. *Cerebral Cortex, 18*, 1496-1505.

Abutalebi, J., Della Rosa, P. A., Green, D. W, Hernandez, M., Scifo, P., Keim, R., Cappa, S. F., & Costa A. (2012). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral Cortex, 22*, 2076-2086.

Abutalebi, J., & Green, D. W. (2016). Neuroimaging of language control in bilinguals: neural adaptation and reserve. *Bilingualism: Language and Cognition, 19* (4), 689–698.

Bareham, C. A., Georgieva, S. D., Kamke, M. R., Lloyd, D., Bekinschtein, T. A., & Mattingley, J. B. (2018). Role of the right inferior parietal cortex in auditory selective attention: An rTMS study. *Cortex*, *99*, 30–38.

Bellebaum, C., & Daum, I. (2007). Cerebellar involvement in executive control. *The Cerebellum, 6,* 184-192.

Braem, S., King, J. A., Korb, F. M., Krebs, R. M., Notebaert, W., & Egner, T. (2017). The Role of Anterior Cingulate Cortex in the Affective Evaluation of Conflict. *Journal of Cognitive Neuroscience*, *29*(1), 137–149.

Brockett, A. T., Tennyson, S. S., deBettencourt, C. A., Gaye, F., & Roesch, M. R. (2020). Anterior cingulate cortex is necessary for adaptation of action plans. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(11), 6196–6204.

Buchsbaum, B. R., Ye, D., & D'Esposito, M. (2011). Recency Effects in the Inferior Parietal Lobe during Verbal Recognition Memory. *Frontiers in Human Neuroscience*, *5*, 59.

Bzdok, D., Hartwigsen, G., Reid, A., Laird, A. R., Fox, P. T., & Eickhoff, S. B. (2016). Left inferior parietal lobe engagement in social cognition and language. *Neuroscience and Biobehavioral Reviews*, *68*, 319–334.

Caspers, S., Eickhoff, S.B., Geyer, S., Scheperjans, F., Mohlberg, H., Zilles, K., & Amunts, K. (2008). The human inferior parietal lobule in stereotaxic space. *Brain Structure and Function*, *212*, 481- 495.

Caspers, S., Geyer, S., Schleicher, A., Mohlberg, H., Amunts, K., & Zilles, K. (2006). The human inferior parietal cortex: cytoarchitectonic parcellation and interindividual variability. *NeuroImage*, *33*(2), 430–448.

Caspers, S., Schleicher, A., Bacha-Trams, M., Palomero-Gallagher, N., Amunts, K., & Zilles, K. (2013). Organization of the human inferior parietal lobule based on receptor architectonics. *Cerebral Cortex, 23*(3), 615–628.

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain Research, 1147*, 192–208.

Dang, L. C., O'Neil, J. P., & Jagust, W. J. (2013). Genetic effects on behavior are mediated by neurotransmitters and large-scale neural networks. *NeuroImage*, *66*, 203-214.

Doose, A., King, J. A., Bernardoni, F., Geisler, D., Hellerhoff, I., Weinert, T., Roessner, V., Smolka, M. N., & Ehrlich, S. (2020). Strengthened Default Mode Network Activation During Delay Discounting in Adolescents with Anorexia Nervosa After Partial Weight Restoration: A Longitudinal fMRI Study. *Journal of Clinical Medicine*, *9*(4), 900.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology, 25*(5), 515-530.

Hartogsveld, B., Bramson, B., Vijayakumar, S., Van Campen, A. D., Marques, J. P., Roelofs, K., Toni, I., Bekkering, H., & Mars, R. B. (2018). Lateral frontal pole and relational processing: activation patterns and connectivity profile. *Behavioral Brain Research*, *355*, 2-11.

Horowitz-Kraus, T, & Holland, S. K. (2015). Greater functional connectivity between reading and error-detection regions following training with the reading acceleration program in children with reading difficulties. *Annals of Dyslexia, 65*(1), 1-23.

Jobson, D. D., Hase, Y., Clarkson, A. N., & Kalaria, R. N. (2021). The role of the medial prefrontal cortex in cognition, ageing and dementia. *Brain Communications*, *3*(3), fcab125.

Khamassi, M., Quilodran, R., Enel, P., Dominey, P. F., & Procyk, E. (2015). Behavioral regulation and the modulation of information coding in the lateral prefrontal and cingulate cortex. *Cerebral Cortex, 25*, 3197–3218.

Kragel, P. A., Kano, M., Van Oudenhove, L., Ly, H. G., Dupont, P., Rubio, A., Delon-Martin, C., Bonaz, B. L., Manuck, S. B., Gianaros, P. J., Ceko, M., Reynolds Losin, E. A., Woo, C. W., Nichols, T. E., & Wager, T. D. (2018). Generalizable representations of pain, cognitive control, and negative emotion in medial frontal cortex. *Nature Neuroscience*, *21*(2), 283–289.

Krienen, F. M., & Buckner, R. L. (2009). Segregated frontocerebellar circuits revealed by intrinsic functional connectivity. *Cerebral Cortex, 19*, 2485–2497.

Mars, R. B., Neubert, F. X., Noonan, M. P., Sallet, J., Toni, I., & Rushworth, M. F. (2012). On the relationship between the "default mode network" and the "social brain". *Frontiers in Human Neuroscience*, *6*, 189.

Menon, V., & D' Esposito, M. (2022). The role of PFC networks in cognitive control and executive function. *Neuropsychopharmacology*, *47*(1), 90–103.

Raichle, M. E. (2015). The brain's default mode network. *Annual Review of Neuroscience*, *38*, 433–447.

Reineberg, A. E., Andrews-Hanna, J. R., Depue, B. E., Friedman, N. P., & Banich, M. T. (2015). Resting-state networks predict individual differences in common and specific aspects of executive function. *NeuroImage*, *104*, 69–78.

Ruschel, M., Knösche, T. R., Friederici, A. D., Turner, R., Geyer, S., & Anwander, A. (2014). Connectivity architecture and subdivision of the human inferior parietal cortex revealed by diffusion MRI. *Cerebral Cortex*, *24*(9), 2436–2448.

Shenhav, A., Cohen, J. D., & Botvinick, M. M. (2016). Dorsal anterior cingulate cortex and the value of control. *Nature Neuroscience, 19*, 1286–1291.

Silvetti, M., Seurinck, R., & Verguts, T. (2013). Value and prediction error estimation account for volatility effects in ACC: a model-based fMRI study. *Cortex, 49*, 1627–1635.

Smallwood, J., Bernhardt, B. C., Leech, R., Bzdok, D., Jefferies, E., & Margulies, D. S. (2021). The default mode network in cognition: a topographical perspective. *Nature Reviews Neuroscience*, *22*(8), 503–513.

Tabassi Mofrad, F., & Schiller, N. O. (2020). Cognitive demand modulates connectivity patterns of rostral inferior parietal cortex in cognitive control of language. *Cognitive Neuroscience*, *11*(4), 181–193.

Tabassi Mofrad, F., & Schiller, N. O. (2022). Mapping caudal inferior parietal cortex supports the hypothesis about a modulating cortical area. *NeuroImage*, *259*, 119441.

Tabassi Mofrad, F., & Schiller, N. O. (2023). Connectivity profile of the middle inferior parietal cortex confirms the hypothesis about modulating cortical areas. *Neuroscience, 519,* 1–9.

Twait, E., & Horowitz-Kraus, T. (2019). Functional Connectivity of Cognitive Control and Visual Regions During Verb Generation Is Related to Improved Reading in Children. *Brain Connectivity*, *9*(6), 500–507.

Zanto, T. P., & Gazzaley, A. (2013). Fronto-parietal network: flexible hub of cognitive control. *Trends in Cognitive Sciences*, *17*(12), 602–603.