Introduction and rationale for task switching paradigm.

Introduction:

Initial investigation of task switching paradigms reveals a staggering explosion of task design, theories, and neuroimaging data. Yet the quantity and heterogeneity of experimental designs address specific factors related to switch cost, and by proxy, cognitive function (Box 1). Switch cost is defined as the deficit in task performance incurred when switching between two tasks rather than repeating trials or continuous task performance (Jersild, 1927; Rogers and Monsell, 1995). Behavioral switch costs are viewed as a result of the increasing demand on executive function incurred by restructuring one mental "task set" (the goals, rules, and focus of attention unique to one task) to a differing one. Put simply, switch costs are a result of interference in cognitive restructuring processes. However, previous literature is divided on what types of interference and restructuring processes are responsible for the switch costs, often settling in camps that point to switch costs as a result of either bottom up or top down (Rubenstein et al 2001; Kim et al 2012) reconfiguration. (Box 1). Briefly, bottom-up reconfiguration results from updating a held task set with learned/cued information, and the dissolution of the previously held task set. Top-down reconfiguration is viewed as the endogenous, active process of recalling/ attending to the rules and objectives of a new task. Neuroimaging studies often look at the reconfiguration process as a result of the changes in brain network dynamics that reflect the changes in task set. It is for this reason I will refer to the neural correlates of switching task sets as switches in the task activity and connectivity profile (TACP). TACP refers to the activity and connectivity that compose the neural networks that represent the mentally held task set. Describing the task set as a neural network gives an impression of a static infrastructure and fails to capture the shifting, dynamic brain states that characterize a task set. TACP is similar to the definition employed by Deco et al, who instead chose the term as Probabilistic Metastable Substates (PMS states) (Deco et al 2019).

Many studies have investigated how unique, overlapping, dissociable, and predicative these TACP are (Hampshire et al 2019; Shi et al 2017; Soreq et al in press). Though many studies provide evidence for a multiple demand cortex (MDC) (Qawi et al 2016; Hampshire, Sharp 2015; Eyal et al 2019) there is a staggeringly high pile of literature that (1) selects key regions from a MDC unique to their respective task, or (2) are a part of a correlational neuroimaging study that identified a relationship between these regions and the state they were observing.

Confronted by this body of literature, a natural question that arises is "How unique are the TACP?" A study by Eyal et al 2019 built a classifier that identifies which task a participant was completing based on their TACP. Not only was the classifier successful (78.5% accuracy compared to chance's 8.3%), they found the three tasks out of 12 that exhibited the most dissociable TACPs correspond with the elemental distinctions between the cognitive tasks, their psychometric distance. From these results arises the follow-up question of "What does the reconfiguration between these different TACP look like in the brain?" The literature here is sparser. Many studies model the brain during these cognitive states and compare them to one another, there are a few studies characterizing the network dynamics when switching from rest to a task (Schultz and Cole 2016), and fewer still characterizing the *transition* from one discrete task to another (referred to as "set switching" or "context switching" (Kim et al 2012)). How is this different? Switching between tasks that utilize the same psychometric properties would still result in a switch cost, and still result in a shift of neural network dynamics, though the starting and ending TACP would presumably be largely similar. For example, one could construct a paradigm where either an even vs odd number or vowel vs consonant requires a left or right motor response. Switching between stimuli would utilize a similar cognitive process, and likely recruit similar networks (Karayanidis et al 2009; Cohen et al 2012). This makes it difficult to answer the question above- "What does the reconfiguration between these different TACP look like in the brain?" To answer this question, we constructed a cued, task-switching paradigm using the three most psychometrically opposed tasks as characterized by Eyal et al 2019. By utilizing tasks that have highly dissociable TACPs we can better ascertain whether reconfiguration is a top-down or bottom-up process.

Aims & Objectives:

The EEG and fMRI data collected from this task, in conjunction with DWI scans from each participant, will be used to generate a model of brain network dynamics during a task switch. This model will be used to determine an optimal node that, when modulated, will drive the shift in network dynamics to the target TACP. We envision that eliminating the neural correlates that are responsible for the switch cost we may eliminate the behavioral switch cost as well.

The first step is then to create a task that generates a behaviorally and physiologically measurable switch cost and characterize the behavioral and neural correlates of the switch- for example, is the reconfiguration reflective of a top down or bottom up process? Rather than scour conflicting literature and decide outright if our task is representative of process or another, we can collect the neuroimaging data from the task and test whether the physiological correlates of the switch between two tasks indicate top down or bottom up reconfiguration. *Once we have a better idea of the analysis methods to do this, we can begin to discuss their rationale here.*

We created a cued task switching paradigm between three psychometrically opposed tasks as defined by Soreq et al 2019 and will collect EEG and fMRI data whilst participants perform the task. We hypothesize that the inter-task window in a cued task switching paradigm will reflect a top-down reconfiguration process. We are constructing our task to reduce bottom-up interference by any display or motor confounds, so the neuroimaging correlates are representative of the cognitive/psychometric properties of the task as opposed to display or motor responses.

If the neural correlates of switch costs are representative of top-down reconfiguration then we expect to see dissolution of the TACP after cue the task ends, and a restructuring process reflective of recalling and implementing the next task set. The elimination of the switch cost would presumably reflect a settled TACP. However, the neural correlates of a bottom-up reconfiguration process may result in concurrent activation of both TACPs, then dissolution of the prior TACP reflecting in a settled TACP and eliminated switch cost. It is interesting to note that the central difference between top down and bottom up reconfiguration processes is in their view of *when* the dissolution of one TACP occurs. Top down processes view the dissolution of the first TACP as an initial step, with the switch cost relating to the time it takes to recall and implement a second TACP. Bottom up processes view the dissolution process as one that occurs simultaneously with the recall and implementation of the secondary TACP, and switch cost reflective of holding two conflicting task sets at once.

We hypothesize the reconfiguration process can be separated into dissociable (though perhaps not wholly discrete) components. After the “Next Task” cue we predict there will be a dissolution of the initial

BOX 1: GLOSSARY OF TERMS

Switch Cost: The behavioral deficit in task performance when switching as opposed to repeating trials.

Task set: The mental representation of rules, goals, and focus of attention unique to a task (Rogers and Monsell 1995).

Task activity and connectivity profile (TACP): TACP refers to the neural correlates unique to each task’s “task set.”

Interference: The increasing demand on executive function incurred by stimuli or goals conflicting with the current task set.

Top-down process: The active dissolution of a TACP and subsequent reconfiguration to another. In a cue-based task, this may consist of recall and implementation of a tasks’ rule set (SOURCE), while in a learning task this will be an active process of reevaluating performance on a developing rule set.

Bottom-up process: The parallel process dissolving a prior task set and replacing it with another.

Bottom-up interference: Also know as *stimulus driven* interference, results from exogenous stimuli regardless of advance goals, attention, or knowledge (Kim et al 1999).

Selection history interference: A propensity to attend to stimuli that you’ve previously attended to or selected.

Reward interference: A propensity to attend to previously rewarding stimuli. This is observed in both top-down (Pessoa and Engleman 2010) and bottom-up processes (Hickey et al 2010; Anderson et al 2011a; Anderson et al 2011b).

TACP, an increase in activity of ROI associated with attention (rIFG), and finally, the recall and implementation of the appropriate TACP for the next task. Ultimately, the brain will reflect the TACP of the current task coinciding with the elimination of the behavioral switch cost.

Commented [DK1]: We have ideas on what this will look like in fMRI based on Eyal's paper and others

REFERENCES AND TAKEAWAYS:

1. Wolff, Beste, 2017: Neural mechanisms and functional neuroanatomical networks during memory and cue-based task switching as revealed by residue iteration decomposition (RIDE) based source localization.
2. Shi, Ruge, 2017: When global rule reversal meets local task switching: The neural mechanisms of coordinated behavioral adaptation to instructed multi-level demand changes.
    a. fMRI: FPN and cortico-striatal network (CSN) are networks involved with global or local task switching processes. Hierarchical analysis defined global levels as temporally more stable rule sets, with local levels as trial-by-trial switching.
        i. Local effects: higher activation in regions during switches
        ii. Global effects: larger activation during instruction phase in regions that are active during implementation phase in local levels.
    b. Main takeaway: "On a general level, the neuroimaging results suggest that different aspects of global and local adaptation processes are implemented by partly overlapping and partly segregated neural systems."
3. Eyal, Hampshire, 2019: Dynamic brain states underlie dissociable factors of human intelligence
    a. fMRI FC: tasks can be classified based on their respective TACP. Digit span, spatial rotation, and self-ordered search are the three most TACP-disparate tasks, which is interesting as they represent the classical separation of working memory mechanisms.
4. Hampshire, Violante, 2019: Probing cortical and sub-cortical contributions to instruction-based learning: Regional specialization and global network dynamics
    a. Main takeaway:
        i. Throughout the task switch there are several steps characterized by networks
        ii. Rule-instruction slide presented = strong activation peaks and increased connectivity btwn anterior caudate and frontoparietal regions. Peak in anterior caudate in practice phase. Roles of networks in task are
            1. Throughout task = Cingulo-opercular
            2. Early task = Fronto patietal
            3. Late task = Default mode
5. Jamandar, Karyandis, 2010: The spatial and temporal dynamics of anticipatory preparation and response inhibition in task-switching
    a. EEG: early-cue-locked, positive, ERP of dlPFC consistent with goal activation process. Dissociation between dlPFC and vlPFC, as dlPFC involves "top-down biasing" with latter showing a role in response inhibition due to a negative correlation of the vlPFC and basal ganglia to "a frontal P3"
    b. Anticipatory preparation of task switching involves goal and category-response activation, as well as fxnl dissociation btwn dl and vl PFC.
    c. State even with prep there is residual switch cost
6. Pani, Fraschini, 2019: Subject, session and task effects on power, connectivity and network centrality: a source-based EEG study
    a. Three source level EEG analysis (power spectral density, phase locking value, and eigenvector centrality) use eigenvector centrality confirm that functional brain networks are stable over time and are independent from specific tasks.
7. Braun, Bassett, 2015: Dynamic reconfiguration of frontal brain networks during executive cognition in humans
    a. Reconfiguration of TACP is initiated/coordinated by the frontal cortex, and that people who can more flexibly shift the modular networks will perform better than those with more rigid network structures
    b. They used some fucking crazy "dynamic community detection" to form a multilayer network model.
    c. They conclude "dynamic network reorganization is taking place predominantly in frontal systems and is driven by a constant readaptation and interaction of frontal systems with each other"
    d. Some modules are more integratory than others- less integratory modules = visuo and somato-motor modules have relatively weak interaction with other modules. Frontoparietal modules show a high variance in connectivity over different tasks.

Commented [DK2]: Application to paper: what we may expect to see in imaging data

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8. Deco, Kringlebach, 2019: Awakening: Predicting external stimulation to force transitions between different brain states
    a. Objective is to model a forced transition from sleep to wake + vice versa. Whole-brain study of brain states to provide a solid, comprehensive model, followed by in-silico modelling
    b. View brain as an ensemble of metastable "sub-states": See LEIDA below. Definition of brain states: "characterization of the probabilistic metastable sub-state (PMS) space"
    c. Summary of LEIDA:
        i. Used FSL to extract average BOLD signal from 90 ROIs. Average bold from 90 ROIs was Hilbert transformed to yield phase evolution of signals.
        ii. Phase coherence of each node = cosine of phase differences, between 1 & -1.
        iii. Gives a 3D matrix with n = 90, and T = # of images. Rather than use the entire matrix, it is cut down significant using LEIDA to increase signal-to-noise ratio (see below).
        iv. The method relies on the extraction of the first (Nx1) eigenvector, V1, of each dFC matrix, from which one can reliably detect a discrete number of reduced dFC patterns by applying clustering across time points and subjects. Due to the symmetry of the dFC matrices, each leading eigenvector may be used in turn to estimate the corresponding dFC matrix. The obtained k-cluster centroids define the "metastable substates," for which one can compute the probability of the centroid, as well as its transition probabilities.
    d. After LEIDA, it has to fit the functional data to structural data
    e. Get models for two different brain states (in their case, sleep and wakefulness)
    f. Forcing a state transition! Did this using a Hopf model and changing the bifurcation parameter
9. Kim, Gold, 2012: Meta-Analysis: Domain general and domain preferential brain regions associated with different types of task switching
    a. Our task would be a "context switching" task, where the participant shifts between task rules or cognitive sets, and "emphasizes the endogenous control processes associated with the maintenance and switching between multiple cognitive sets"
    b. There are "domain general" areas of activation in task switching paradigms, as well as specialized switching areas. The IFJ and PPC seem to be important in representing and updating task sets. Other studies corroborate this through noting increased anatomical connectivity between the two.
    c. Frontopolar cortex and dlPFC = preferential activation with context switching = lateral and medial FPC, ACC, as well as PPC, middle frontal gyrus, cuneus, inferior temporal areas, visual areas, thalamus and lentiform nucleus.
    d. "The anterior-to-posterior task switching gradient we observed according to the level of endogenous control is consistent with evidence for a similar gradient across several other cognitive domains [Badre and D'Esposito, 2007"
10. Schultz, Cole, 2016: Higher intelligence is associated with less task-related brain network reconfiguration
    a. Used fMRI and FC on Connectome data to characterize changes in TACP and map to behavioral performance.
    b. Task performance on 3 different tasks (language, reasoning, working memory) is correlated with reconfiguration efficiency from rest OR from multiple-demand cortex
    c. FC reconfig efficiency is partially network specific across tasks
    d. High-performing participants have resting states "preconfigured" to switch to TACP
11. Yehene, Merian, 2007: Is there a general task switching ability?
    a. NO IMAGING
    b. Looked at two tasks that operate on separate psychometric foundations; found switching, mixing, + congruency to effect scores on all 3 with ample preparation time; w/out prep time = congruency effects are paradigm specific
12. Hampshire, Sharp, 2015:
    a. Key quote in favor of top-down updating: There are computational reasons to favour top-down control via a potentiating signal. A specific top-down inhibitory system would be an inefficient use of resources Consider monitoring a sequence of targets in a noisy scen where distracting stimuli constantly change. To

Commented [DK4]: Hilbert transformation: by imparting a 90 degree phase shift to every Fourier component you produce another function of a real variable (frequency?)

Commented [DK5]: In the mathematical theory of bifurcations, a **Hopf bifurcation** is a critical point where a system's stability switches and a periodic solution arises.[1] More accurately, it is a local bifurcation in which a fixed point of a dynamical system loses stability, as a pair of complex conjugate eigenvalues - of the linearization around the fixed point - crosses the complex plane imaginary axis. Under reasonably generic assumptions about the dynamical system, a small-amplitude limit cycle branches from the fixed point.What is this?

prevent task processes from being disrupted, any source of topdown inhibition would have to represent and downregulate each distracting item individually. Sensory inputs would have to be scanned to identify new distractors and the representation of distractor items would have to be continually maintained, monitored, and updated. As the number or rate of distractors increased, such a system would reach capacity and fail. By contrast, the source of a topdown potentiating signal could represent, process, and potentiate just those items that were relevant to the current task. Local competition within sensory processing streams would efficiently work to downregulate all competing distractors in parallel. Given the computational advantages of top-down potentiation, it is unsurprising that electrophysiology research has provided a wealth of evidence demonstrating that frontal cortex neurons represents task-relevant inputs, rules, and responses

13. ERP studies support top down reconfig (from Jamandar et al 2010):
    a. The below studies support a "multi-component model of task set reconfiguration" (Rogers and Monsell, 1995; Rubenstein et al 2001). The first section below represents anticipatory TACP reconfiguration processes, and section c reflects either stimulus-triggered processes that complete TACP reconfiguration or processes that resolve interference after stimulus onset
    b. "ERP waveforms time-locked to beginning of prepatory interval show a larger posterior positivity for switch trials compared to repeat. (Goffauz et al 2016; Karayanidis et al 2003; Kieffaber and Hetrick, 2005; Miniussi et al 2005; Nicholson et al 2005, 2006a, 2006b; Poulsen et al 2005; Rushworth et al 2002, 2005; Swainson et al 2006)
        i. Some call it increased P3b (Goffauz et al 2016; Kieffaber and Hetrick, 2005; Poulsen et al 2005)
        ii. Some call it late parietal positivity (Astle et al 2006, 2008; Swainson et al 2006)
        iii. Some call it differential switch positivity or switch positivity (Karayanidis et al 2003, Nicholson et al 2005, 2006a, 2006b). Emerges as early as 150 ms after cue onset, and can resolve fully before stimulus with long enough interval. Not due to preparation interval, but rather is preparation is complete before task begins or not.
        iv. LFN = late frontal negativity; conflicting evidence for it (often but not exclusively using a common average reference (Astle et al 2006, 2008; Lavric et al 2008; Mueller et al 2008; Rushworth et al 2002, 2005) vs against it (Goffauz et al 2016; Karayanidis et al 2003; Miniussi et al 2005; Nicholson et al 2005, 2006a, 2006b)
    c. ERP for switch trials show smaller positivity than repeat trials over central and parietal scalp, reffered to as stimulus locked differential switch negativity.
        i. For long preparation intervals (what we have) it emerges as early as 150 ms and peaks around 400-500 ms after stimulus onset. Short = different with different sources.
        ii. (Karayanidis et al 2003; Kieffaber and Hetrick 2005; Miniussi et al 2005; Nicholson et al 2005; Poulsen et al 2005)
14. Sdkjxn
    a. previously selected targets to minimize selection history interference (Awh 2012)
15. G. Deco et al., Perturbation of whole-brain dynamics in silico reveals mechanistic differences between brain states. Neuroimage 169, 46–56 (2018).
16. G. Deco, M. L. Kringelbach, V. K. Jirsa, P. Ritter, The dynamics of resting fluctuations in the brain: Metastability and its dynamical cortical core. Sci. Rep. 7, 3095 (2017).
17. G. Deco, T. J. Van Hartevelt, H. M. Fernandes, A. Stevner, M. L. Kringelbach, The most relevant human brain regions for functional connectivity: Evidence for a dynamical workspace of binding nodes from whole-brain computational modelling. Neuroimage 146, 197–210 (2017)