Meta-Control Demands Deactivate Cognitive-Control Regions

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Abstract

Control interventions (e.g., attention, inhibition) are well-known to activate frontoparietal regions and increase pupil size. Here, we characterize a different facet of cognitive-control that deactivates these very same regions and decreases pupil size. Control interventions always occur in the context of extended task episodes (e.g., 'block of trials'). Since these extended episodes are controlled and executed as one entity, the various control interventions made across their duration are brought about via common goal-directed programs. These programs are instantiated at the beginning of the episode and are the means of organizing and controlling the numerous control interventions to be made across the task duration. These programs, therefore, are meta-control in function in that they control and organize the control interventions to be made across the task episode. Difficult episodes begin with the instantiation of more complex programs that will go on to bring about a more complex set of control interventions. Across four experiments, we show that while the instantiation of more complex control interventions during difficult task episodes expectedly activated control-related frontoparietal regions and increased pupil size, instantiation of more complex programs at the beginning of these episodes deactivated these very regions and decreased pupil size. Neural and psychophysiological signatures of the meta-control programs are thus categorically different from those of control interventions made through these programs.

Significance Statement

Activation of control-related frontoparietal regions and increased pupil size during difficult tasks is a well-known finding and forms the basis of our understanding of how cognition is controlled in the brain. We show that these very regions deactivate at the beginning of these very tasks that will activate them later. We suggest that this deactivation is due to meta-control structures through which control interventions across extended tasks are goal-directedly organized and instantiated. We also show that meta-control demands decrease pupil size and thus differ in their psychophysiological signatures from control demands that typically increase pupil size.

Introduction

Foundational to neurocognitive accounts of cognitive-control is a ubiquitous neuroimaging finding – activation of a set of fronto-parietal regions to diverse control processes. Attention, working memory (WM), response inhibition, rule-switching, cognitive-conflict, etc. – all activate the same set of frontal and parietal regions variously referred to as multiple demands (MD), cognitive-control, attentional, or task-positive network (Aron, 2007; Botvinick et al., 2004; Corbetta & Shulman, 2002; D'Esposito & Postle, 2015; Duncan & Owen, 2000; Fox et al., 2005; Niendam et al., 2012; Posner & Rothbart, 2007; Ptak, 2012). While varying in their details, these accounts consider MD regions' activation as reflecting their top-down intervention into sensory/motor regions to enhance task-related processing, create stimulus-response links, maintain relevant representations in working memory, filter out irrelevant processing, etc. (e.g., Desimone & Duncan, 1995; D'Esposito & Postle, 2015; Miller & Cohen, 2001). Control-related MD activations are accompanied by the deactivation of a separate set of regions referred to as the default mode regions (DMN), which has been interpreted variously as the deactivation of regions involved in internal cognition, self-processing, or mind-wandering due to resources being directed to the current task execution (Andrews-Hanna et al., 2014; Mason et al., 2007; Raichle et al., 2001). Control processes that activate MD regions are also accompanied by an increase in pupil size, reflecting the activation of specific modulatory systems in the brain stem with diffuse cortical projections (Clewett et al., 2020; Joshi et al., 2016; Murphy et al., 2014; Porter et al., 2007; Sara & Bouret, 2012; Unsworth & Robison, 2018; van der Wel & van Steenbergen, 2018).

Existing accounts, however, have ignored an essential aspect of cognitive-control. Control interventions, e.g., attention, WM, response-inhibition, always occur in the context of overarching extended tasks (e.g., 'block of trials', 'reading a text', 'solving a problem') where they are instantiated as part of a larger set of goal-directed changes being made across the task duration. Extended tasks, e.g., require an evolving task-focus that continually brings to the fore relevant learnings, memories, predictions, skills, and dispositions such that at every point within the task, cognition is in the most optimal state for the demands anticipated at that point (Bartlett & Bartlett, 1932; Logan & Gordon, 2001; Miller et al., 1960; Nobre & van Ede, 2023; Palenciano et al., 2019). Extended tasks also require multiple control processes, many of which will be sustained across time but with their aim and object changing across this duration. A

task, e.g., may require a variety of attentional interventions over an extended period. Some junctures may require attending to some part of the environment; others may require preparing a motor act. Still, others may require recalling a cognitive routine, etc. Furthermore, tasks require dynamic coordination across different but simultaneous control processes. The attention being sustained may be in relation to something being maintained in working memory and, at various junctures, may be guided through coordinated recollection of numerous episodic memories and procedures.

All of these – the dynamic task focus and the various control processes being instantiated and maintained across time – cannot be brought about by separate and independent cognitive acts (e.g.) every millisecond and can only be instantiated via a common subsuming program that sets and evolves the cognitive focus for relevant control operations, and organizes, instantiates and maintains various control interventions (Farooqui et al., 2023; Farooqui & Manly, 2019). Such programs would be the means through which goals retroactively organize the period of cognition culminating in them (Gollwitzer & Sheeran, 2006; Greenwald, 1972; James, 1890; Jeannerod, 1988; Kruglanski & Kopetz, 2009; Lewin, 1926). Well-characterized control processes like attention, WM, response inhibition, etc., must be instantiated via these programs at the right time, for the right duration, and in the right combination, making these programs *meta-control* in function in that they are not control processes themselves but are the means of goal-directedly controlling the control processes.

Extended task executions begin with the instantiation of meta-control programs that will then go on to hierarchically organize and control the ensuing execution. Since these programs are related to the entire task, longer or more complex tasks require larger or complex programs. These causes the famous finding that executing the first step of the extended tasks requires some additional time, and that this additional time is longer for longer/more complex tasks (Henry & Rogers, 1960; Logan, 2004; Rosenbaum et al., 1983; Schneider & Logan, 2006). Since these programs will necessarily be hierarchical, completion of a subtask can be expected to dismantle the subtask-related program, leaving the overarching task-related program intact. Task completion, in comparison, can be expected to dismantle programs at all levels. This causes task completions to elicit more intense and widespread activation than subtask completions, which in turn elicit more widespread activation than sub-subtask completions (Farooqui et al., 2012).

If these meta-control programs are the means of instantiating control across extended tasks, difficult tasks will require complex programs embodying commands for instantiating complex control operations. Such complex meta-control programs will put a greater demand on

cognitive resources. There indeed is a limit on the size of programs that can be instantiated at a time. Longer and more complex tasks, therefore, get chunked and executed as a series of subtasks, each executed through a smaller program (Farooqui et al., 2023; Vallacher & Wegner, 1987).

Neural and psychophysiological responses to instantiating more complex meta-control programs are not known but are likely to differ from that of instantiating control processes. Attention and other control processes involve changing ongoing processing in (e.g.) sensory or motor cortices to favor or select task-relevant processes, and MD activation is thought to represent this top-down intervention (Aron, 2007; Desimone & Duncan, 1995; D'Esposito & Postle, 2015; Gregoriou et al., 2009; Kastner & Ungerleider, 2000; Miller & Cohen, 2001). In contrast, instantiating meta-control programs at the beginning of complex tasks requires assembling the set of commands that will go on to bring about the relevant set of control interventions later in the ensuing task. Since this does not require a top-down intervention into ongoing sensory or motor processing, it may not activate MD regions. The cognitive demands of these programs have indeed been linked to the widespread deactivation seen during task execution, and the beginning of tasks expected to have larger programs, e.g., longer attentional search episodes compared to shorter episodes, elicit stronger deactivation in both MD and DMN regions (Farooqui & Manly, 2018).

Difficult extended tasks require both – a more complex meta-control program instantiated at the beginning as well as a more complex set of control processes instantiated subsequently through this program. If the demands related to instantiating meta-control programs are indeed different from the demands related to instantiating control processes, then the difference between hard and easy tasks will be different at their beginnings, when demanding meta-control programs must be instantiated, compared to later steps when demanding control interventions are to be made. We tested this across four experiments.

Materials and Methods

MR acquisition and Preprocessing

MRI scans were acquired on a 3-Tesla Siemens MAGNETOM Tim Trio scanner with a 32-channel (in Experiment 1) and a 12-channel (in Experiments 3 and 4) phased array head coils. A sequential descending T2*-weighted gradient-echo planar imaging (EPI) acquisition sequence was used with the following parameters: acquisition time of 2000 ms, echo time of 30 ms, 32 oblique slices with a slice thickness of 3 mm and a 0.75-mm interslice gap, in-plane resolution of 3.0 × 3.0 mm^2, matrix dimensions of 64 × 64, a field of view measuring 192 mm, and a flip angle of 78°. T1-weighted MPRAGE structural images were acquired for all subjects, characterized by a slice thickness of 1.0 mm, resolution of 1.0 × 1.0 × 1.0 mm^3 isometric voxels, a field of view spanning 256 mm, and 176 slices. Experiment 1 used GRAPPA and phase oversampling at 20% with an acceleration factor of 2, GRAPPA and phase oversampling were not used in experiments 3 and 4.

Preprocessing was conducted using Statistical Parametric Mapping (SPM) through automatic analysis (aa) pipeline (version 5; Cusack et al., 2015). During preprocessing, functional images were slice-time corrected using the middle slice as a reference, co-registered with the structural T1-weighted images, and followed by realignment and normalization to the Montreal Neurological Institute (MNI) template. In Experiments 3 and 4, normalization was done through the DARTEL toolbox. EPI images were resampled to a 2 x 2 x 2 mm^3 resolution and subsequently smoothed using an 8-mm full-width at half-maximum Gaussian kernel. The dataset underwent high-pass filtering with a cut-off frequency of 128 seconds.

Experiments 1 and 2

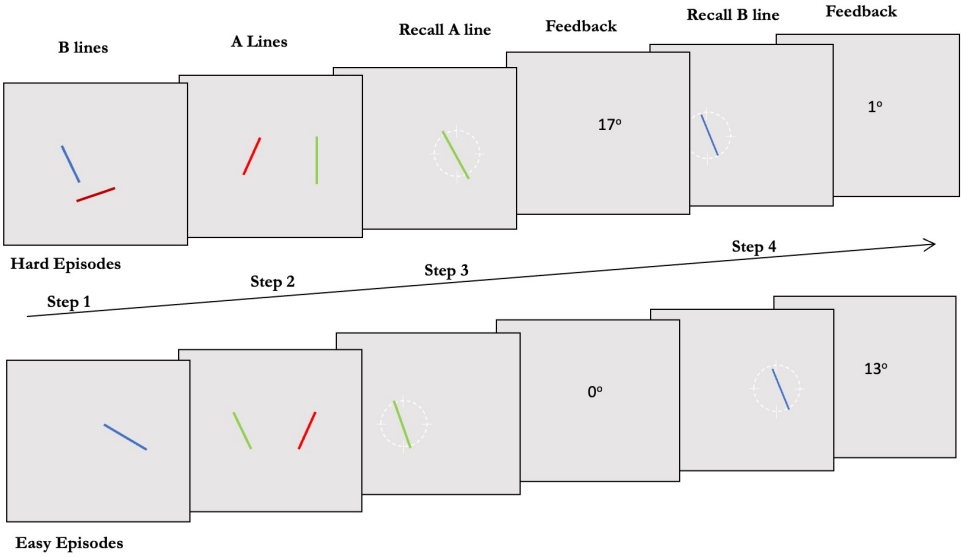

Figure 1. Participants executed two kinds of extended task episodes. Hard episodes began with the presentation of two lines whose orientations were to be kept in mind for subtask-B (step 1). They then (step 2) saw two different lines (referred to as subtask-A lines), kept their orientations in mind, and were probed to recall the orientation of one of these by orienting the probe to the same angle (step 3). After finishing this subtask-A, they were probed to recall the orientation of one of the subtask-B lines (step 4). Easy episodes were identical to hard episodes except that they started with a single subtask-B line presentation. Hard and easy episodes thus differed in the number of subtask-B lines that were to be kept in mind across the duration of the episode while subtask A was being executed.

Experiment 1

Both easy and hard episodes started with a start-screen that stayed on until participants pressed a button and were followed by step 1 (subtask B-line presentation). The lines were presented around the center. The two lines presented during hard episodes were never of the same color. These lines stayed on until participants pressed a button. Immediately at the offset of these lines, a mask screen was presented for 500 milliseconds. This was followed by Step 2 (subtask A-line presentation). These, too, stayed until a button was pressed, and a mask screen also followed their offset. Participants were then probed to recall one of these A-line orientations (step 3). The probe for the line orientation to be recalled was presented at the same spot and in the same color as the original line. Participants changed the probe orientation using repeated button presses. Index and middle finger presses changed the orientation in clockwise and anticlockwise directions respectively, each press changing it by 1°. After participants were satisfied with the probe orientation, they made a separate button press to confirm their answer and were given feedback that displayed the angular deviation between the actual orientation and their answer. Lastly (step 4), they recalled the orientation of one of the B lines presented in step 1. The probe again was of the same color and at the same spot as the line to be recalled. The probe manipulation was identical to that at step 3. This step, too, was followed by feedback

that told participants of the angular deviation between their answer and the original orientation. The start-screen for the next episode followed step 4. Each of the steps was separated by a jittered gap of 0.5 to 6 seconds calculated from the offset of the previous step to the onset of the next.

Participants executed a total of 20 easy and 20 hard episodes interleaved with each other. The order re-set after every 4 episodes, e.g., for the first four episodes, the order may be easy-hard-easy-hard. For the next four, the order may shift to hard-easy-hard-easy. Data were collected through two separate fMRI runs, each run included 10 easy and 10 hard episodes and lasted between 15 to 25 minutes. An MR-safe 32-inch LCD Monitor (refresh rate: 60Hz, spatial resolution 1600 x 1200 pixels) displayed the stimuli that the participants saw through a mirror attached to the head coil. Responses were recorded using an MR-safe button box. The experiment was run using PsychoPy version 2021.2.3 (Peirce et al., 2019).

Imaging Analysis

To capture the activity linked to each of our events of interest without making hemodynamic assumptions, we modeled 12 seconds of activity succeeding the beginning of each of the four steps using six 2-second-long finite-impulse regressors (Glover, 1999). Steps related to easy and hard episodes were separately modeled. We contrasted the estimates of activity following steps 1 and 2 of easy and hard episodes. We used two kinds of contrasts. In the first, we used a hard>easy t-contrast to look for regions that had higher average activity across the six regressors following steps 1 and 2 of hard compared to easy episodes. Contrast estimates were then put into a second group-level analysis (Figure 2). In the second we did a repeated-measures ANOVA to look for regions where the change in activity between hard and easy episodes was different across steps 1 and 2 (Figure 3).

Experiment 2

The design of the experiment was identical to experiment 1, except that a jittered gap no longer separated the component steps; they were instead separated by a constant 1-second gap. Stimuli were delivered in a dark room on a computer monitor (NEC MultiSync LCD 2190UXP monitor, size 21 in, resolution: 1600x1200, refresh rate: 60 Hz) placed 57 cm from participants whose heads were fixed with their chins rested. Pupil sizes were recorded using Eye Tracker 6 (Applied Science Laboratories, Bedford, MA, USA) at a sampling rate of 50 Hz. Participants responded via arrow keys on a QWERTY keyboard.

The width and color of lines were chosen such that easy and hard screens were iso-luminant (https://www.w3.org/Graphics/Color/sRGB). In-house developed Python scripts were used for the analysis of pupil-size data. NaNs replaced eye-blink values. Extreme pupil sizes were discarded using a cutoff value of four standard deviations above and below the median pupil diameter for each subject. We did not apply any smoothening to the data. The timing of pupillometric and behavioral outputs was aligned via a marker sent from the experiment script to the eye-tracker via the XDAT port at the beginning.

Experiments 3 and 4

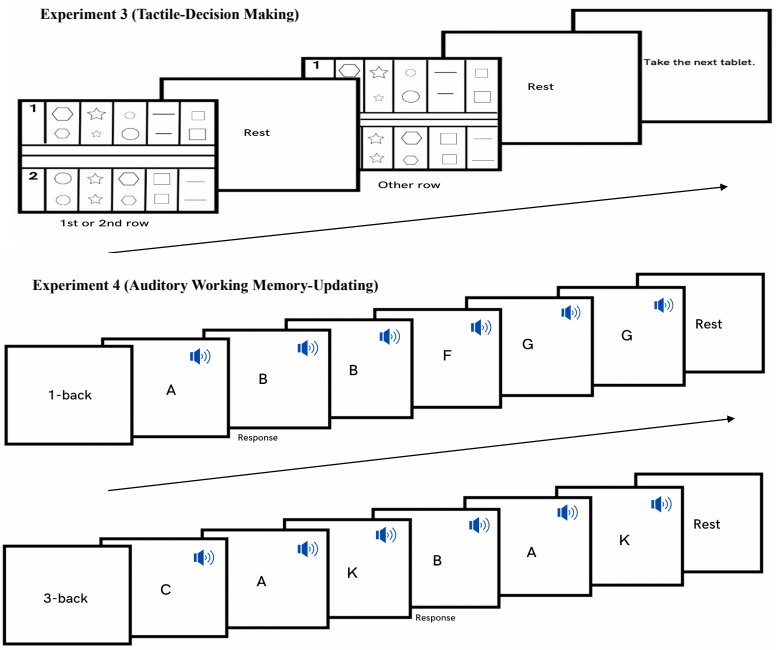

Figure 2. Experiment 3 (Tactile-Decision Making) and Experiment 4 (Auditory Working Memory-Updating). Both tasks had an easy and a hard episode, each lasting 15-30 s. (Upper) Tactile Decision-Making: Participants decided which of the two shapes was larger in size. The task was done through a plexiglass tablet that had an easy and a hard part, each of which had 5 trials. Each trial involved a pair of shapes drawn with raised margins. Margins of shapes on easy trials were more raised above the surface, making them easier to perceive by touch. Further, the size difference between the shapes of a pair was larger on easy trials. (Lower) Auditory working-memory updating: Each episode had 10 trials. Participants decided if the letter they heard on a given trial was the same as 1 (on easy blocks) or 3 (on hard blocks) trials prior (see Methods).

Participants did a tactile decision-making and an auditory working memory updating task across two different fMRI sessions (Figure 2). The tactile decision-making task had participants make judgments about the size of geometric shapes (e.g., circles, squares, and rectangles) embossed on plexiglass tablets. Trials were organized into easy and hard episodes, each consisting of 5-trials. On each trial, participants were presented with a pair of geometric shapes, with one always being larger in size than the other. They indicated their decision using a button box. The difficulty of the decision was modulated through two main manipulations:

the magnitude of the difference between areas of the two shapes and the raised-ness of the shapes' margins above the tablet. Shapes on trials of easy episodes had a size difference between 0.8 and 1 cm^2. On hard episodes, this difference was 0.3 to 0.5 cm^2. Each tablet had stimuli for the 5 trials constituting an easy episode and 5 trials constituting a hard episode. An experimenter replaced the tablet after every two episodes. The tablets were positioned either on the chest or the abdomen of participants. Participants executed 4 easy and 4 hard episodes for their pre-scan practice. During the scan, they executed 10 easy and 10 hard episodes. The experiment was coordinated through pre-recorded auditory instructions delivered through Psychtoolbox on MATLAB. These told the participants when to start a trial, when to make their button-press response, and when to rest (2 to 10 seconds after the completion of an episode). They could rest as long as they wanted and then press a button to inform that they were beginning the next episode.

The auditory working memory updating task was a modified auditory n-back task. On easy episodes, participants did a 1-back task, and on hard, a 3-back task. Each episode had 10 trials. On each trial, participants heard a Turkish letter. They responded if the presented letter was the same or different compared to that presented *n* trials earlier (index-finger: same, middle-finger: different). Easy and hard episodes alternated with each other. 5 to 15 seconds after the completion of an episode, participants heard rest instructions. They could rest as long as they wanted and then press a button to start the next episode. Participants completed a 10-minute pre-scan training before the fMRI session. For 3 participants whose responses remained erroneous at the end of this 10-minute session, the hard episodes were changed to 2-back.

Imaging Analysis

Each task episode was modeled using three regressors. The start of the episode was modeled as an event of no duration to capture the activity elicited by the beginning of the episode. The entire episode was separately modeled as an epoch of the same duration as the episode. This was to capture the average activity elicited during the episode. The completion of the episode was modeled as an event of no duration to capture the activity elicited by the completion of the episode. The easy and hard episodes were separately modeled with a different set of regressors. Movement parameters were added to the GLM as covariates of no interest. Regressors and covariates were convolved with the standard hemodynamic response function and entered into the GLM. We did two t-contrasts. The first looked at hard>easy at the beginning of the episodes. The second looked at hard>easy during the main episode epoch.

Contrast estimates from each participant were entered into a group-level analysis. We also did a whole-brain repeated measures ANOVA to look for regions where the effect of these two contrasts was different.

Regions of Interest

To investigate regions involved in cognitive control demands, we used well-characterized regions of interest (ROIs) belonging to the MD and DMN regions. We used spherical ROIs (10 mm diameter). These were bilateral inferior frontal sulcus (IFS ± 41 23 29), intraparietal sulcus (IPS; ± 37 -56 41), anterior insula extending in the frontal operculum (AI/FO; ± 35 18 3), anterior pre-frontal cortex (APFC; 27 50 23 and -28 51 15). IFS, IPS, and AI were taken from Duncan (2006), and APFC was taken from Dosenbach et al (2006). DMN ROIs included: posterior cingulate cortex (PCC; -8 -56 26) and anteromedial pre-frontal cortex (aMPFC; -6 52 -2), temporoparietal junction (TPJ ± 54 -54 28) (Andrews-Hanna et al., 2010: Vatansever er al., 2015). All coordinates are in MNI space. ROIs were made by using the MarsbaR toolbox for SPM. ROI analyses was also done using MarsbaR. Related statistical analyses were done on JASP platform (version 0.16.4)

Participants

Experiments 1 and 2 had 30 participants each (experiment 1: 20 females, mean age = 21.5 years, range = 18-34; experiment 2: 20 females, mean age = 20.6 years, range = 18-23 years). Participants were all right-handed and mostly undergraduates (57 undergraduates, 3 post-grads). Experiment 3 and 4 had 21 participants (13 females, 6 left-handed, mean age = 27.1 years, range = 20-43; 2 high school graduates, 14 undergraduates, 5 post-graduates). These participants did these experiments blindfolded. This is because this data was originally collected for a different study. All participants gave their written consent prior to participation. The Research Ethics Committee of Bilkent University approved all experimental protocols and procedures. All data collection occurred in National Magnetic Resonance Research Center (UMRAM), Ankara.

Results

Experiment 1

Hard episodes involved a more complex set of control operations, e.g., more WM maintenance operations to maintain more lines, a more complicated set of operations to keep subtask-A lines from interfering with subtask-B lines, etc. Hard episodes can, therefore, be expected to involve a more demanding meta-control program instantiated at step 1 of the episode. Note that step 1 of the hard and easy episodes pits the effects of two demands against each other. Harder episodes at this step involve acquiring a greater WM load, a well-known elicitor of MD activation, but they also involve instantiating a more complex program, suggested to be deactivating brain regions, including MD regions (Farooqui & Manly, 2018). In comparison, by step 2, the meta-control program is already in place, and hard episodes require more complex WM operations (instantiated through this program) to keep line representations related to the two subtasks from interfering.

If the demands of instantiating meta-control programs are categorically different from those of instantiating control processes and deactivate MD regions, then step 1 of hard episodes should deactivate these regions despite involving higher WM load. Step 2 of hard episodes, in comparison, should activate MD regions because this step requires a more complex control operation.

Figure 3 shows regions where activity at steps 1 and 2 of hard episodes was higher (hot colors) and lower (cold colors) compared to the corresponding steps of easy episodes. Only at step 2 do we find increased activation of MD regions during hard episodes. Compared to step 1 of easy episodes, at step 1 of hard episodes, when more demanding meta-control programs were to be instantiated, key MD regions either did not activate or deactivated (e.g., right prefrontal regions). Only, extra-striate visual regions showed higher activity during step 1 of hard episodes. This was also evident in ROI analyses.

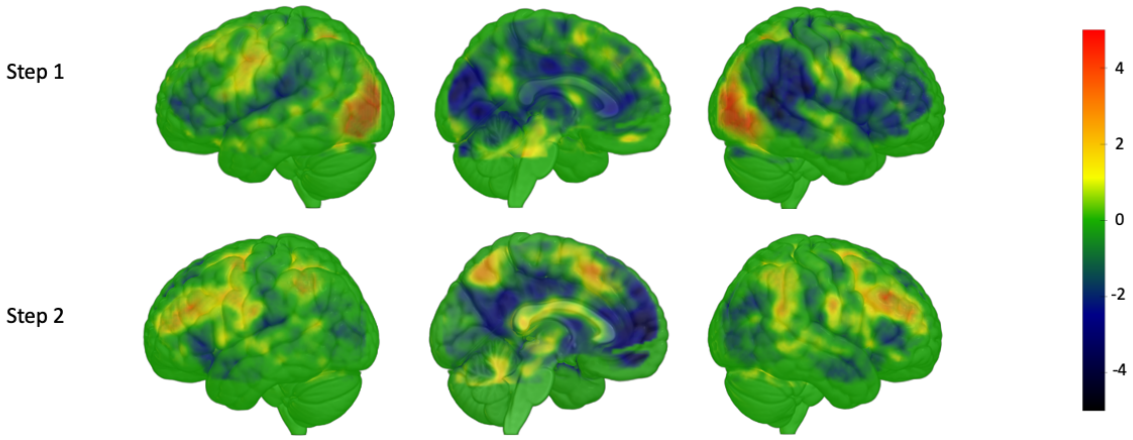

Figure 3. (Experiment 1) t-maps of the contrast hard>easy at steps 1 and 2. Note that many regions that show increased activity for hard episodes at step 2 showed decreased activity for these episodes at step 1 e.g., right lateral prefrontal regions.

Plots in Figure 4 show activity time-series during steps 1 and 2 of easy and hard episodes. In many MD regions, at step 1, activation was lower during hard compared to easy episodes. In contrast, at step 2, activation was higher during hard episodes. This difference between the effects of difficulty at steps 1 and 2 was present in widespread regions that included regions belonging to both MD and DMN regions (brain render in Figure 4).

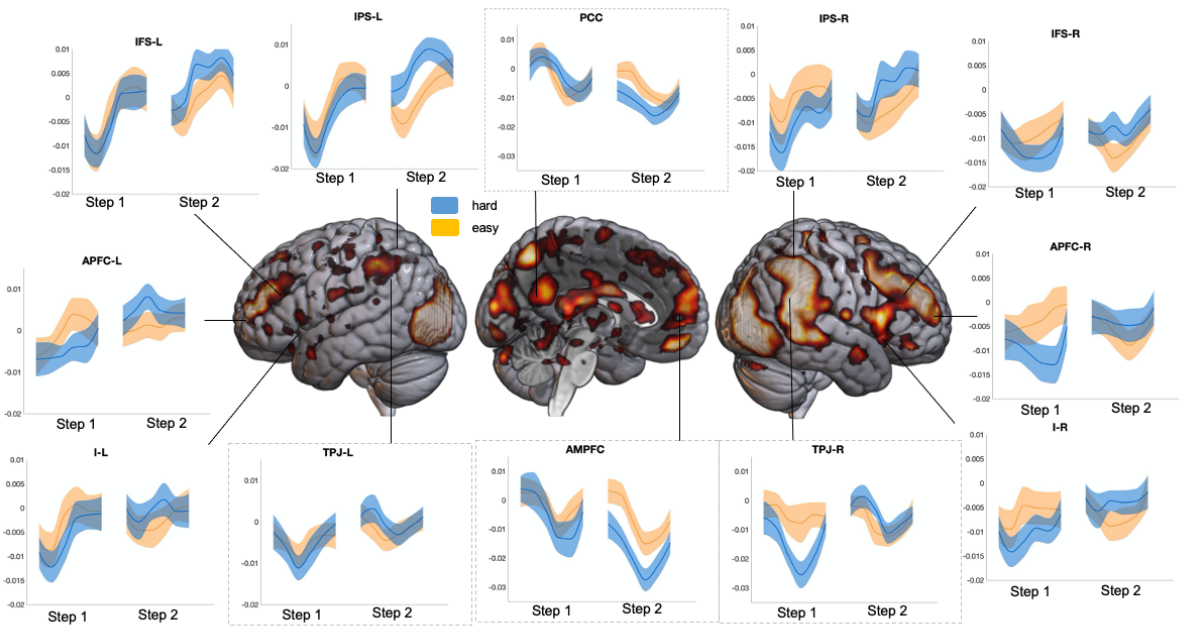

Figure 4. (Experiment 1). Whole-brain render shows regions where the effect of difficulty was different across steps 1 and 2 (FDR, $p < 0.05$). Plots show the time-series of activity across 12 seconds following the onset of steps 1 and 2. In all MD regions, hard step 1 elicited lower activity, while hard step 2 elicited higher activity than analogous easy steps ($F_{5,145} > 2.3$, $p < 0.04$ for all ROIs depicted). Plots in the inset show DMN regions. Note the difference in TPJ's response patterns from that of PCC and AMPFC. TPJ, especially on the right, showed decreased activity on hard step 1 but not on hard step 2. In contrast, PCC and AMPFC showed the opposite – decreased activity on hard step 2 but not on hard step 1 (this interaction being significant, $F_{5,145} = 6.2$, $p < 10^{-4}$).

Amongst DMN regions that are well-known to deactivate to cognitive demands, we noted a dissociation between midline DMN regions – anteromedial prefrontal cortex (AMPFC) and posterior cingulate cortex (PCC), from those at the temporoparietal junction (TPJ). Compared to easy, during hard episodes, TPJs showed decreased activity at step 1 but increased activity at step 2 ($F_{1,29} = 7.7$, $p < 0.01$). In contrast, AMPFC and PCC had nearly the opposite response. These showed no difference at step 1 but decreased activity at step 2 of hard compared to easy episodes ($F_{1,29} = 7.4$, $p = 0.01$). Bilateral TPJs' behavior was significantly different from that of PCC and AMPFC (interaction between the effects of difficulty, step, and ROIs, $F_{5,145} = 6.2$, $p < 10^{-4}$). Neural effects of instantiating more demanding meta-control programs at step 1 of hard episodes were thus categorically different from the demands of instantiating more demanding control processes later in the episode. Only the latter increased MD activation; the former decreased activity in many MD regions.

Experiment 2

In experiment 2, we investigated if the same occurs with pupil-size. Pupil-size is well known to increase during more demanding control interventions. We investigated if, like MD activity, the effect of difficulty on pupil-size was different at steps 1 and 2.

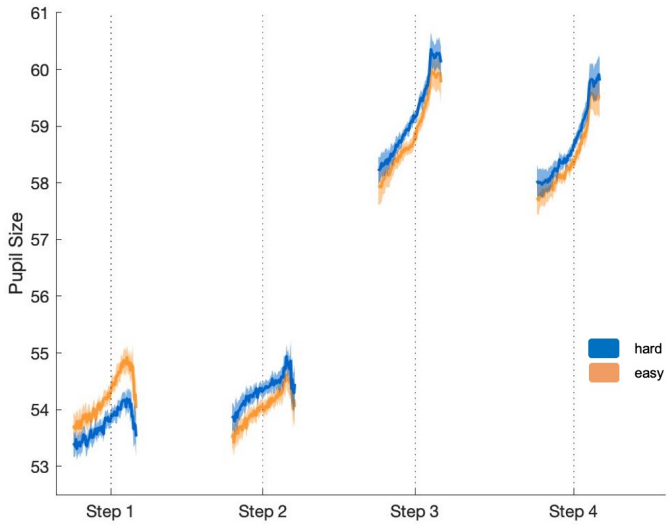

Figure 5. (Experiment 2) Time-series of pupil size across the four steps of the hard and easy task episodes. Dotted vertical lines represent the time when participants pressed the button marking the completion of the respective step. Plots show pupil size 750 ms before and after this button press.

The well-known increase in pupil size with increased task difficulty was only present at step 2 (and subsequent steps) but not at step 1 (Figure 5). At step 1, pupil size decreased during hard compared to easy episodes ($F_{74, 2146} = 2.4$, $p < 10^{-9}$). Again, the effects of difficulty at steps 1 and 2 were significantly different ($F_{1,29} = 12.3$, $p = 0.001$).

Behavior (averaged over Experiments 1 and 2) showed expected results (See Supplement for details). Participants' recollections were more erroneous during the hard episodes for both B and A-line orientations ($t_{59} > 3.7$, $p < 0.001$). Participants took longer to register and recall B-lines during hard episodes ($t_{59} > 6$, $p < 0.001$). However, these times were not different for A-lines across hard and easy episodes ($t_{59} < 1.46$, $p > 0.15$).

Experiments 3 and 4

We checked the generalizability of the above finding through two experiments with very different designs and contents. Participants executed easy and hard episodes made of a sequence of trials. We investigated if the beginning of hard episodes again elicited lower MD activity than the beginning of easy episodes. In session 1 (experiment 3), participants executed easy and hard episodes involving tactile size judgements (Figure 2). In session 2 (experiment 4), the same participants executed easy and hard task episodes involving 1-back and 3-back tasks, respectively.

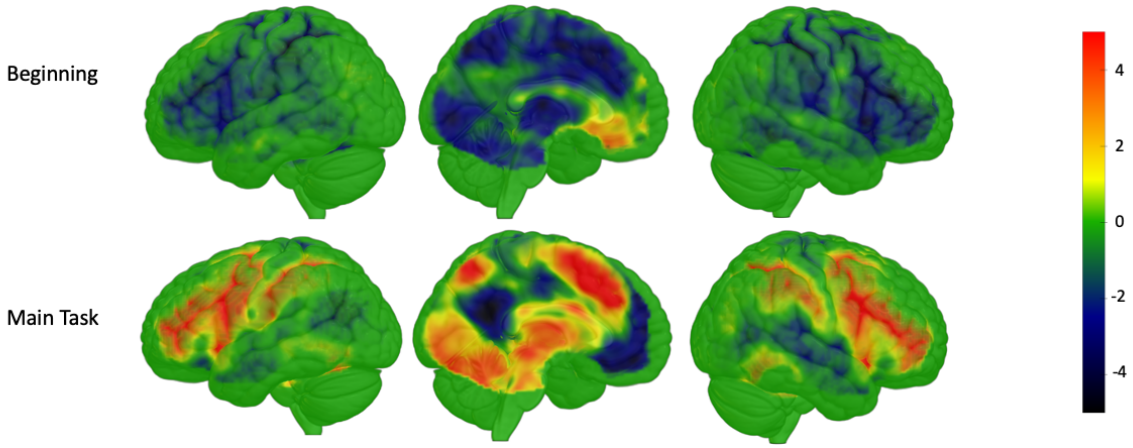

Figure 6. Experiments 3 and 4. T-maps of the contrast hard>easy at the beginning of the episodes and during the main episode. MD regions activated more for hard episodes only during the main episode epoch. At the beginning of the episodes, MD regions, along with other regions, decreased their activity for hard episodes.

We present results combined over experiments 3 and 4 (See Supplement for individual experiment results, which are identical to the combined results). In every MD region, the phasic activity elicited at the beginning was lower during hard compared to easy episodes (Figures 6). In contrast, the sustained activity in these regions during the subsequent execution of these episodes was higher during hard compared to easy episodes. This difference in the effects of difficulty at different junctures of execution, i.e. at the beginning compared to during subsequent execution, was significant in nearly all MD regions (Figure 7; $F_{1,20} > 14.7$, $p < 0.001$).

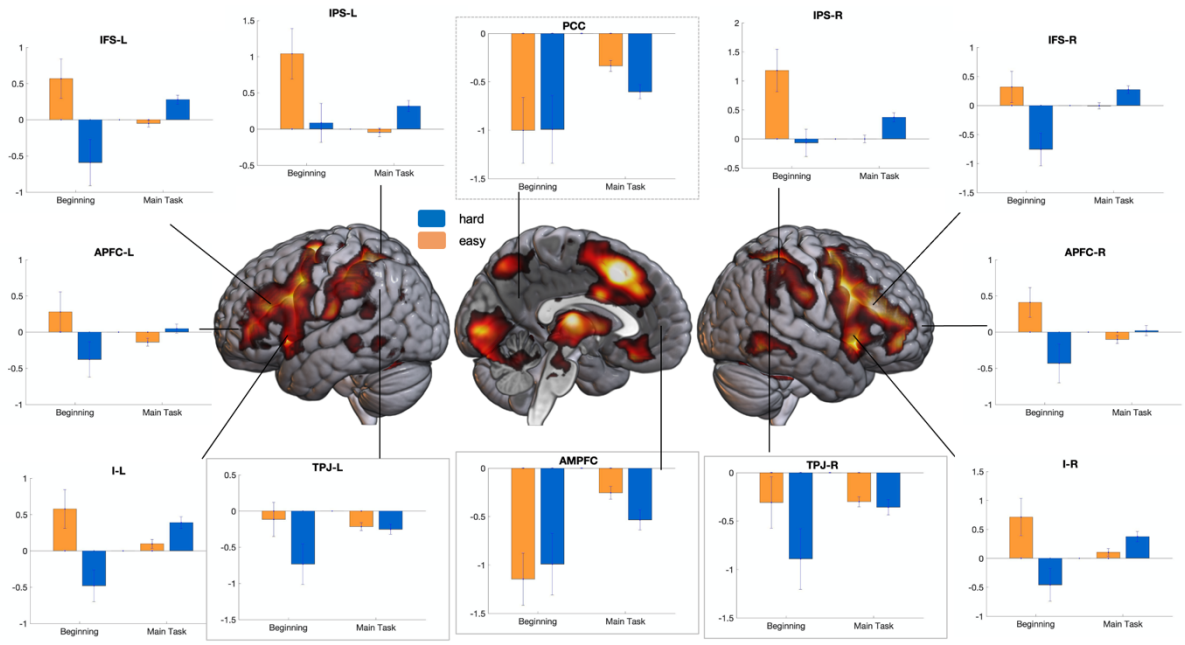

Figure 7. Brain render shows regions where the effect of difficulty was different at the beginning of the episodes compared to during these episodes (FDR, p < 0.05). Plots show the estimates of activity at the beginning and during the task episode for easy and hard conditions. The beginning of hard episodes in all MD regions elicited lower activity than the beginning of easy episodes. MD activity, however, was higher during the subsequent execution of the hard compared to easy episodes. The distinction between TPJs and the medial DMN regions (PCC and AMPFC) seen in Experiment 1 (Figure 3), was also present here. Again, TPJs deactivated more at the beginning of hard episodes but not during their subsequent execution. In contrast, PCC and AMPFC did not deactivate more at the beginning of hard episodes but did deactivate more during their subsequent execution.

The distinction amongst DMN regions – temporoparietal junction vs. posterior cingulate and anteromedial prefrontal cortex – seen in Experiment 1 was also evident in the current experiment. Temporo-parietal junction, bilaterally, showed lower activity at the beginning of hard compared to easy episodes but showed no difference between these episodes during their subsequent execution. PCC and AMPFC, in contrast, showed the opposite – no difference at the beginning but a greater deactivation during the subsequent execution of hard episodes. This interaction between effects of difficulty, junctures of execution (beginning vs. during the main block), and ROIs (bilateral TPJs vs. PCC and AMPFC) was again significant ($F_{1,20} = 14.4$, $p = 0.001$). Behavioral results were as expected. Participants were faster ($F_{1,20} = 589$, $p < 0.001$) and made fewer errors ($F_{1,20} = 53.7$ $p < 0.001$) during easy compared to hard task episodes.

In all experiments, we found that easy and difficult episodes differed differently at their beginning compared to subsequent steps. The canonical markers of increased MD activity and pupil size were only seen on the later steps of hard episodes. At the beginning, when a new meta-control program was to be instantiated, both MD activity and pupil size were decreased during hard episodes. So strong was this effect that in experiments 1 and 2, the first step of difficult episodes had lower MD activity and decreased pupil-size even though this step

involved a higher WM load, which is otherwise well-known to both activate MD regions and increase pupil-size (D'Esposito & Postle, 2015; van der Wel & van Steenbergen, 2018).

Discussion

We showed that the demand of instantiating meta-control programs at the beginning of task episodes is categorically different, both neurally and psychophysiologically, from the demands of making control interventions subsequently in the episode. The former decreased MD activity and pupil-size while the latter increased both. Activation and deactivation to cognitive demands are well-known but have been thought to involve distinct sets of regions, i.e., MD and DMN regions, respectively (Duncan, 2010; Raichle et al., 2001). In contrast to this, we show the deactivation and activation of the very same set of MD regions (as well as the very same psychophysiological response) at different junctures of difficult task episodes. This opposite response of the same MD regions to increased demands at the beginning versus during the subsequent execution of task episodes shows that the demands of instantiating complex meta-control programs at the beginning are categorically different from those of instantiating control operations during the task episode.

Note that in terms of control demands intrinsic to component steps, the initial steps of hard episodes had higher control demands. In experiment 1, the first step involved a higher WM load; in experiment 3, the first step involved higher attentional and perceptual demands. Both should have increased MD activity. That these still decreased MD activity shows that the effect of meta-control demands is stronger than that of control demands.

A prior study linked these meta-control programs to the ubiquitous task-related deactivation seen whenever tasks are executed (Farooqui & Manly, 2018). It showed that this deactivation gets elicited at junctures where extended tasks are construed to begin. The subsequent time-course of this deactivation follows the predicted load of these programs. This load would be highest at the beginning of the task since the program, at this point, embodies commands related to the entire episode. It would decrease as parts of the task get executed and related parts of the program are no longer active. Midway through the episode, the program will only embody commands related to the remaining part of the episode. By the last step, most of the program would have dissolved. Paralleling this, the intensity of deactivation is maximal at the beginning and then decreases gradually as parts of the task get executed, with the activity reaching baseline by the last step. Furthermore, the deactivation is larger at the beginning of longer tasks that will begin with a larger program (e.g. 40 s long vs 20 s long tasks). Crucially, it also showed that this deactivation need not be limited to the DMN but can also involve MD

and other regions. The current study affirmed these and showed that instantiating complex programs at the beginning of difficult episodes deactivates widespread regions including those MD regions that will be activating later in the episode.

Execution and control of extended tasks are well-recognized to require a hierarchical cognition with entities (representations/operations/processes) at multiple levels, with higher-level entities controlling lower-level ones (Broadbent, 1977; G. A. Miller et al., 1960; Norman & Shallice, 1986). Meta-control programs are fundamental to hierarchical control and execution of extended tasks in that they are the means of controlling and executing extended tasks as one unit (Farooqui & Manly, 2018, 2019). However, demands related to them were not accompanied by increased activity in any brain region. This is very different from the expectations of many current accounts of hierarchical cognition. For a set of accounts, more anterior regions of the PFC activate to higher-level entities (Desrochers et al., 2015; Koechlin, 2003). More recent accounts have suggested that the DMN may be about higher-levels of cognition and may represent temporally extended events in cognition (Margulies et al., 2016; Speer et al., 2007; Wen et al., 2020). Other accounts have argued that MD regions may be the ones instantiating programs that control and execute extended sequences of thought and behavior (Duncan, 2013). These accounts would, respectively, predict that anterior prefrontal regions, DMN, and MD regions will have higher activation at the beginning of more demanding task episodes. In contrast, we show that the demands related to higher-level entities through which extended tasks are executed correlate with *deactivations* in widespread regions, including MD regions. Hierarchical organization of control may be brought about by organizing neural processing in regions that instantiate control processes (see below), and may not be brought about by a separate set of neural regions.

While this deactivation is empirically evident, its reason is unclear. Below is our current speculation. MD regions' activity patterns during task execution continuously move through a sequence of states, with each step of the task corresponding to a unique task phase and, by extension, to a unique control state (Kadohisa et al., 2020, 2023; Marcos et al., 2019; Nobre & van Ede, 2023; Sigala et al., 2008). Instantiation of programs at the beginning of tasks may correspond to the creation of the set of synaptic changes that will ensure that the ensuing trajectory of neural activity patterns keeps them prospectively in the most optimal goal-directed state achievable for the demands expected at that moment. It is plausible that this requires cessation of ongoing neural activities in these regions, causing a net decrease in metabolic demands and, consequently, in BOLD activity. Further, since this happens in very widespread cortical regions, it may also correspond to a decrease in the activity of modulatory brainstem

systems like locus coeruleus that project diffusely to the cortex and enable cortical processing, resulting in decreased pupil-size that reflects the activity of these regions (Joshi et al., 2016).

In summary, current neurocognitive theories of control take the activation of MD regions in response to control demands as their starting point. Current findings show that this is only part of the picture. Tied to these activations is the deactivation of these very same regions at the beginning of demanding task episodes. We suggest that these deactivations are related to the instantiation of meta-control programs that will go on to instantiate and organize control interventions that activate MD regions.

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