Default mode contributions to automated information processing

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Concurrent with mental processes that require rigorous computation and control, a series of automated decisions and actions govern our daily lives, providing efficient and adaptive responses to environmental demands. Using a cognitive flexibility task, we show that a set of brain regions collectively known as the default mode network plays a crucial role in such “autopilot” behavior, i.e., when rapidly selecting appropriate responses under predictable behavioral contexts. While applying learned rules, the default mode network shows both greater activity and connectivity. Furthermore, functional interactions between this network and hippocampal and parahippocampal areas as well as primary visual cortex correlate with the speed of accurate responses. These findings indicate a memory-based “autopilot role” for the default mode network, which may have important implications for our current understanding of healthy and adaptive brain processing.

Significance

In addition to dealing with variable demands of the environment in everyday life, we are continuously faced with routine, predictable challenges that require fast and effective responses. In an fMRI-based cognitive flexibility task, we show greater activity/connectivity centered on the default mode network during such automated decision-making under predictable environmental demands. Furthermore, we report on a significant correlation between this network and hippocampal connectivity and individual differences in the participants' ability to make automated, fast, and accurate responses. Together, these results suggest an "autopilot" role for this network that may have important theoretical implications for our understanding of healthy brain processing in meeting worldly demands.

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Each rule was repeated four times with the total task consisting of 16 (4 blocks × 4 rules) blocks of 10 trials. Importantly, although the participants were notified when the rule had changed (i.e., after every 10 trials), they were not told the new sorting dimension. Thus, during the first few trials following the rule change, participants had to rely on feedback to deduce the context and make appropriate selections. This trial-and-error stage was defined as the “acquisition” (learning) phase of each block. Once the rule was firmly established, participants could then rely on the learned responses from memory for choosing the appropriate card, here referred to as the “application” phase. We operationally stratified the task into these two phases after completion of half the trials to facilitate this network

Based on the autopilot account of DMN function, we hypothesized that (i) the DMN regions would be more active in the application phase relative to the rule acquisition phase of the paradigm, i.e., when the task demanded greater access to learned, memory-based information for fast, automated, and efficient responding; (ii) the connectivity of the DMN regions would be altered to reflect this network’s differential contribution during the rule-application phase of the cognitive flexibility task; and (iii) greater functional interaction of the DMN regions would be predictive of faster and more accurate decision making, specifically in the application phase. In addition, this performance relationship would be dissociated from that of the dorsal attention network (DAN), traditionally linked to the controlled and effortful processing of attention-demanding, external information (17, 18).

**Results**

**Differential Brain Activity During Cognitive Flexibility Task.** In line with our expectations for the behavioral stratification of the task, participants were less accurate in the acquisition phase, with an average of 91.92% correct responses, than in the application phase, with an average of 98.94% correct responses \( t_{(27)} = 17.64, P < 0.0001 \) (Fig. 1B and SI Appendix, Table S2). Similarly, the correct response latency was longer for the acquisition phase (1,252.31 ms) in comparison with the application phase (1,119.30 ms) of the task condition \( t_{(27)} = 8.28, P < 0.0001 \). This phase-specific result of a slower response was also significant in the control conditions \( t_{(27)} = 6.82, P < 0.0001 \); however, after multiple comparison correction, no significant difference was observed in accuracy \( t_{(27)} = -2.12, P = 0.17 \). These results indicate that the participants were less accurate and slower in finding the correct response under novel environmental demands, whereas once the rule was acquired, the responses were faster and more accurate, demonstrating context-specific, learned decision-making.

Having demonstrated the expected differentiation in behavioral performance, the next step was to examine the relative differences in brain activity between the acquisition and application phases of the cognitive flexibility task. Similar to the brain areas observed in effortful task performance (Fig. 1C and SI Appendix, Table S3), in a given environmental context (i.e., task rule), we postulated that a greater number of regions commonly associated with controlled, effortful processing would be more active in the acquisition phase compared with the application phase (1, 18). This would allow more perceptual information to be extracted from the environment to aid the decision-making process. In contrast, greater DMN activity would be observed during the application phase in comparison with the acquisition phase, allowing the use of memory-based information for responding to environmental demands.

Comparable to this hypothesis, the results revealed a highly symmetrical bilateral set of frontoparietal, insular, subcortical, and cerebellar brain regions more active in the acquisition compared with the application phase of the task (Fig. 2A and SI Appendix, Table S4). These areas, often referred to as the multiple-demand network (19), have been previously shown to engage during the WCST (20) as well as other tests of cognitive flexibility (2). From a
Differential task-evoked activity profiles of distinct brain regions in the large-scale brain network organization perspective, these coactivating brain regions have been largely associated with the frontoparietal, dorsal attention, cingulo-opercular, salience, and visual networks (21), which have been denoted as “externally directed” networks. More specifically, the dorsal attention network (DAN) activity has been previously shown to anticorrelate with that of the DMN during resting state conditions (17).

On the other hand, compared with the acquisition phase, the application phase displayed greater activity centered on the default mode as well as somatomotor network regions including the ventromedial (orbitofrontal) prefrontal cortex; parts of the ventral anterior cingulate cortex, posterior cingulate cortex, and precuneus; medial temporal lobe structures including the hippocampal formation and parahippocampal gyrus as well as the right amygdala, superior, and middle temporal gyri, posterior insula, Heschl’s gyri, and Rolandic operculum; middle cingulate and paracentral lobule; postcentral and precentral gyri; parts of the left angular gyrus; and the left middle occipital gyrus (Fig. 2B and SI Appendix, Table S5).

Although the DMN has not been extensively studied in tasks of cognitive flexibility, emerging evidence suggests its contribution to tasks associated with this function (22, 23), i.e., our ability to apply learned rules. For instance, Provest and colleagues have investigated the brain’s responses to changing or continuous application of WCST rules in an experiment in which the participants were explicitly informed about the relevant rules to be applied (24). In line with findings from our experiment, in which the participants had to implicitly deduce the rule via trial-and-error, the continuous application of the same rule was linked to greater activity in regions commonly associated with the DMN, suggesting the potential contribution of this set of brain regions to memory-based, automated phases of goal-oriented tasks.

Altered Brain Network Connectivity During Cognitive Flexibility Task. Following this observed differential activity of brain regions commonly associated with controlled, effortless processing (e.g., DAN) and those belonging to the DMN in the acquisition and application phases of the WCST task, respectively, our next objective was to determine the extent of the dorsal attention and default mode networks’ interactions with the rest of the brain during task performance. Specifically, we aimed to assess any changes in the functional connectivity of these two networks, which are commonly anticorrelated at rest (17) and are purported to mediate externally and internally directed cognition, respectively (25).

First, we examined DAN connectivity during the acquisition and application phases of the WCST, using a seed on the left frontal eye field (FEF) (26). In both phases of the task condition, the results revealed an extensive DAN that encompassed the FEF and inferior parietal lobule as has been previously discussed in the literature (17). However, the DAN illustrated altered connectivity with the middle/superior temporal and inferior/superior parietal gyri in the acquisition phase compared with the application phase (Fig. 3A and SI Appendix, Tables S6–8), i.e., regions which have all been previously implicated in attentional control relevant to the task at hand (27, 28).

Next, we investigated DMN connectivity in the two phases of the task using a seed that was placed on the left posterior cingulate cortex/precuneus (PCC/PCUN) region, a main hub of the DMN. In both the acquisition and the application phases, the results revealed an extensive DMN as defined in the literature (29). However, the DMN showed greater connectivity to a range of areas in the application phase compared with the acquisition phase, including the PCC/PCUN, ventromedial prefrontal cortices, and left angular gyrus. In addition, reduced connectivity was observed with the bilateral insular gyri and right presupplementary motor area as well as increased anticorrelation with regions commonly linked to the DAN (Fig. 3B and SI Appendix, Tables S9–S11). These findings illustrate the robust temporal correlations of these two networks throughout the two phases of the WCST, with alterations in their functional connectivity in response to the variable demands for access to external or memory-based information to be used in the decision-making. Most importantly, the results indicate continuous DMN engagement in a goal-oriented task with alterations in its spatial topography in response to changing demands for access to learned information.

Double Dissociation of Brain and Behavior Relationships. Following these results on the altered, yet continuous engagement of DAN and DMN regions during the two phases of the WCST, the final question we asked was whether the connectivity of these two networks in their respective phases would differentially relate to behavioral performance. Beyond the DMN’s usual association with task-unrelated internal mentation (30), our aim was to illustrate this network’s contribution to WCST performance via memory-based, automated decision-making that is differentiated from the contribution of the DAN (traditionally associated with controlled, effortful information processing).

For that purpose, we first investigated the relationship between DAN connectivity and reaction time to correct responses in the acquisition and application phases of the WCST. The results indicated that greater connectivity between FEF and somatomotor regions (precentral and postcentral gyrus and the paracentral lobule) in the acquisition phase correlated with faster reaction times and thus better performance (Fig. 4A and SI Appendix, Table S12). However, no such correlation between the FEF and any brain regions was found in the application phase (Fig. 4B). This connectivity between the FEF and the precentral gyrus is believed to control saccades when processing visual information (28, 31), which is an important component of this task, i.e., facilitating an extensive visual search and extraction of information during rule acquisition.

For the DMN, greater connectivity of the PCC/PCUN with the parahippocampal gyrus, hippocampal formation, amygdala, and primary visual cortices correlated with faster reaction time to correct responses and thus better performance in the application phase of the WCST (Fig. 4D and SI Appendix, Table S13). Nevertheless, no such correlation of the PCC/PCUN with any other brain region was found in the acquisition phase (Fig. 4C). Given the vast amount of literature that indicates the role of medial temporal lobe structures in context-specific, memory-based information processing, the reported clusters are uncorrected at the voxel level (P = 0.001), and FWE-corrected for multiple comparisons at the cluster level (P = 0.05).
processing (32, 33) and the visual nature of the task at hand, it is plausible that the observed correlation indicates the participants’ ability to access and utilize learned responses in dealing with stable environmental contexts during the application phase of the WCST.

In summary, these brain and behavioral results reveal a double dissociation in which the relative DAN and DMN connectivity in the acquisition and application phases of the WCST, respectively, correlate with enhanced behavioral performance. Specifically, these results strongly suggest the DMN’s task relevance in the application phase of the WCST, indicating its ongoing contribution to learned, automated, and fast responses for decision-making under a given behavioral context (or rule).

**Discussion**

Despite the mounting evidence on its extensive structural and functional connections (34) and implication in a variety of neuropsychiatric as well as neurodegenerative disorders (35), the exact functional role of the DMN in human cognition remains elusive. To this end, the major aim of this study was to provide evidence for this network’s positive contribution to the performance of an externally directed, attention-demanding, goal-oriented, non-self-referential task of cognitive flexibility and to outline a general framework within which it may operate to contribute to adaptive cognition. Overall, the findings allude to the involvement of the DMN in automated information processing, i.e., when rapidly selecting appropriate responses under specific, predictable environmental demands.

Recent models of brain function suggest that our brains are wired in a way that maximizes the anticipation of external events (36). The internalization of statistical regularities through worldly experiences forms the foundations of our expectations (priors or best guesses), which can then be used to interpret, predict, and act upon environmental demands (36–38). Indeed, the intrinsic activity of the brain, specifically that of the DMN, which uses a considerable portion of our brain energy supplies (9), is suggested to reflect such internal models of the world that could aid in the interpretation of our surroundings (16, 39–41). Although such predictive processing may constitute the common mechanism by which the brain processes information as a whole, what may distinguish the DMN is its ability to provide a common workspace for convergence of information with its extensive functional and structural connections to the rest of the brain and specifically its access to memory-based information (34). This integrative capacity of the DMN (13) is thought to be a hallmark of consciousness (42), the levels of which have been previously associated with DMN integrity (43).

From this perspective, the relatively increased activity/connectivity of the DMN in the application phase of the WCST observed in this study may indicate this network’s ability to integrate memory-based information (13), generating top-down associative predictions under stable environmental contexts (16) for automated, fast, and efficient...
decision-making. In contrast, unpredictable, novel, or salient events, beyond the scope of the DMN’s memory-based processing, such as the one required in the acquisition phase of this task, may demand further external attention and perceptual information for making decisions. This would increase the involvement of networks commonly associated with controlled, effortful processing such as the frontotemporal, cingulo-opercular, salience, and dorsal attention networks (18). Thus, the anticorrelation previously reported between the DMN and DAN (17) might represent these networks’ differential but complementary roles in facilitating the automatic decision-making to provide fast best-guesses, and another (System 2) used to make calculated and effortful decisions. Based on our results, we propose that the DMN may contribute to an “autopilot mode” that makes memory-based predictions to aid decision-making under established behavioral contexts, whereas control networks are involved in a “manual mode” that overrides the automatic system when the DMN fails to reliably predict the environment. This proactive framework of brain function may provide an all-important scaffold to explain not only the DMN’s ongoing activity in stable “rest” conditions, but also its contribution to social interactions (e.g., theory of mind, intuition, and stereotyping), a conscious sense-of-self, creativity, and a variety of other cognitive domains (49) that all require the stable use of learned information for predicting the world around us. Hence, future studies will be required to assess the potential role that the DMN may play in the formation of habitual behavior for the neuro-economics of decision-making and its potential breakdown in disorders such as addiction, obsessive-compulsive disorder, or clinical depression.

Materials and Methods

Participants. Ethical approval was obtained from the Cambridge Psychology Research Ethics committee in accordance with the Declaration of Helsinki. All volunteers gave informed consent before their participation. Following the exclusion criteria, this right-handed, healthy control group consisted of 28 participants (22-34 y old, mean = 26.8, SD = 2.8, 13/15 female to male ratio) with an average National Adult Reading Test (NART) score of 121.22 (SD = 3.17).

Experimental Paradigm Specifications. The experimental paradigm was a variant of the WCST (50) that was modified for the scanner environment, utilizing a mixed design. Stimuli were delivered, and responses were recorded, using an open source software package called PsychoPy (Version 1.83). In addition to the task and control blocks conventionally used in this paradigm, we operationally stratified the task into “acquisition” and “application” phases. Full details about the experimental paradigm and procedures followed for the preprocessing and analysis of both the behavioral and imaging data are provided in the SI Appendix; SI Materials and Methods.

MRI Data Acquisition. The participants were scanned in a Siemens MAGNETOM Tim Trio 3T scanner (32-channel head coil) at the Wolfson Brain Imaging Centre, Cambridge. The scanning session started with a high-resolution T1-weighted, magnetization-prepared rapid gradient-echo (MPRAGE) structural scan (TR = 2,300 ms, TE = 2.98 ms, slice thickness = 1.00 mm). The echo planar imaging (EPI) sequence parameters for the WCST functional data acquisition were as follows: 32 slices in each volume, 3.0 mm slice thickness, 3.0 × 3.0 × 3.0 voxel size, TR = 2,000 ms, TE = 30 ms, flip angle = 78°. The number of 3D volumes varied according to the speed of the participants’ responses to the task (mean = 347 volumes, SD = 12).

MRI Data Preprocessing. MRI data preprocessing and statistical analyses were carried out using the SPM software package (Version 12.0), based on the MATLAB platform (Version 15a). For preprocessing, functional volumes were slice-time and motion-corrected, coregistered to the high-resolution structural image, spatially normalized to the Montreal Neurological Institute (MNI) space using the unified-segmentation algorithm (51), smoothed with an 8 mm FWHM Gaussian kernel, and carried forward onto statistical analyses.

MRI Data Analysis. Task-evoked activation analysis. Subject-level analyses with the appropriate contrasts were set up using the general linear model (GLM). For the task > control contrast, a task < control contrast, the design matrix included the onsets and durations of the task and control conditions. When comparing the acquisition and application phases of the task, the events were modeled as impulses, including the onsets of the correct/incorrect responses for the two phases of the task with zero duration. The resulting subject-specific contrast maps were carried forward onto group-level analyses using one-sample t tests. Functional connectivity analysis. For the seed-based functional connectivity analysis, the MNI coordinates of two seed regions representing the DAN and the DMN (17, 26) were selected from the literature. The closest local peaks to these coordinates (in terms of Euclidean distance) were identified in the acquisition > application (for the DAN) and acquisition < application (for the
DMN) contrasts of the group-level task-evoked activation analysis. Subsequently, spheres with 6-mm radius were constructed around the MNI coordinates for the two regions of interest (ROIs) described above. Group-level analyses were carried out using t-statistics in which a one-sample t-test assessed the group-level spatial extent of DMN and DAN connectivity in the acquisition and application phases, whereas a paired t-test between these phases examined any changes in these networks’ functional connectivity.

The voxel-based correlation analysis. The voxel-based correlation analysis involved using the connectivity maps obtained from the seed-based functional connectivity analyses for the two phases in separate linear regressions with the reaction times to correct responses used as the variable of interest. All reported findings for the MNI data analyses were uncorrected at the voxel level (P = 0.001) and multiple-comparison-corrected at the cluster level using the FWE detection technique (P = 0.05).

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