

Review

Cognitive flexibility in and out of the laboratory: task switching, sustained attention, and mind wandering

Yunji Lee and Eric H Schumacher



Our daily lives require cognitive flexibility to optimize our behavior in changing environments. Cognitive psychology has studied this topic in a variety of ways — from task switching to studies of sustained attention and attention lapses in simple laboratory and more complex tasks. The current paper integrates these topics and briefly reviews the neuroscience underlying the external and internal attentional states responsible for cognitive flexibility. Functional connectivity between brain networks associated with cognitive control (e.g. dorsal attention, frontoparietal, and ventral attention networks) and mind wandering (e.g. default mode network) play an important role in cognitive flexibility. The antagonistic relationship between these and other attentional networks mediate task switching and task engagement. Here, we provide a summary of recent findings on how these dynamics between brain networks are associated with flexible cognitive control between tasks and within a task.

Address

Georgia Institute of Technology, USA

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Cognitive flexibility, the ability to switch tasks and adjust one's behavior according to a changing environment, updating goals, other internal states, etc., is one of the core functions of cognitive control [19,53–55]. The prefrontal cortex (PFC) plays a key role in cognitive control [53]. Implementation of cognitive control closely depends on the dynamics and the functional organization of the brain networks connecting PFC regions with other

regions throughout the brain [26,52]. Four networks especially important to cognitive control and flexibility are the frontoparietal network (FPN), dorsal attention network (DAN), ventral attention network (VAN), and default mode network (DMN) [46,73].

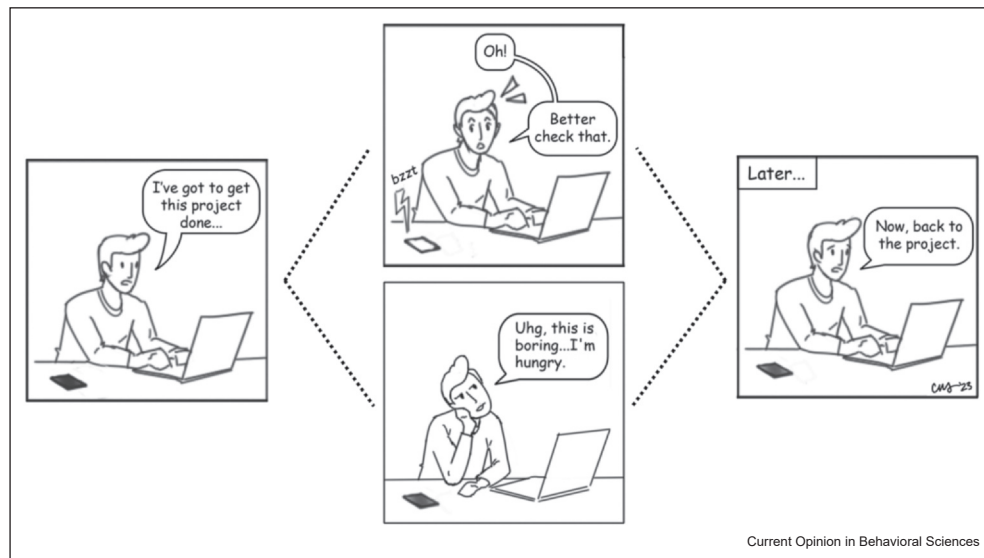
Our daily lives require cognitive flexibility to shift attention between multiple tasks, disengage from no-longer-relevant tasks, refocus on a task after losing focus, and otherwise flexibly adjust our behavior (Figure 1). We typically experience performance decrements when we switch between tasks. That is, our performance may decrease, and/or our ability to get back 'on task' may falter [7,13,29,39,43,56].

One key idea is that, when humans perform goal-directed behavior, we activate a knowledge representation (i.e. a task set) that includes attentional, memory, motoric, goal, motivational, and perceptual features relevant to the current task [5,32,33,62,64,65]. These representations are encoded into episodic long-term memory [27,34–36]. As our tasks change, different task sets become relevant and may be activated and compete with each other [2,37,48]. The key to this flexible control is how we adjust or alter these representations based on the current task demands.

Cognitive flexibility has often been studied in the laboratory with task switching procedures that require people to switch between two or more tasks (Figure 2). Research shows that responses are generally slower and less accurate when subjects switch to a new task compared with when they perform the same task on separate trials [39,42,43,56]. This *switch cost* has been interpreted as an index of the difficulty of flexibly adapting to our environment. It may reflect the cognitive control processes for activating, reconfiguring, or otherwise dealing with interference in the new task set [31,50,51,62] or the automatic competition among task sets [2,48].

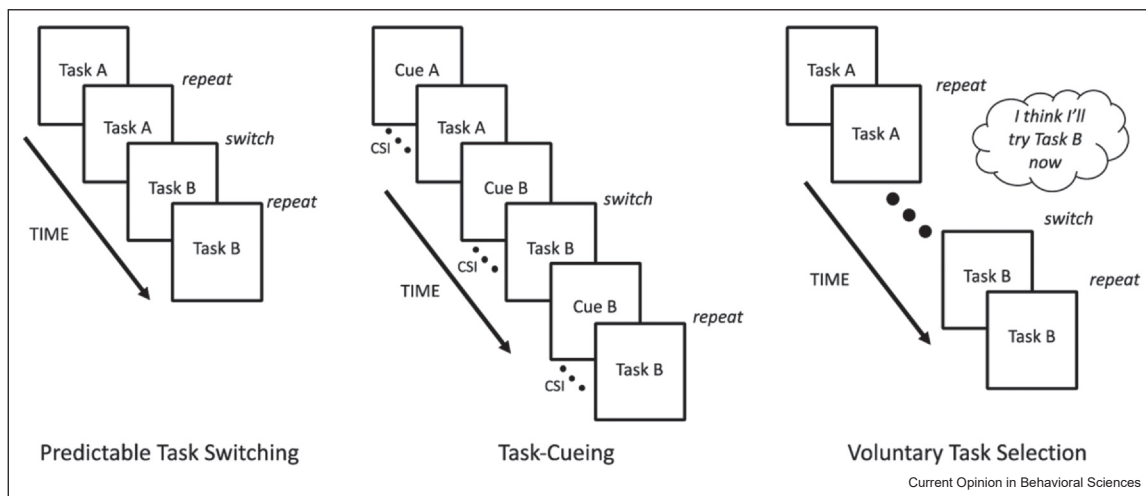
Three experimental procedures have often been used by cognitive psychologists to investigate task switching (Figure 2; for a review, see Ref. [39]). In the predictable task switching procedure, also known as the alternating-runs procedure, tasks switch after a predictable sequence (e.g. every two trials; AABB sequence; [62]). In the task cueing procedure, cues are presented before the task stimuli to indicate the currently required task [50]. In this procedure, the interval between the cue and target

Figure 1



Examples of 'task switching' outside the laboratory. We are often performing one important task (like working on a project on our laptop) when another important task (a text or other message on our phone) interrupts us, and we flexibly adapt our thoughts and behavior (i.e. switch) to the new task). In other situations, it may be internal factors (e.g. boredom or hunger) that distract us and capture our attention.

Figure 2



Examples of common procedures used to study task switching in the laboratory. In the predictable switch procedure, subject knows when the task switch will occur. In the task cueing procedure, subjects get a cue indicating the upcoming task. The task stimulus follows a CSI. In the voluntary task selection procedure, subjects perform one task until they decide to switch to the other. These laboratory tasks capture some aspects of task switching outside the laboratory.

stimulus can vary, and switch costs decrease with longer cue-stimulus intervals (CSI) [41,51]. Voluntary task selection asks participants to decide themselves on each trial which task to perform [3,30]. In all procedures, performance on task switch trials is compared with task repetition trials and reveals the costs of switching in general.

While the behavioral mechanisms of task switching in the laboratory are well reviewed in the existing literature [39,42], the neural mechanisms are not fully understood. A meta-analysis of neuroimaging studies on task switching procedures reveals common and task-specific brain activations within the FPN and attentional networks [40], consistent with the major role in cognitive

control and task engagement of FPN as flexible hubs of global brain processing [15] and posterior parietal cortex (a region in the DAN) as common hub of control for attentional shifting [28]. Specifically, anterior cingulate cortex (a region in the VAN) may configure the priorities of the tasks subjects are performing and dorsolateral prefrontal cortex (a region in FPN) may modulate attention to control the interference from previously activated task sets [10,38,61]. The activation of FPN and DAN regions during task switching was confirmed in a more recent meta-analysis that specifically identified left inferior frontal junction (IFJ; a region in the FPN), intraparietal sulcus (a region in the DAN), pre-supplementary motor area (a region in the DAN) and precuneus (a region on the DMN) were selectively associated with task switching [76]. These brain regions also drive the creation of task sets in task-relevant brain regions (e.g. fusiform face area for face stimuli) that may guide attention to perceptual features [14].

Additionally, recent neuroimaging studies have investigated the relationship between brain and cognitive flexibility using a variety of new methods. Qiao et al. [58] used functional magnetic resonance imaging (fMRI) and representational similarity analysis (RSA) to investigate cognitive flexibility when subjects switched between identifying faces and buildings. This technique measures the similarity of activation patterns across the cortex in different experimental conditions. Qiao et al. found that frontal and parietal brain regions for task repeats were more similar than task switches and the amount of similarity predicted task performance. This suggests that these regions flexibly recode changing task sets in a trial-by-trial manner. Another fMRI study using brain signal variability observed that the individuals with higher trial-to-trial variations in brain activation in the IFJ showed smaller switching costs, which reflects effective task switching performance [4].

The DAN, FPN, and VAN are involved in processing external stimuli and producing goal-directed behavior [15,17,74]. Another network, the DMN, may also be involved in these processes. The DMN includes the medial temporal lobe, medial PFC, and posterior cingulate cortex. It is usually more active when our attention is internally focused and less active when we are engaged in task [11,25,60].

Several studies suggest that DMN activity and the dynamic relationship between FPN and DMN are closely associated with cognitive control and flexibility [20,49,66,72]. Douw et al. [20] showed that at rest and when performing a version of the Stroop task, intraindividual variability between FPN and DMN was significantly correlated with cognitive control and flexibility. That is, higher variability in the functional connectivity between the two networks during the Stroop task predicted greater cognitive control and flexibility,

and higher variability between these two networks during rest was related to poorer cognitive control and flexibility. These findings demonstrate that the relationship between DMN and other networks may be an important aspect of cognitive flexibility.

Interestingly, additional evidence suggests that the DMN may be directly involved in task switching. Crittenden et al. [18] reported increased DMN activity during task switching. They suggested that DMN may be involved in the release from sustained attention to the current task to allow reconfiguring the new task sets. Another study replicated this finding and showed that DMN activated during cross-domain switching (e.g. faces to buildings) but not within-domain switches [67] — so the complexity of the switch may be an important aspect for DMN contribution to cognitive flexibility.

Wen et al. [75•] provide additional support for this idea by using a more real-world situation in their experiment. They had subjects perform task sequences involving everyday locations (e.g. tasks done in the kitchen, like cooking a meal). They performed RSA to examine the neural presentation of the tasks and the steps in each task. They found the neural activation patterns in DMN was different between tasks (e.g. make a stew, bake cupcakes) and activity in FPN was different for each step and item within a task (e.g. take food from fridge, wash vegetables). These results suggest that DMN may represent broad task context and FPN may represent specific details of each task sequence. Cognitive flexibility requires both broad context and step-level information. Flexible cognitive control may depend on the balance between DMN and FPN, which modulates our focus on broad or specific task requirements.

Wen et al. [75] point to the importance of investigating these issues with tasks that have ecological validity. Related to this point, our group has shown how regions of the VAN and DMN are related to attention and engagement while subjects process complex audio-visual narratives (e.g. film clips) [6,8,9]. It may seem strange to call Hollywood films realistic, but they may be when compared with most laboratory work on cognitive flexibility, which often involves switching tasks between simple stimuli and responses and externally defined tasks (e.g. press the left button for even numbers and right for odd). Participants must comprehend the narrative of the film from the stream of incoming audio-visual sensory information. The dynamics of these visual and auditory features mimics as aspect of real-world processing where complex information unfolds over time. Film viewing elicits task engagement, attention switching, sustain attention, narrative comprehension, and disengagement from external tasks (for a review, see Ref. [7•]).

Using a film viewing task, our group found that increased narrative suspense leads to increased activity in

the VAN and reduced activity in the DMN ([6,9], under review). Somewhat inconsistent with our findings, Song et al.s [68] reported DMN activity increased during engaging moments in film narratives, particularly those with emotional content. This DMN activity was more synchronized across individuals during these engaging moments, and functional connectivity between the DMN and FPN was positively correlated with engagement. A recent study by Nanni-Zepeda et al. [57] had participants watch emotionally negative films and assessed their engagement during viewing. They found that increased DMN activity correlated with emotional engagement, while disengagement was indicated by simultaneous activation of the FPN and DMN. Thus, DMN activity and functional connectivity between networks during task engagement may vary according to the content, decreasing with suspense but increasing with emotional arousal. More work will be necessary to clarify these complex relationships.

Despite these complexities, film viewing, like real-world situations often require us to flexibility modulate our attention states to our current external task (e.g. watching a movie or working on a work project) and other competing internally motivated thoughts and representations (i.e. task engagement and mind wandering; Figure 1). Task switching occurs in response to external demand change, while our ability to sustain our attention to the current task fluctuates from moment to moment due to a range of factors, such as reduced motivation, boredom, executive failure, or focus on internal thoughts. This inability to sustain engagement with the external task is often referred to as mind wandering. It is defined as a spontaneous thought more deliberate than dreaming but less deliberate than goal-directed thinking [13].

Our group has recently investigated the behavioral and neural characteristics of mind wandering. Godwin et al. [29] demonstrated that there are different types of inattentive states. In that experiment, we examined reaction time (RT) variability and neural correlates within and between different attentional states during the performance of a simple tapping task. Subjects could either be (1) on-task; (2) experiencing task-related interference (i.e. thinking of other aspects of the task); (3) off-task (i.e. mind wandering); or (4) experiencing inattention (i.e. not thinking about anything in particular). Behavioral results showed that the RT variability was largest when subjects were inattentive and smallest when participants were on-task. Individuals exhibit a spectrum of on- and off-task, and our cognitive system may transit between these attentional states as we behave.

Like sustained attention and mind wandering (for the relationship between sustained attention and mind

wandering, see Refs. [24,69]), activity within and between brain networks spontaneously fluctuates from moment to moment. As described previously, DMN is often less active when we are engaged in a cognitive task and more active during mind wandering and off-task states [7,11,12,59,60,72]. Furthermore, the DAN, which mediates top-down guided selective attention and motor responses to external stimuli in the environment [16,74], is often negatively correlated with DMN during rest [25,47,78] and task [1,59,71]. The antagonistic relationship between DMN and DAN has been broadly found in a variety of task fMRI studies [59]. A stronger anticorrelation between these two networks has been associated with enhanced sustained attention [44,45,63,70].

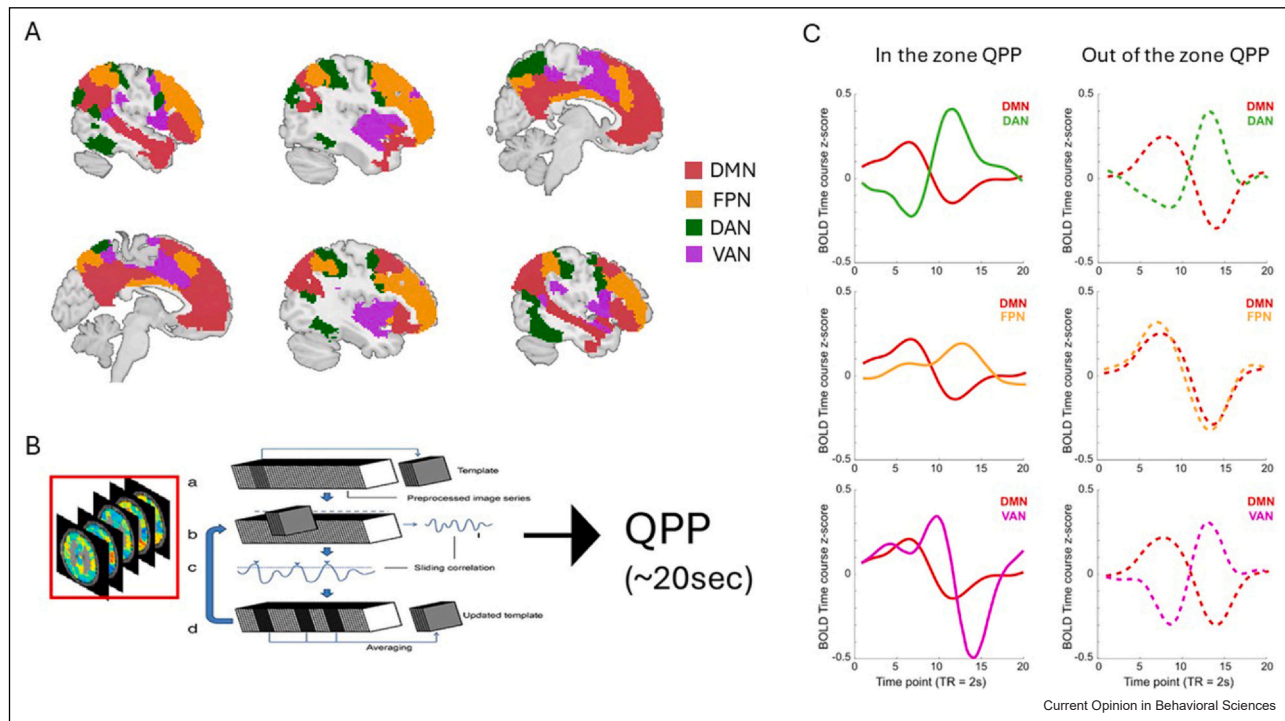
Our group has shown that activity in the DMN and the FPN and DAN (which are sometimes grouped into the task-positive network [TPN]) fluctuate over roughly 20 s cycles and are negatively correlated at rest (Figure 3b). We have called these dynamic changes in activity quasi-periodic patterns (QPPs) [47,77,78]. Additionally, we've demonstrated that subjects are faster to notice targets in a sustained attention task when the targets appear when the TPN is more active than the DMN [70]. This finding suggests that fluctuating patterns of activity in these networks may mediate attentional control and task engagement.

Researchers have also used behavioral variability as an index of on- and off-task processing. For example, Esterman et al. had subjects perform a visual recognition task in which stimuli (e.g. face, scenes, etc.) became clearer (e.g. faded in) as the trial progressed. Across several studies, they identified moments of high RT variability as 'out-of-the-zone' performance and moments of low variability as moments of 'in-the-zone' performance [22–24,45]. By employing a gradual onset continuous performance tasks, Esterman et al. observed higher DMN activation 'in the zone' and increased DAN activity in 'out of zone' performance. Likewise, Kucyi et al. found the same pattern when subjects performed a finger tapping task, in which they pressed a key to a continuous beat. These results demonstrate antagonistic relationship between the two brain networks and their anticorrelation is closely related to the task engagement states.

Esterman et al. report a negative relationship between DMN and DAN during in-the-zone and out-of-the-zone performance [22,23,45]. We and our colleagues report a fluctuating pattern of anticorrelation between these networks at rest and during the performance of attention and working memory tasks [1,47,70,78,77].

We have recently investigated the relationship between activity in these two networks and cognitive engagement. Subjects performed a serial tapping task (from

Figure 3



(a) QPPs identified in brain networks from Schafer et al., 2018. The DMN, DAN, FPN, and VAN are shown. Areas within the DAN, FPN, and VAN are sometimes identified as the TPN. (b) The basic QPP algorithm uses a sliding window to identify periodic patterns in a voxel, region, or network. It uses the results to create a template and then uses a sliding window to identify the template in the data. The algorithm iterates and updates the template. The result is a QPP, which is typically a fluctuating pattern of network activity over about 20 s. (c) Results from Seeburger et al. [66] that indicate a change in the relationship between DMN and FPN and VAN during in-the-zone and out-of-the-zone performance on a metronome tapping task. DMN and FPN are anticorrelated during engaged performance and correlated when subjects are less engaged in the task. The VAN shows the opposite pattern.

Ref. [29]). We identified the blocks of lowest RT variability (in-the-zone) and highest (out-of-the-zone). We then investigated how these different cognitive states related to QPP activity. We showed that the QPPs for DAN and DMN were anticorrelated for both zone states (Figure 3c). The FPN, however, was negatively correlated with DMN when subjects were in the zone but positively correlated when out of the zone. The QPP for VAN and DMN showed the reverse pattern — positively correlated to the DMN when in and negatively correlated when out-of-the-zone [66]. Taken together, task engagement states were related to the antagonistic relationship between DMN and DAN, and this relationship may be modulated by FPN. This result is consistent with the previous studies [22,23,45] and supports the idea that sustained attention relies on the balance between activity in DMN and DAN [22].

In this paper, we briefly review literature indicating that cognitive flexibility depends on external demands (e.g. task switching) and attentional state changes (e.g. task

engagement) and that the neural correlates associated with behavioral flexibility involve the DAN, DMN, FPN, and VAN. Flexible cognitive control is associated with the dynamic pattern of activity between these brain networks rather than activation of a single region. The functional connectivity between brain networks associated with cognitive control (e.g. DAN, FPN, and VAN) and mind wandering (e.g. DMN) are closely related to cognitive flexibility between tasks. Our internal fluctuation in sustained attention may relate to on-task and off-task performance. The anticorrelation between DMN and attention network (e.g. DAN) plays a key role in task engagement — perhaps mediating the complex relationship between maintaining a task set and switching between sets [21].

Despite the obvious differences between tasks often used in the laboratory to study task switching and mind wandering (e.g. Stroop and serial tapping tasks) and more complex tasks (e.g. watching movies or cooking), the same patterns of activity across the same brain

networks seem to emerge. This suggests a close relationship between the cognitive control processes involved and cognitive flexibility shown in these disparate domains. It highlights the ecological validity of the simple experimental tasks and offers an avenue for future research with more complex tasks.

Declaration of Competing Interest

Neither Eric Schumacher nor Yunji Lee have any conflicts of interest to report. Both authors were involved in the writing and editing of the article. Yunji Lee wrote the first draft.

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