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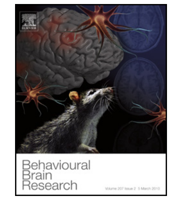

Research report

Changes in default mode network as automaticity develops in a categorization task

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HIGHLIGHTS

- In a categorization task, DMN is less deactivated at the automatic stage.
- DMN increases its coherence with some non-DMN regions at the automatic stage.
- Premotor areas increase their coherence with a DMN region at the automatic stage.

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ABSTRACT

The default mode network (DMN) is a set of brain regions in which blood oxygen level dependent signal is suppressed during attentional focus on the external environment. Because automatic task processing requires less attention, development of automaticity in a rule-based categorization task may result in less deactivation and altered functional connectivity of the DMN when compared to the initial learning stage. We tested this hypothesis by re-analyzing functional magnetic resonance imaging data of participants trained in rule-based categorization for over 10,000 trials (Helie et al., 2010) [12,13]. The results show that some DMN regions are deactivated in initial training but not after automaticity has developed. There is also a significant decrease in DMN deactivation after extensive practice. Seed-based functional connectivity analyses with the precuneus, medial prefrontal cortex (two important DMN regions) and Brodmann area 6 (an important region in automatic categorization) were also performed. The results show increased functional connectivity with both DMN and non-DMN regions after the development of automaticity, and a decrease in functional connectivity between the medial prefrontal cortex and ventromedial orbitofrontal cortex. Together, these results further support the hypothesis of a strategy shift in automatic categorization and bridge the cognitive and neuroscientific conceptions of automaticity in showing that the reduced need for cognitive resources in automatic processing is accompanied by a disinhibition of the DMN and stronger functional connectivity between DMN and task-related brain regions.

1. Introduction

Automatic activities are usually effortless and are done without the need for conscious monitoring [18]. Many daily tasks and behaviors are processed automatically. For example, for some people playing piano and riding a bicycle are done automatically. Walking is also usually done automatically. One essential skill required to function in everyday life is the ability to recognize and categorize objects [9]. For example, people need to be able to categorize faces and scenes accurately without expending too much effort in order to determine appropriate sets of actions. In most cases, categorization is done automatically [12,13].

Even though intuitively automaticity is understood easily, it's hard to rigorously define from a scientific point of view [18]. Helie and Cousineau [10] proposed that automaticity can be defined by using behavioral signatures or the cognitive processes underlying the behavioral signatures. While there is no consensus on a definitive list of behavioral signatures, proposed lists usually include efficiency, inflexibility, need for extensive practice, and fast response. Some of these signatures are more intuitive (e.g. need for extensive practice), but some are more controversial (e.g. inflexibility) and there is no general agreement that all the signatures need to be present for automatic action. Furthermore, it is not clear if it

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is possible to define automaticity by behavioral features alone. One alternative to feature-based approaches is to use process-based explanations of automaticity. Two possible processes for explaining automaticity are strategy shift and algorithm strengthening. Strategy shift approaches claim that qualitatively different cognitive processes are responsible for automatic and non-automatic actions whereas algorithm strengthening views claim that the same algorithm is used for non-automatic and automatic behavior, the difference being that participants get better at using that algorithm after extensive training.

This article focuses on the relationship between the default mode network (DMN) and automaticity. The DMN is a network of connected regions that is active when participants are not engaged in an external task and inhibited when focusing on an attentionally demanding task [19,22]. The following brain regions are generally considered part of the DMN [16]: Precuneus (pC), posterior cingulate cortex (PCC), ventral anterior cingulate cortex (vACC), dorsal medial prefrontal cortex (MPFC), bilateral inferior parietal lobules (IPL), bilateral middle temporal gyri (MTG), and left middle frontal gyrus (LMFG). Although the relationship between DMN activity and automaticity has never been explored, the fact that automatic tasks require less attentional resources than controlled tasks [21] allows for the prediction that DMN inhibition should be reduced when performing an automatic task (compared with a controlled task).

In addition, Helie et al. [12,13] showed that the brain areas involved in automatic rule-based categorization are different from those involved in initial rule-based category learning. Specifically, initial category learning is processed by a subcortical network centered around the head of the caudate nucleus but after some practice the learned categories are re-encoded in the ventrolateral prefrontal cortex. Finally after extensive practice this cortical system becomes more caudal and dorsal, centering around the premotor areas. This suggests that the cognitive task performed by participants changes with practice [3,10,17]. Interestingly, there is also evidence suggesting that the DMN pattern of functional connectivity changes depending on task [23]. Hence, another prediction is that functional connectivity of the DMN changes with the development of automaticity. Comparing functional connectivity at early stages of categorization and automatic stages could be interesting because at the automatic stage (unlike early stages of categorization), participants do not need to disrupt their background thinking process after stimulus presentation: Participants can continue day dreaming, and nonetheless perform the task well. This may result in a stronger coupling between DMN and task-related regions.

The goal of this study is to explore the alterations in DMN activity and functional connectivity after automaticity develops in a categorization task. We re-analyzed data first published in Helie et al. [12] to study changes in blood oxygen level dependent (BOLD) signals related to automatic categorization. Specifically, the focus of this article is on changes in DMN deactivation and changes in functional connectivity patterns with three seed regions: precuneus (a key DMN region), medial prefrontal cortex (another key DMN region) and Brodmann area 6 (BA6; an important region for categorization at the automatic stage;) [12,26]. These analyses are new in that: (1) deactivation was not explored in Helie et al. [12], (2) functional connectivity analyses were not included in Helie et al. [12], and (3) the current article focuses on the DMN, reduction in attentional demands, and the change in cognitive task accompanying the development automatic processing. Thus, this article focuses on attention in automaticity whereas Helie et al. [12] focused on training-related changes in brain activity in a categorization task. To anticipate, the results show that (1) DMN deactivation is reduced after the development of automaticity in a rule-based categorization task and that (2) functional connectivity with both DMN and non-DMN regions generally increases after the development of automaticity. These results are consistent with the hypotheses of a reduced need for cognitive resources and a strategy shift in automatic categorization.

2. Materials and methods

2.1. Sample

The hypotheses were tested by re-analyzing event-related functional magnetic resonance imaging (fMRI) data of 14 participants trained for 20 sessions in a rule-based categorization task at University of California Santa Barbara [12]. Participants gave written consent to participate in the study and before each scanning session consent was reaffirmed.

2.2. Stimuli and apparatus

The stimuli were circular sine-wave gratings of constant contrast and size that could be separated into two categories using a unidimensional rule on frequency (bar width). The orientation of the bars in the stimuli also varied from trial-to-trial but was irrelevant for categorization. Participants responded using two button boxes: Button box in the left hand for category A and button box in the right hand for category B. Each stimulus was presented for 2 s (1 TR). Correct responses were followed by a green check mark displayed for 2 s (1 TR). Incorrect responses were followed by a red "X" mark displayed for 2 s (1 TR). More details on the stimuli and task can be found in Helie et al. [12].

2.3. Neuroimaging

Sessions 1, 4, 10, and 20 were conducted at University of California Santa Barbara Brain Imaging Center using a 3 T Siemens TIM Trio MRI scanner with an eight-channel phased array head coil.[1] The experiment was a rapid-event related design. Before the functional runs, a localizer, a GRE field map (not used) and a T1-flash were run. The parameter values for the T1-flash were: Repetition time (TR) of 15 ms, echo time (TE) of 4.2 ms, flip angle (FA) of 90° and field of view of 192 mm. Each slice was 0.89 mm thick with 1×1 mm in-plane resolution (256×256 matrix). These scans were followed by 6 functional runs [echo planar imaging (EPI)]. The parameters for EPI were as follows: TR of 2000 ms, echo time (TE) of 30 ms, flip angle (FA) of 90° and field of view of 192 mm. Thirty-three slices were acquired in each repetition, which were parallel to the anterior commissure-posterior commissure plane. Slices were interleaved, each 3 mm thick with 0.5 mm gap between each of them and the resolution was 3×3 mm in-plane (64×64 matrix).

2.4. Data analysis

Behavioral analyses in Helie et al. [13] suggest that automaticity in this task developed between Session 14 and Session 20. As a result, the fMRI data from Session 1 (with no previous practice) and Session 20 (after 11,040 trials of practice) were re-analyzed to compare initial learning with automatic performance. Before comparing deactivation levels and functional connectivity between Sessions 1 and 20, preprocessing steps were done on the data through the FMRIB Software Library (FSL) [14]. Motion correction was done using an affine transformation and blocks with more than 3 mm head motion after spatial transformation were excluded

[1] The other training sessions were performed outside the scanner on a regular desktop computer. For details on the training sessions outside the scanner, see Ref. [13].