Neuroscience Letters 626 (2016) 174–181

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Research paper

How the brain detects invariance and inhibits variance during category induction

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HIGHLIGHTS

- Invariance detection was the critical subprocess of category learning.
- Invariance detection was explored by using a step-wise approach.
- Detecting invariance activates the left prefrontal cortex.
- Fronto–parietal–striatal network plays a crucial role in category induction.

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 1 May 2016
Accepted 18 May 2016
Available online 19 May 2016

Keywords:
fMRI
Invariance detection
Category induction
Left PFC
Putamen

ABSTRACT

A stepwise category-learning task was designed to examine brain activation associated with invariance detection and variance inhibition during category induction (CI). Three stimuli were displayed sequentially and participants were asked to learn the target category based on the invariant feature among stimuli. The processes of invariance detection and variance inhibition were necessary during certain events; however, these processes were not required for other events. Functional magnetic resonance imaging (fMRI) results indicated that the processes of detecting invariant features and inhibiting variant features were associated with significant activation in the left prefrontal cortex, including the left superior frontal gyrus, middle frontal gyrus, and mid-ventrolateral prefrontal cortex, as well as other regions (e.g., bilateral parietal cortex and putamen). These findings confirmed the important role of the fronto-parietal network and striatum in the invariance detection of category learning.

1. Introduction

Invariance is the property of entities to stay the same in some respect after undergoing a transformation or change [1]. For example, when a child sees two different balloons and is told that they are balloons, then this child might refer to all circular objects held by a thin thread as a "balloon" despite changes in color or size. Invariance detection is the process of detecting the invariant properties among category members. It is a precondition of concept formation or category learning, which is the ability to recognize category membership of sensory stimuli, such as whether a piece of fruit is "ripe" or "unripe" [2,3].

By comparing the differences and similarities (or invariance), relationships among stimuli can be abstracted and categories formed. This process of perceptual comparison and abstraction is referred to as category induction (CI) [3]. The judgment of whether a new object belongs to a specific category is called categorization, and CI is the precursor of categorization [4,5]. Thus, CI plays a key role in category learning.

For over 60 years, researchers have intensely studied the cognitive neural mechanisms that correspond to the psychological categorization processes [6]. For example, the generalized context model (GCM) indicates that the mind forms categories or concepts by determining similarities between different examples of a category [7]. In a more general framework, Vigo proposed a generalized invariance structure theory (GIST), which posits that the process of

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http://dx.doi.org/10.1016/j.neulet.2016.05.038
0304-3940/

concept formation necessitates the detection of qualitative patterns referred to as "invariants" [8]. To some extent, similarity determination and invariance detection are two overlapping processes that are both core components of CI.

Numerous studies have suggested that category learning relies on multiple neural regions, including the visual cortex and medial temporal lobe, which help us represent and memorize individual stimuli while facilitating the processing of relevant features [3,9]; the prefrontal cortex (PFC) is involved in learning and representing categorization rules and strategies [10], and the basal ganglia, parietal lobe, and motor cortices might aid decision making and the selection of behavioral responses based on categorical information [11]. However, the brain activations associated with CI, especially with the core component—invariance detection—remain unclear.

The purpose of the current study was to explore the brain activation associated with invariance detection in CI. We modified the paradigm used in Cai et al. [4] in which participants were sequentially presented with three stimuli and were asked to learn the target category corresponding to the common attribute among the stimuli. Cai et al. [4] designed two conditions, including a baseline condition and a CI condition. The features of three stimuli in the baseline condition were identical. In the CI condition, some features changed and some were unchanged. During the presentation of stimulus1, participants would have to remember all three features for subsequent perceptual comparison and categorical induction. During the presentation of stimulus2, participants might have detected two invariant features between stimulus1 and stimulus2, while excluding one variant feature. During the presentation of stimulus3, one invariant feature between all three stimuli would be detected. After several trials, the participants would then understand the task structure. Specifically, after presentation of stimulus2, participants in the CI condition might expect stimulus3 to differ someway from stimulus2. In contrast, in the baseline condition they might expect stimulus3 to be the same as stimulus2. Consequently, the CI process might confound with the expectation process. In order to control for the expectation process, we added two new CI conditions in the present study.

Invariance detection is necessarily accompanied by the inhibition of variance information [10,12], and these two processes are the two core components of CI [5]. Previous studies revealed activation in the prefrontal and parietal regions, as well as the striatum, during category learning [2,9,11–13]. Other studies have found that the frontal area activation, including the pre-SMA, dorsolateral PFC (DLPFC), and ventrolateral PFC (VLPFC), has been observed during hypothesis rejection [4,10,14]. The basal ganglia (especially the caudate and putamen) are also related to maintaining relevant and ignoring irrelevant information [13,15,16]. As a result, we predicted greater activations in the frontal area and the basal ganglia when invariant information should be detected and more invalid information should be inhibited or rejected.

2. Materials and methods

2.1. Participants

Twenty right-handed, healthy volunteers were included in the experiment (10 males, 10 females; mean age = 22 years; age range = 19–23 years). All participants met the criteria for magnetic resonance imaging (MRI) scanning. All participants were neurologically healthy. Data from four participants were excluded prior to the analysis due to unacceptable head motion or poor performance on the experimental task. Informed consent was obtained from each participant prior to scanning session and this study was approved by the ethical review board of the Department of Psychology at Southwest University.

2.2. Materials and tasks

The paradigm used here is modified from Cai et al. (2014). The stimuli labeled as edible biscuits were displayed sequentially in the center of a 17-inch screen. These biscuits were arranged to form fifteen letters. They varied along three two-feature attribute dimensions: color (white or black), letter case (uppercase or lowercase), and orientation (upright or diagonal). The variation in three dimensions was randomized across stimuli and trials. Each stimulus was set in bold, and the figures were approximately 6.60 cm in height and 4.80 cm in width. The color of the background was light grey (50% grey). The horizontal and vertical visual angles were both less than 3°.

During the CI task, the process of invariance detection and variance inhibition is used to extract common features and inhibit different features between stimuli (Fig. 1). In each trial of the task, participants were presented sequentially with three stimuli that were kept invariant or varied either in one or two dimensions. They were informed that all the presented stimuli were edible biscuits, and then answered the question "what kinds of stimuli were the edible biscuits?". To respond accurately would have to find the target category corresponding to the invariants across the three stimuli. Based on the possible answers for each stimulus presentation, four conditions were designed as below.

In Cond3-2-1 trials, the possible answers reduced gradually after invariance detection. For the example as shown in Fig. 1, if a participant first saw stimulus 1 (e.g., a letter ***A***), they might have to remember all three features for subsequent perceptual comparison and categorical induction (e.g., black, uppercase, or diagonal), because all three features might be the final answer. Following presentation of stimulus 2 (e.g., letter ***b***), participants might detect the two invariant features (e.g., black and diagonal) by comparing stimulus 2 with stimulus 1, while excluding one variant feature (uppercase). Thus, the process of invariance detection and variance inhibition would be prominent during this phase, and the number of possible answers is reduced to two. During the presentation of stimulus 3 (e.g. letter **F**), only one invariant feature (e.g. black) would be detected, and a new variant feature (e.g. diagonal) would be inhibited. At this phase, one more possible answer was excluded and leaving only one answer. Finally, the Chinese words"黑色", which means "black" in English, were presented, and participants were instructed to judge whether the presented Chinese words were the answer (Fig. 2).

In Cond3-2-2 trials, participants needed to detect two invariant features and exclude one variant feature during phase 2. However, during phase 3, there was no invariance detection or variance inhibition, because the stimulus did not change from phase 2 to phase 3.

In Cond3-3-1 trials, there was no invariance detection or exclusion/inhibition of variant features during phase 2, because the stimulus did not change from phase 1 to phase 2. However, during phase 3, one invariant feature could be detected and two variant features could be ruled out. Therefore, the process of cognitive control would be most intensive during phase 3 in this condition.

In Cond3-3-3(Baseline) trials, all features were identical across the three phases. For example, all three stimuli might be black, uppercase, and diagonal. When the second or third stimulus was presented, participants would not find any variant features between stimuli, and therefore, would not eliminate any possible answers. The perceptual encoding and features maintaining in working memory (WM) would be involved in the baseline task, but the processes of invariance detection and variance inhibition would not be required.