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REVIEW

THE ROLE OF SENSORY CORTEX IN BEHAVIORAL FLEXIBILITY

LAN GUO, [†] **NICHOLAS D. PONVERT** [†] **AND SANTIAGO JARAMILLO** *

Institute of Neuroscience and Department of Biology, University of Oregon, Eugene, OR 97403, United States

Abstract—To thrive in a changing environment, organisms evolved strategies for rapidly modifying their behavioral responses to sensory stimuli. In this review, we investigate the role of sensory cortical circuits in these flexible behaviors. First, we provide a framework for classifying tasks in which flexibility is required. We then present studies in animal models which demonstrate that responses of sensory cortical neurons depend on the expected outcome associated with a stimulus. Last, we discuss inactivation studies which indicate that sensory cortex facilitates behavioral flexibility, but is not always required for adapting to changes in environmental conditions. This analysis provides insights into the contributions of cortical and subcortical sensory circuits to flexibility in behavior.

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Key words: reversal learning, extinction, attentional set shifting, sensory cortex, sensory thalamus, reward.

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INTRODUCTION

Behavioral flexibility is defined as the ability to shift response patterns (or strategies) after changes in environmental conditions (Ragozzino, 2007). These environmental conditions define the statistical relations between a stimulus, possible behavioral responses, and outcomes (such as a rewards or punishments). We refer to these relations as *contingencies*. The ability to adapt to changing contingencies is impaired in several human neurological disorders, including schizophrenia (Goldberg and Weinberger, 1988; Morice, 1990) and autism (Hill, 2004). Our quest to develop better diagnostic and therapeutic strategies for these disorders would greatly benefit from detailed knowledge of the circuits and mechanisms responsible for flexibility in behavior. Research on the neural basis of flexible behaviors in mammals has identified regions of the frontal cortex that detect changes in contingencies, inhibit undesired responses, and help acquire new strategies (Dias et al., 1997; Ragozzino, 2007; Sotres-Bayon and Quirk, 2010). In contrast, it is not clear whether sensory cortex plays a role in implementing flexibility in behavior beyond extracting features of sensory stimuli.

Understanding the neural mechanisms underlying flexible behaviors, and the role of sensory cortical neurons, requires monitoring neuronal activity with single-cell resolution and manipulating the system in ways difficult to achieve in human subjects. For this reason, we focus here on experiments that use animal models of flexible behaviors. We review studies in which sensory neurons are monitored ed during changen contingencies to address the following questions: What roles do sensory pathways play in behavioral flexibility beyond conveying sensory information? What flexible behaviors require sensory cortex? Which subcortical pathways can implement flexible behaviors without the need of the sensory cortex?

Several parallel neural pathways link sensation to action, including circuits in the brainstem that mediate reflexive responses, subcortical circuits via the amygdala that can mediate fear responses, and higher-order pathways that rely on sensory and motor cortex.

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*Corresponding author. Address: Institute of Neuroscience, 1254 University of Oregon, Eugene, OR 97403, United States.
E-mail address: sjara@uoregon.edu (S. Jaramillo).

[†] These authors contributed equally to this work.

Abbreviations: AM, amplitude-modulated; CS, conditioned stimulus; MGm, medial geniculate nucleus of the thalamus.

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In this review, we investigate how a stimulus can drive different behavioral responses depending on environmental conditions. A neuronal population within a sensory pathway can play at least three different roles during flexible behaviors. First, these neurons may be the first stage in the ascending sensory pathway that can discriminate the stimuli presented in a task. These neurons will be required for successful performance of the task, even though they do not play a direct role in rerouting information upon a contingency change. Second, this population may be the first stage in the ascending pathway that can communicate with circuits that reroute signals to implement behavioral flexibility. In this case, even though other regions (closer to the periphery) may be able to discriminate the stimuli in the task, information has to go through this specific stage before it can be flexibly rerouted to drive distinct actions. Third, a population of sensory neurons may play an active role in signal rerouting—passing or filtering out signals depending on the desired behavioral outputs for a given contingency. In this last scenario, we say that these neurons take part in implementing flexibility. Brain regions can play one or more of these roles, and do so in the context of coordinated activity across multiple other regions.

Here we review studies that quantify the correlations between sensory neural representations and behavioral contingencies. These studies indicate that sensory representations are modulated by expected outcomes associated with a stimulus, and when animals selectively attend to relevant stimulus features. In addition, we discuss the behavioral effects of manipulating neural activity in sensory cortex during tasks that require flexibility. Sensory cortex lesions often impair behavioral adaptation following contingency changes. However, some flexible behaviors are possible after inactivation of sensory cortex.

TAXONOMY OF ADAPTIVE BEHAVIORS

In this section, we provide a framework for classifying different types of adaptive and flexible behaviors according to the relations between sensory stimuli, behavioral responses, and outcomes (such as rewards or punishments). We start by discussing phenomena in which these relations do not change, yet the nervous system can adapt to the statistics of a stimulus ensemble. We then discuss phenomena in which these relations do change, and classify these phenomena into three categories of flexible behaviors.

Neural correlates of adaptation to stimulus ensemble statistics can be observed even in anesthetized animals, and occur independently of reward contingencies. Examples include changes that result from contrast adaptation in the retina (Baccus and Meister, 2002) and from adaptation to repetitive acoustic stimuli observed in the midbrain (Malmierca et al., 2009), thalamus (Anderson et al., 2009) and cortex (Ulanovsky et al., 2003). In behaving animals, this adaptation provides a performance advantage by allocating neuronal resources to maximize the detection or discrimination of stimuli. Some cases of *perceptual learning*, defined as the improvement in sensory discrimination by practice (Goldstone, 1998), are examples of this type of adaptation without changes in reward contingencies. For instance, auditory cortical circuits change their sound frequency tuning as animals are trained to discriminate small differences in the frequency of sequentially presented tones (Recanzone et al., 1993). In addition, subjects can use selective attention in tasks where the stimulus–action–outcome associations do not change. In this case, subjects allocate resources to space (Posner et al., 1980) or time (Jaramillo and Zador, 2011) in order to improve task performance, resulting in changes of sensory cortical neural responses. In all these scenarios, the relation between the stimulus, action and outcome does not change, and the only environmental feature driving adaptation is the stimulus ensemble. We exclude these phenomena from our discussion of behavioral flexibility.

Here we focus on a different class of phenomena in which adaptation is driven by changes in the statistical relation between stimuli, behavioral responses and outcomes, i.e., changes in behavioral contingency. We first discuss scenarios in which the outcome associated with a stimulus varies across contingencies, as illustrated in Fig. 1A. In this example, the star stimulus predicts a rewarding outcome in one condition (C1), but not in the other (C2). The circle stimulus, in contrast, is not associated with any outcome in the initial condition, but predicts reward when the contingency changes. In this class of phenomena, which include acquisition and extinction of conditioned responses, actions may not be required to trigger a reward or punishment.

In the second type of scenario discussed, animals are required to change the action associated with a stimulus, but the outcome that can be achieved for each stimulus remains the same. This is illustrated with the discrimination task in Fig. 1B. To obtain reward after a stimulus is presented, the subject must perform one of two possible actions: move right (R) or left (L). In the initial contingency (C1), the star stimulus predicts that the subject will obtain reward only after action R, while the circle predicts reward for action L. In contingency C2, the actions that yield reward for each stimulus are reversed. In contrast to the scenario described in Fig. 1A, both stimuli predict reward under all contingencies in this task.

Separately, we discuss a special case of reversal phenomena in which selective attention can be used to filter out some features of the stimulus (Fig. 1C). During stimulus-driven behaviors, not all features of the environment are relevant at all times, i.e., some features may not predict outcomes. Depending on how the relevance of stimulus features changes across contingencies, we can define two different types of tasks. In the reversal task presented in Fig. 1B, irrelevant features of the stimulus (such as the background in which it is presented) never become relevant. In contrast, parts of the stimulus in the task presented in Fig. 1C change from being predictive of reward to being irrelevant. In this scenario, it can be advantageous for the organism to filter out a different set of irrelevant features in each contingency by engaging selective attention. The right panel of Fig. 1C