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XOR style tasks for testing visual object processing in monkeys ☆

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Abstract

Using visually complex stimuli, three monkeys learned visual exclusive-or (XOR) tasks that required detecting two way visual feature conjunctions. Monkeys with passive exposure to the test images, or prior experience, were quicker to acquire an XOR style task. Training on each pairwise comparison of the stimuli to be used in an XOR task provided nearly complete transfer when stimuli became intermingled in the full XOR task. Task mastery took longer, accuracy was lower, and response times were slower for conjunction stimuli. Rotating features of the XOR stimuli did not adversely effect recognition speed or accuracy.

Keywords: Conjunction; Monkey; Visual; Behavior; Learning

1. Introduction

"Binding by synchrony" is a current, but controversial, hypothesis for explaining how the brain represents visual objects Shadlen and Movshon, 1999; Singer, 1999. Binding by synchrony proposes that the synchronous occurrence of neuronal action potentials is of particular importance in tagging which neurons go with which and consequently which visual features are bound together. Testing this theory is conceptually straightforward; one measures the joint firing statistics of multiple neurons when a subject is viewing the same visual features in two conditions: one where they do, and one where they do not "go together." Operationalizing these ideas, however, produces substantial practical problems. The one which we focus on here is the need, in the case of primate neurophysiology, for a monkey to solve a non-linear mapping from stimulus to response.

In a typical monkey, visual classification task, images of objects are displayed on a computer screen and the monkey is required to make a physical response by touching the screen, pressing a lever, or looking at a specific target. If the monkey is more accurate than chance, then the experimenter asserts that the image is being correctly recognized. When object identification is studied at the individual level, it is common to have several, but almost always many less than one hundred, images from the same basic category (e.g., Kobatake, Wang, & Tanaka, 1998; Sigala, 2004). When the objects in the set appear to us as visually similar, we may believe that the monkeys' responses are based on more than individual diagnostic elements, but we do not actually know this. It is still possible for such relatively small sets of objects, there is, for each image, a unique feature that allows classification. What the monkeys may learn through our training is which features are diagnostic for which images. To evaluate the neurological mechanisms of visual feature binding, we must guarantee that this is not the case. There must be, at a minimum, at least two areas of the image necessary for correct categorization. However, this requirement introduces a new difficulty: if we want any

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one feature to be uninformative, but have correct responses require the conjunction of two features, we are in the domain of non-linearly separable mappings. The canonical example of a non-linear mapping problem is the exclusive-or (XOR). In an XOR task, the combinations of either both (1 and 1) or neither (0 and 0) stimuli are mapped to one response and the either conditions (1 and 0 or 0 and 1) are mapped to the alternative response (see also Fig. 1). There is little data on explicit solutions of non-linearly separable problems in animals and the little data available suggests that they are hard, especially for monkeys.

Many studies on learning non-linear mappings use implicit learning techniques in the tradition of classical conditioning. Two such techniques are biconditional discrimination and negative patterning. Biconditional discrimination had been shown for rabbits (Saavedra, 1975), pigeons (Rescorla, Grau, & Durlach, 1985), monkeys (Saunders & Weiskrantz, 1989), and humans. For example, Lober and Lachnit (2002) successfully trained people to associate two-letter strings (B, G, T, and X) to either shock (reinforcement condition) or no shock (no reinforcement condition) and measured galvanic skin conductance changes. Negative patterning is even more clearly an XOR like task (Kehoe & Macrae, 2002). In a study of eye blink conditioning, Kehoe and Graham (1988) exposed rabbits to cross-modal combinations of tone and light stimuli. They observed responses to the stimuli individually and declining responses to the conjunction. Similar results using two auditory stimuli and reward with food have been shown in rats, pigeons, and bees (Deisig, Lachnit, Giurfa, & Hellstern, 2001; Redhead & Pearce, 1995).

Studies showing explicit learning of an XOR like task in primates are few. Thorpe, O'Regan, and Pouget (1989) displayed a 4×4 grid of lights that flashed patterns at 5/s; all patterns were evaluated according to a specific rule, one of which followed an XOR pattern. The human subject was never able to learn the XOR mappings. Baker, Behrmann, and Olson (2002) used an XOR task as a component of an electrophysiological study of monkey inferotemporal cortex. Stimuli were simple geometric patterns connected by a central baton (similar to those used in Experiment 3 of this report). Learning for one monkey took ~5000 trials per stimulus for a set of eight objects and the other monkey required ~7000 for another set of eight objects. Compared to conventional classification tasks, this is a large number of trials. This result is in accord with those of Smith, Minda, and Washburn (2004). They assessed the ability of four monkeys to learn a variety of problems using simple geometric shapes of varying size and color. One of the problems was of the XOR type and was more difficult for monkeys, relative to other learning tasks, than for a comparison group of human subjects. The *unitization* tasks used by Goldstone (2000) to test normal human subjects are also similar to XOR tasks in that the "squiggles" used required that multiple pieces be recognized for correct classification. Performance was shown to vary with the number of conjunctions required, but Goldstone argued that eventually response times became equivalent across stimuli suggesting that functionally a unitary representation had been performed.

The common result of these studies is that XOR tasks are hard for primates (people and monkeys), often

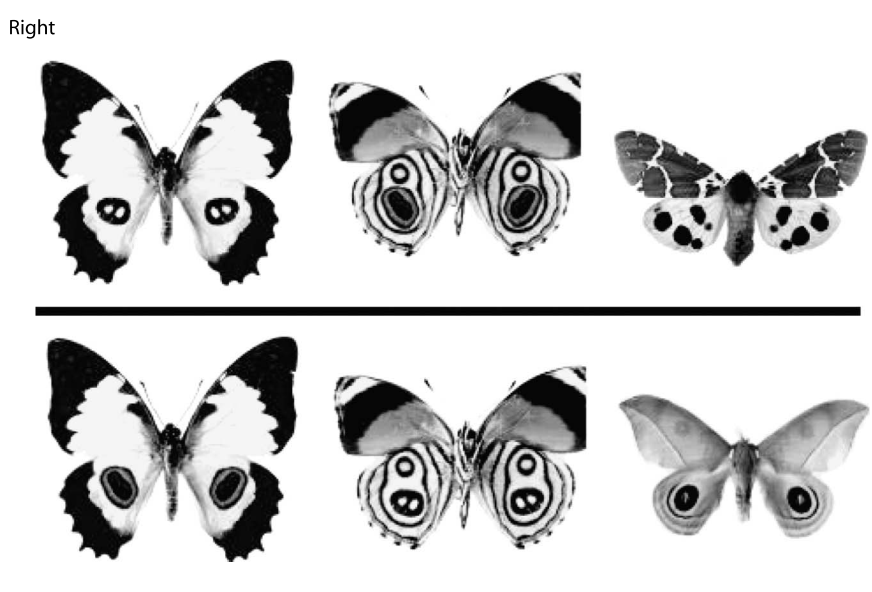

Fig. 1. The six stimuli used in Experiment 1. The top row shows the stimuli associated with the right button press and the bottom row those associated with the left button press. The 2 moths on the far right were unique stimuli and provided an index for how quickly traditional stimuli were learned in comparison to the XOR stimuli. The four butterflies on the left are the XOR set. The features are the butterfly body: white or orange; and the tail spots: brown or black with white spots. What makes the task an XOR task is that neither the body type or tail spot type alone allow responding above chance; the combination is needed to determine the correct button press. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)