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Rapid long lasting learning in a collinear edge-detection task

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Abstract. We have developed a detection task in which subjects identify a pair of collinear edges in a field of polygons. Five of our six subjects showed significant, rapid learning at this task. Four showed evidence of retention a day and a week later. In several transfer tests, we found that disruption of the distractors produced a significant drop-off in performance. These results are consistent with a model in which collinear targets initially produce a salience signal too weak to be reliably detected over the noise of the distractors. As the experiment proceeds, the visual system learns to dampen the distractor signals, allowing for more reliable detection.

1 Introduction

The existence of plasticity in early visual processing is supported by perceptual-learning studies where learning is specific to very precise features of the stimuli such as size, orientation, or retinal position (Ramachandran and Braddick 1973; Fiorentini and Berardi 1980; Ball and Sekuler 1982; Karni and Sagi 1991; Ahissar and Hochstein 1996b). In the classical perceptual-learning studies, subjects showed improvement only gradually, over hundreds or thousands of trials. However, recently there have been a number of reports of comparatively rapid learning which seems to be occurring early in processing (Jeo et al 1995; Ahissar and Hochstein 1996a; Rubin et al 1997; Tanaka and Sagi 2000).

These studies encouraged us to look for paradigms to study such rapid, low-level learning. We began with the stimuli used by Jeo et al (1995). Instead of asking subjects to identify whole geometric figures, however, we asked them to detect a pair of collinear edges in an array of distractors. Below, we demonstrate that human subjects can improve rapidly at this task, and that traces of this improvement remain up to a week. We also tested the retention of learning in several transfer experiments, and we propose a model for its underlying mechanism.

2 Methods

2.1 *Experiment 1*

2.1.1 *Observers.* Six adult subjects with normal or corrected vision were tested. Two were female and four male. Of the six, three were totally naïve to the goals of these experiments.

2.1.2 *Stimuli.* Computer-generated circular arrays of polygons were used as stimuli. Each subject learned 96 of these. Each array image had a radius of about 4 deg visual angle, containing approximately 19 quadrilaterals whose edges ranged from 0.5 to 1.25 deg. These were also separated from each other by 0.5 to 1.25 deg. Half of the images were target images containing two polygons sharing a collinear edge. These two target polygons fell within a 2.5 deg radius of the fixation point. For each target, there was a corresponding catch image, which was identical to the target except for the two target polygons whose collinear edges were disrupted by 10 – 15 deg (figure 1a). To test the specificity of learning for particular characteristics, we devised several types of

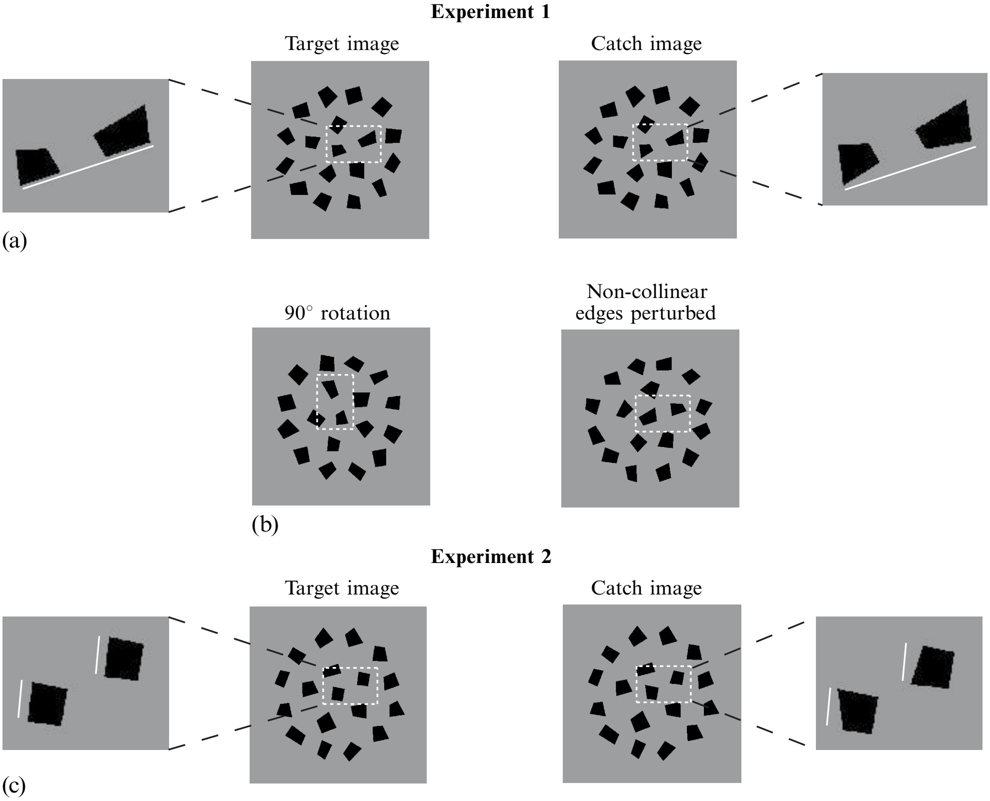

Figure 1. White boxes indicate target polygons. (a) Experiment 1: target image (left); white lines in blow-up of target polygons emphasize collinear edge; catch image (right) with that edge perturbed. (b) Experiment 1: stimuli for transfer conditions, 90° rotation (left); an image where all edges except the two collinear ones have been perturbed (right). (c) Experiment 2: target image (left) containing two identical polygons; catch image (right) with one edge in each perturbed; white lines in blow-up emphasize the two edges which differ between target and catch (note that in the target image these lines have the same orientation, but are not collinear).

transfer conditions. In one condition, the original training images were rotated by 90°. In the other all the edges of every polygon were perturbed except the two collinear edges in the target polygons (figure 1b).

2.1.3 *Procedure.* Each subject performed six experimental sessions with a total of 96 images. One or two sessions were performed on a single day. In each session, 8 target and 8 catch images were presented once in each of ten training blocks (figure 2b). A single trial consisted of the presentation of a polygon array followed by an interstimulus interval (ISI) and a mask (figure 2a). When subjects saw the mask, they responded by pressing a button to indicate whether the presented array had been a target or a catch. They received auditory feedback after each incorrect response. After target trials they also received visual feedback in which the target polygons were drawn in white. Stimulus presentation times varied among subjects, and were in the range 167 – 190 ms. ISI times were between 25 and 325 ms. See below for explanation of how these were determined. In subsequent testing blocks, subjects were tested without feedback on several transfer conditions, then tested again on the originally trained images. A day and a week after each initial training session, subjects were trained again for five blocks on the same stimuli.[1]

[1] For one subject, SS, the transfer conditions were tested after retraining a week later, instead of on the initial day.

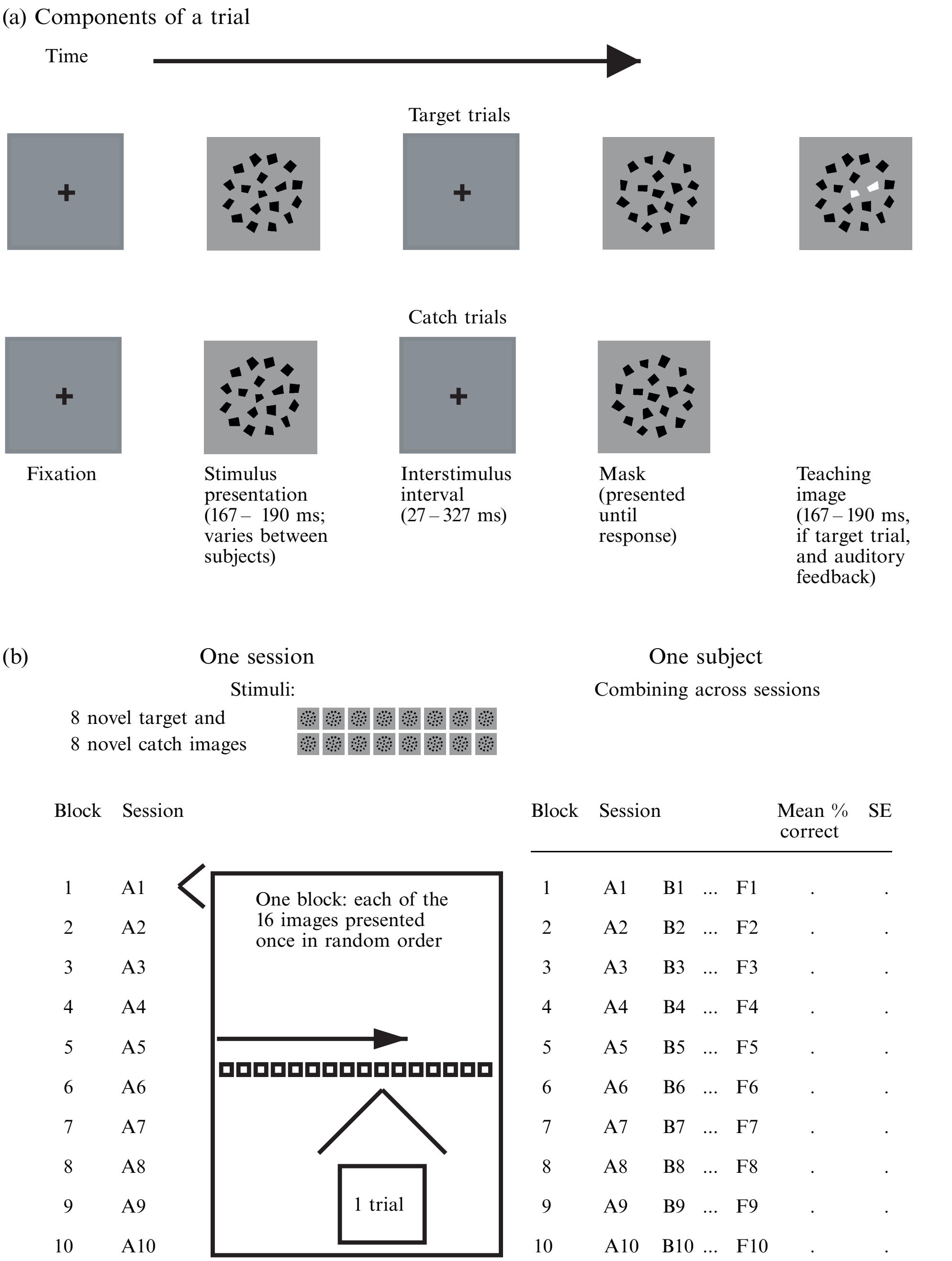

Figure 2. The subject's task was to distinguish target from catch images. (a) Trials began with fixation, followed by a brief presentation of the stimulus, an ISI, and a mask. Subjects responded when they saw the mask. They were given auditory feedback after incorrect responses. If the stimulus was a target, they were also given visual feedback. (b) A single session involved the presentation of eight target and eight catch images, once per block for ten blocks. For each session, the percentage of correct responses was calculated for each block. Each subject performed six such sessions, which were then averaged to make a plot as in figure 3b.

It was necessary for subjects to perform a number of preliminary sessions for the following reasons. When subjects first performed the task, they were unused to the type of mask we used, and generally required large ISI times of 400 ms or more. As they became more accustomed to this mask type, it was necessary to decrease the ISI in order to keep initial performance close to chance. Because this improvement relative to the mask was rapid, it could have confounded attempts to identify stimulus-specific learning. We therefore continued preliminary sessions until subjects reached a plateau in ISI values. During the course of preliminary sessions, several subjects had initial performance well above chance, even for an ISI of zero. For these subjects the presentation time was reduced to between 167 and 190 ms.

2.2 *Experiment 2*

2.2.1 *Observers.* Four subjects who showed a learning effect in experiment 1 acted as observers. Two were naïve to the purposes of the experiment.

2.2.2 *Stimuli.* Stimuli were arrays of polygons similar to those in experiment 1. Instead of containing collinear edges, target images contained two adjacent polygons of identical shape and orientation. Catch images were target images where one edge in each target polygon was perturbed (figure 1). Thus, just as in experiment 1, the target and catch images differed only in the position of two edges. In experiment 1 those two edges were collinear. In experiment 2 the two differing edges were cooriented. They fell on parallel lines, but were not collinear.

2.2.3 *Procedure.* The experimental procedure was the same as in experiment 1, but without transfer conditions.

3 Results

3.1 *Experiment 1*

Individual subjects generally showed improvement within a single session, as well as when sessions were averaged (figure 3). During the initial training blocks, mean percentage of correct responses across six subjects improved by 18% (figure 4). Five of the six subjects showed significant individual learning (t-test, $p < 0.05$; see table 1). This learning was relatively long lasting. The first five training blocks on the initial day were compared with the five blocks on the day after and week after. Four of the six subjects showed improved performance the day after, and four of the six did so the

Table 1. Values of p from experiment 1. Asterisks indicate significance at the 5% level. Column 2: t-tests on the training sessions for each subject—the first training block is compared with the average of two test blocks at the end of the initial training session. Columns 3 and 4: two-way ANOVAs, where the null hypothesis is that performance the day and week after does not differ from performance on the initial day of training. Columns 5 and 6: t-tests comparing performance on the first block of the initial training session, with performance on the first block the day and week after.

Subject	t-test on training sessions	Two-way ANOVA; comparison of performance with that on the initial day of training		t-test (first block); comparison of performance with that on the initial day of training	
		day after	week after	day after	week after
BS	1.4×10^{-1}	6.9×10^{-1}	2.9×10^{-1}	7.1×10^{-1}	5.6×10^{-1}
EB	7.8×10^{-5}*	4.5×10^{-2}*	3.9×10^{-1}	1.7×10^{-1}	2.9×10^{-1}
GL	1.3×10^{-3}*	1.8×10^{-2}*	2.8×10^{-4}*	4.3×10^{-3}*	1.4×10^{-2}*
HW	6.5×10^{-4}*	7.3×10^{-2}	5.0×10^{-4}*	2.6×10^{-1}	4.3×10^{-2}*
KW	1.8×10^{-9}*	6.4×10^{-6}*	5.8×10^{-12}*	8.5×10^{-5}*	1.1×10^{-6}*
SS	1.6×10^{-2}	6.2×10^{-3}*	1.3×10^{-5}*	6.5×10^{-1}	2.9×10^{-1}

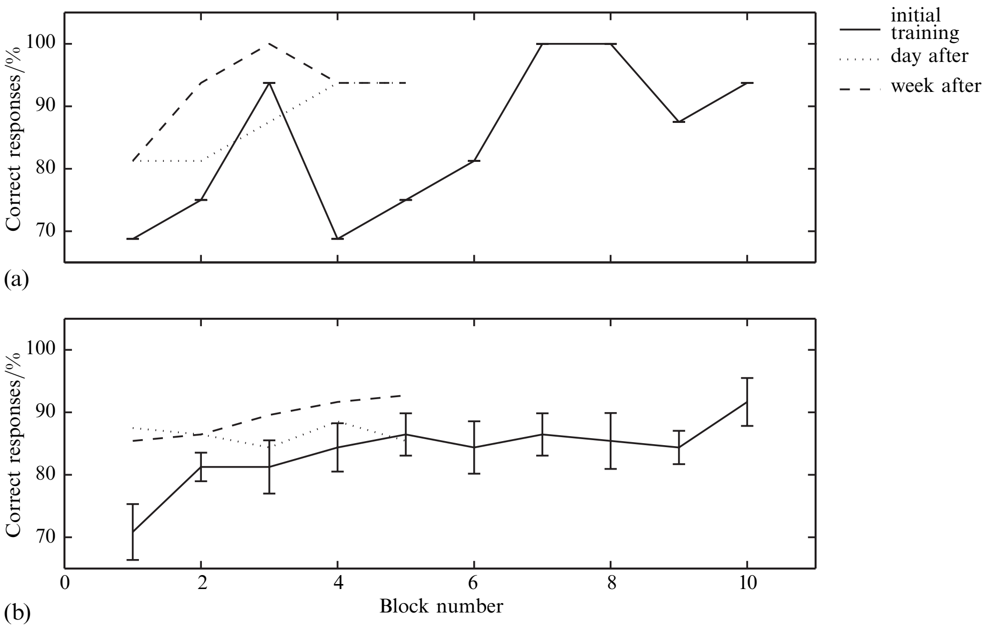

Figure 3. (a) Data are plotted from a typical subject in a single session. Dotted lines represent retraining a day and a week later; 16 images total. (b) Data for the same subject averaged across six sessions. Again dotted lines represent day and week later, for which error bars are not shown; 96 images total.

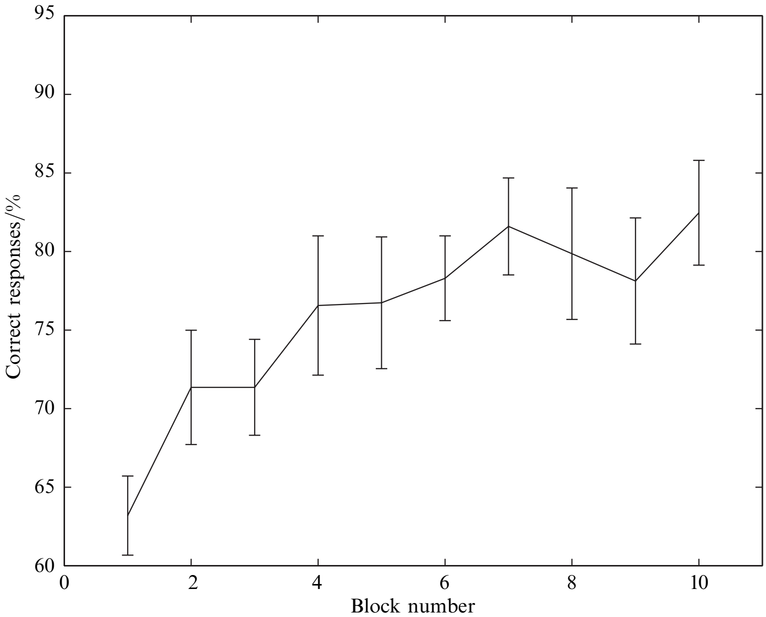

Figure 4. Initial training learning curve for all six subjects combined.

week after (two-way ANOVA, $p < 0.05$; table 1). Even when the comparisons were confined to the first block of the training sessions, two subjects were significantly better on the following day than on the initial day. Three subjects were better on the first block of following-week testing compared to the first block on the initial day (t-test, $p < 0.05$; see table 1).

The test blocks without feedback consisted of transfer conditions as well as the original trained stimuli. We can express the results of the transfer tests by comparing the percentage of correct responses in a given transfer block with the percentage of correct responses on the original trained stimuli. We have done this using the following formula:

$$\frac{\text{transfer block\%} - \text{initial block\%}}{\text{trained stimuli block\%} - \text{initial block\%}} .$$

Initial block% refers to the percentage of correct responses on the first block of training. In both transfer conditions, subjects showed a drop-off in performance (figures 5a and 5b).

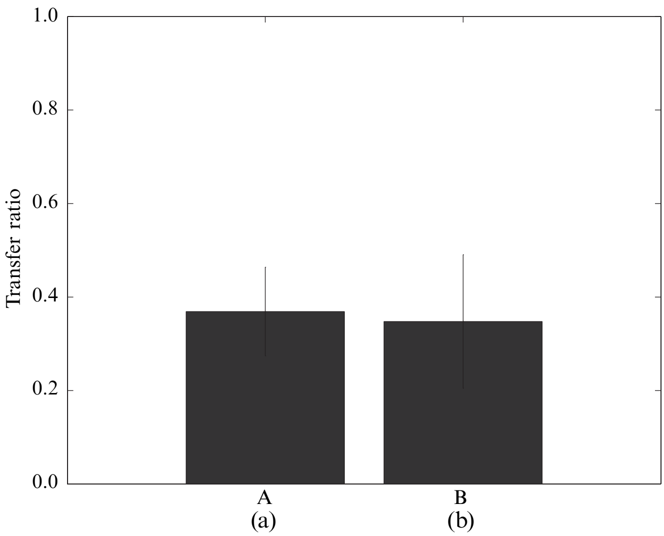

Figure 5. Transfer ratio, combined across subjects. For these tests, data were not included from the subject who failed to show significant learning in the initial training blocks. (a) 90° rotation ($n = 5$). (b) Perturbation of all non-collinear edges ($n = 5$). Bars represent standard error.

Table 2. Values of p from experiment 2: t-tests comparing performance on the first and last block of the training sessions.

Subject	t-test: comparison of performance on the first and last block of the training sessions
EB	0.20
GL	0.56
HW	0.23
KW	0.46

3.2 *Experiment 2*

None of the four subjects showed significant learning on the first day (t-test, $p > 0.05$, see table 2). Typical data for a single subject combined across sessions are shown in figure 6.

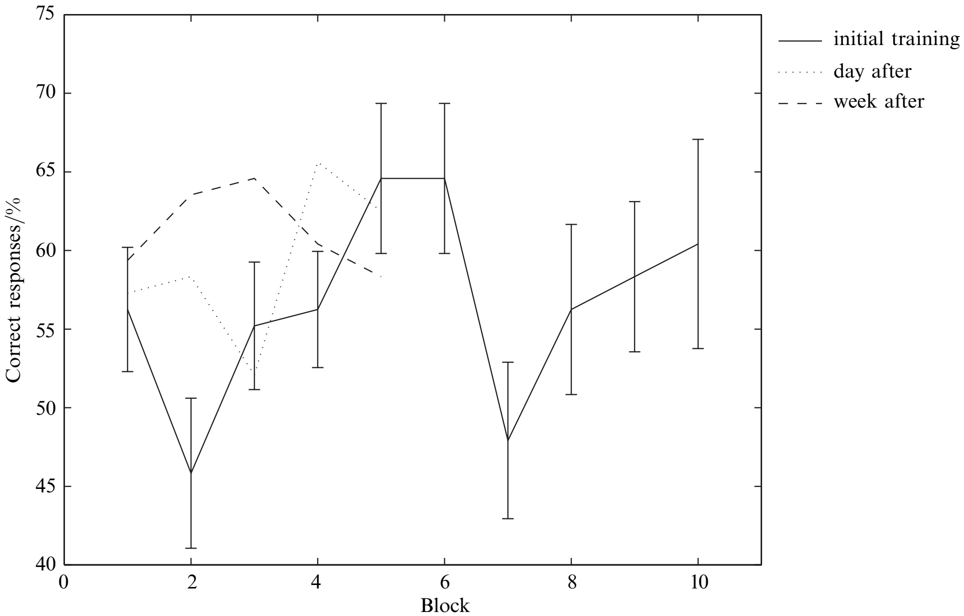

Figure 6. A sample learning curve for one subject where the target consisted of pairs of identical polygons.

4 Discussion

Our results demonstrate rapid and long-lasting changes in subjects' ability to detect collinear lines in a field of distractors. The results of the second experiment show that this improvement cannot have been due simply to memorization of the shape of the target, or of the position or orientation of target edges.

The results of the transfer tests suggest that the plasticity itself lies in the representation of the distractors rather than the targets. Both transfer tests produced similar reductions in performance. When the whole image was rotated by 90°, all the edges changed orientation and/or retinal position. In the second condition, the distractor edges changed, but not the target edges.(2) The fact that performance in the second condition dropped as much as it did in the first suggests that plasticity in the representation of distractors plays a key role in the learning phenomenon. Reports of distractor-dependent learning have been made before in perceptual-learning tasks (Karni and Sagi 1991; Ahissar and Hochstein 1996b), and a search task (Chun and Jian 1998).

One model of the present phenomenon is as follows. Initially, because of the mask and the short presentation time, the salience of the collinear-edged targets relative to the distractors is not sufficient for reliable detection. As the experiment proceeds, however, the visual system learns to dampen the distractor signals. The collinear target edges can then attract attentional resources more reliably, improving the subject's performance on the task. One can imagine this taking place in an orientation-selective region of the cortex. The relatively short presentation times in this experiment, combined with the specificity of the learning, are consistent with that.

(2) We were unable to perform several other types of transfer test because of the nature of this learning phenomenon. In preliminary observations, we found extremely weak learning for stimuli where the target polygons were located significantly outside the fovea. Manipulations of size or retinal image position, in order to be revealing given the sizes of foveal V2 (0.5 – 1 deg) and V4 (1 – 4 deg) receptive fields, would have required moving the target polygons out of the fovea by unacceptable amounts.

Note that the model presented above leaves open the possibility that some other moderately salient stimuli might be able to substitute for collinear edges to produce a learning effect. Future explorations of this possibility might prove quite interesting. The capacity of subjects to learn with a particular set of stimuli and not with another set could reveal something about the kinds of connections present in cortex at the site of learning.

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