Pigeons' recognition of partially occluded objects depends on specific training experience

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Abstract. DiPietro et al (2002 *Perception* **31** 1299 – 1312) reported a dramatic improvement in pigeons' recognition of partially occluded objects after the birds had been trained to recognize objects that were placed on top of another surface. Here, we investigated whether training with partially erased stimuli or with notched stimuli that had a thin gap between the object and another surface would similarly enhance pigeons' recognition of partially occluded objects. We found that erased training had no effect on the birds' recognition of partially occluded objects. Training pigeons to recognize notched objects improved their performance with the same objects when they were partially occluded; but this improvement did not transfer to novel objects, a result that DiPietro et al reported after on-top training. Together, the present results and those of DiPietro et al implicate prior experience as a key factor in pigeons' recognition of partially occluded objects. Training experiences which improve recognition of partially occluded objects may do so because they improve decomposition of complex two-dimensional scenes by pigeons into separate entities.

1 Introduction

Everyday experience requires us to interact with a vast number of objects, many of which partially occlude others. Yet, we seem to have little difficulty recognizing an object by seeing only a portion of its full area. We reach for the visible corner of a book on a messy desk, we recognize a person who is sitting in a car, and we move aside hangers in our cluttered closet to get access to a partially hidden garment. This ability to recognize partially occluded objects may be based on visual or amodal completion: the ability to perceive partially occluded objects as complete. It is possible, however, to recognize a partially occluded object without actually perceiving it as complete. In this paper, we will consider the conditions under which nonhuman animals, specifically pigeons, can recognize partially occluded objects, regardless of whether they amodally complete these objects or recognize them by generalization from a visible portion to the whole object.

It is important at the outset to appreciate that humans' recognition of partially occluded objects, especially in a two-dimensional (2-D) environment, may not be entirely innate. Newborn (Slater et al 1990) and 2-month-old (Johnson and Nanez 1995) infants tested in the habituation/dishabituation paradigm show no evidence of recognizing 2-D, partially occluded objects. By 4 months of age, infants can recognize partially occluded objects in a 2-D environment, but only if the occluded object is moved from side to side (Kellman and Spelke 1983). These and other studies (reviewed by Johnson 2003) suggest that infants' recognition of partially occluded objects in 2-D displays may develop gradually during the first few months of life—perhaps resulting from infants' multiple encounters and training with occluded objects.

Casual observation suggests that animals, including pigeons, can recognize partially occluded objects. Pigeons are constantly interacting with partially occluded objects when they are foraging for food, returning to their nest after an outing, or finding their

fledglings among branches and leaves. The ability to recognize partially occluded objects is clearly as essential for pigeons' survival as it is for ours. Evidence of amodal completion in nonhuman animals, however, is ambiguous. Some species, such as chicks, mice, squirrel monkeys, rhesus monkeys, and baboons, have been reported to exhibit this ability (Deruelle et al 2000; Forkman 1998; Forkman and Vallortigara 1999; Kanizsa et al 1993; Lea et al 1996; Nagasaka and Osada 2000; Regolin and Vallortigara 1995; Sato et al 1997), whereas others, particularly pigeons, have not (Cerella 1980; Fujita 2001; Fujita and Ushitani 2005; Sekuler et al 1996; Ushitani and Fujita 2005; Ushitani et al 2001; but see Nagasaka et al 2005 for indirect evidence of amodal completion in pigeons).

DiPietro et al (2002) trained pigeons to 'name' four shaded shapes—the arch, barrel, brick, and wedge in figure 1—by choosing one of four different report buttons. After the pigeons had acquired this discrimination, they were presented with the four different modifications of the training stimuli that are illustrated in the upper half of figure 2: partially occluded stimuli, in which the brick wall covered 25% of the target shapes; erased stimuli, which revealed the same area of the target objects as the partially occluded stimuli, but without the occluder touching the objects; on-top stimuli, in which the shapes were placed on top of the occluder; and notched stimuli, which were created in the same way as the on-top stimuli, but with a thin gap between the shapes and the occluder.
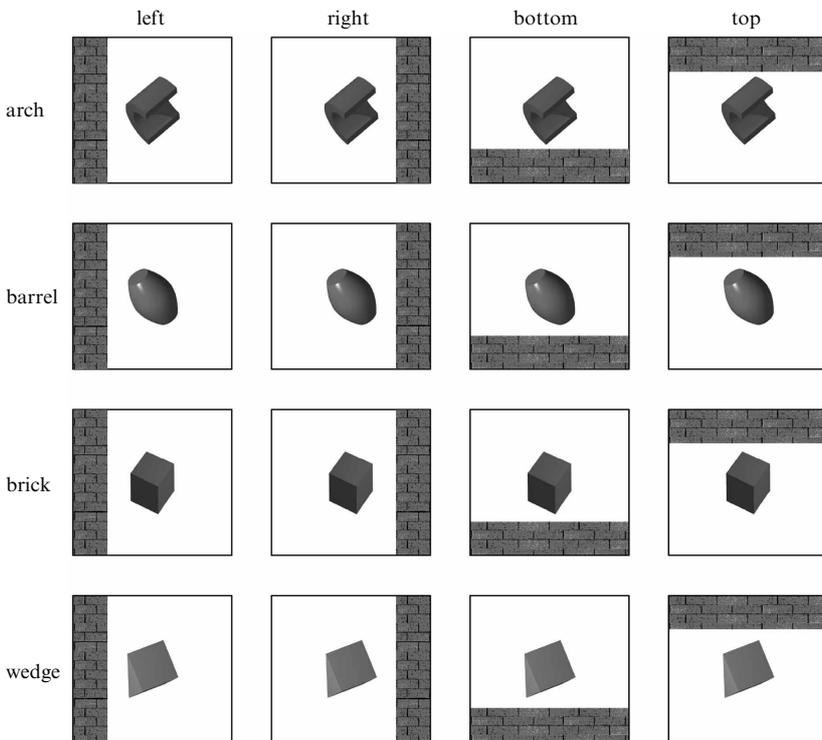

Figure 1. The set of original training stimuli. The four target shapes are shown in the rows and the four possible positions of the wall are shown in the columns.

As figure 2 illustrates, 100% of the training shape was available for viewing in the on-top and notched stimuli, whereas only 75% of the training shape was available for viewing in the occluded and erased stimuli. Surprisingly, the erased and notched stimuli supported the best discrimination performance, whereas the on-top and occluded stimuli supported the worst discrimination performance (DiPietro et al 2002). In follow-up
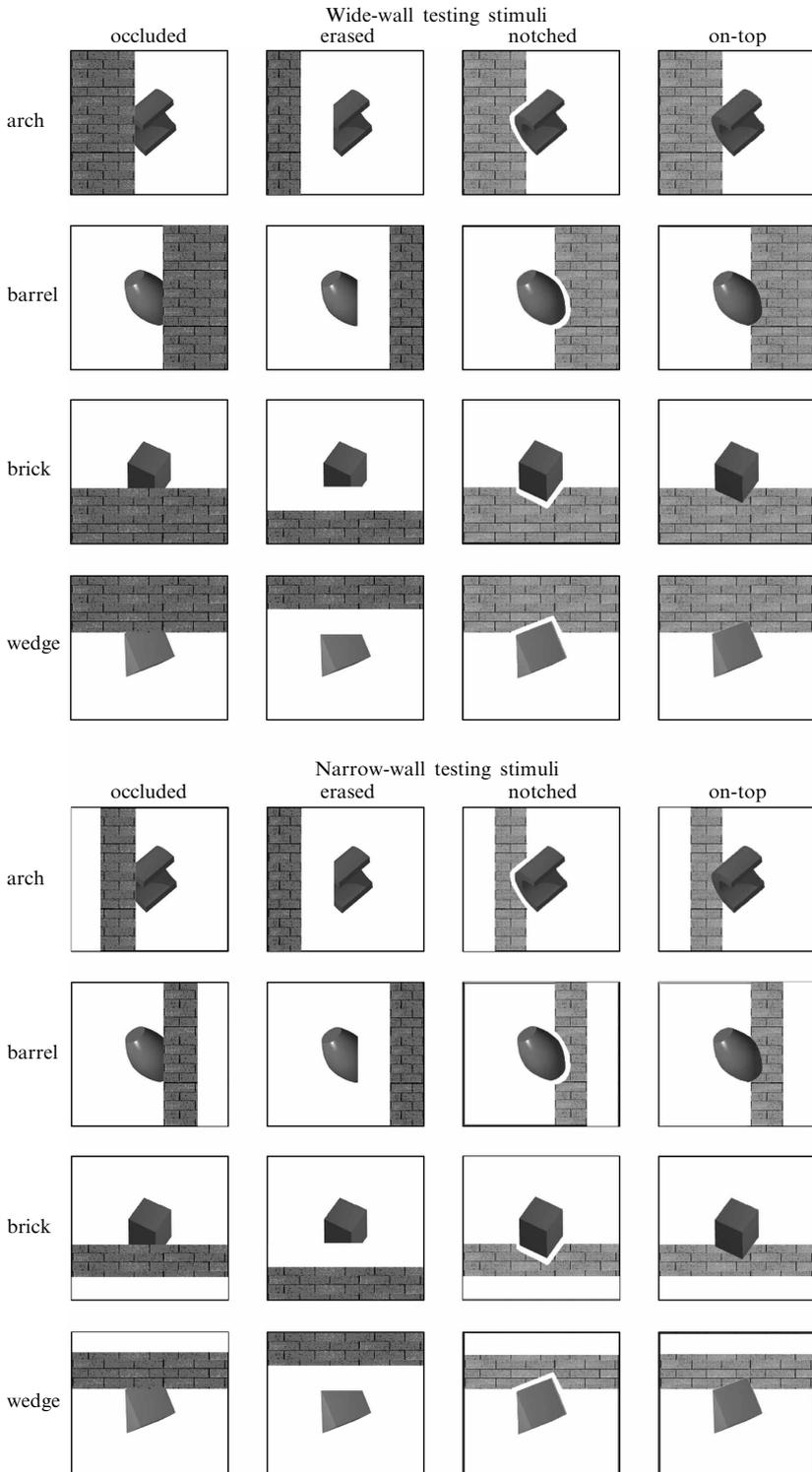
Figure 2. A subset of the wide-wall testing stimuli used by DiPietro et al (2002) and a subset of the narrow-wall stimuli created for experiment 1. The four target shapes are shown in the rows and the four stimulus types are shown in the columns; although the wall could appear in all four locations, only a subset of the possibilities is shown here.

experiments, DiPietro et al retrained pigeons to discriminate the arch, barrel, brick, and wedge placed on top of the occluder, and then retested them with the occluded, erased, and notched stimuli. On-top training dramatically improved pigeons' recognition of the occluded stimuli, from 55% to 90% correct. This improvement even transferred to a set of four novel shapes—claw, cone, cylinder, and noodle—that had not undergone on-top training.

Why did on-top training so dramatically improve the pigeons' visual recognition performance? DiPietro et al (2002) suggested that the pigeons' lackluster initial recognition of the occluded objects could be explained by their difficulty in segregating 2-D objects that appear in close proximity to each other: the target object and the occluding surface. On-top training might have taught the birds to better segregate the object from the occluder in the 2-D visual world of the Skinner box.

Nevertheless, other alternative explanations could account for these results. First, only the erased stimuli of DiPietro et al retained the occluder at its original width; the notched, on-top, and occluded stimuli featured a wider occluder (see the upper panel of figure 2). Although the width of occluder alone is unlikely to explain all of the results of DiPietro et al, it may still contribute to the pattern of responding to the occluded, erased, notched, and on-top stimuli observed before on-top training. Second, on-top training may have taught the pigeons to ignore the brick wall that was located near the object or to attend to those specific parts of the shapes that did not overlap with the occluder, instead of teaching them to segregate the target shape from the occluder. The prime aim of the current project was to investigate these alternative explanations.

In all three of the present experiments, we used the same visual stimuli (arch, barrel, brick, and wedge) and training procedure (four-alternative forced-choice task) as DiPietro et al. In experiment 1, we examined the possibility that the width of the occluder contributed to the pigeons' testing performance by exploring whether pigeons would exhibit the same pattern of performance when they were tested with an occluder whose width was the same as that used in original training. For this purpose, we used the two sets of stimuli (wide wall and narrow wall) that are depicted in figure 2.

In experiment 2, we investigated the possibility that training with on-top stimuli taught the pigeons to attend to those specific portions of the shapes that extended beyond the occluding wall by training pigeons to discriminate the erased stimuli. If the improved performance that was reported by DiPietro et al after on-top training was produced by the pigeons' reallocation of attention to particular portions of the target shapes, then we would expect similar improvements after erased training.

Finally, on-top training might have taught the pigeons to ignore the occluder when it was placed in closed proximity to a target shape. If so, then we would expect that training pigeons to discriminate the notched stimuli should have the same felicitous effect on birds' recognition of occluded shapes. This possibility was explored in experiment 3.

2 Experiment 1
In the first experiment, we explored whether the width of the nearby wall affects pigeons' discrimination of the occluded, erased, on-top, and notched stimuli. The pigeons were first trained to discriminate the arch, barrel, brick, and wedge shown in figure 1 by selecting one of four different report buttons for each shape. After the pigeons had learned the task, they were presented with the stimuli shown in figure 2. The upper panel of figure 2 portrays the same testing stimuli as were used by DiPietro et al, in which the brick wall was widened to create the occluded, notched, and on-top testing stimuli (wide-wall stimuli). The lower panel of figure 2 portrays the new set of testing stimuli, in which the brick wall retained the same width as in training for all four types of testing stimuli (narrow-wall stimuli). If the width of the wall exerts no effect

on pigeons' recognition of the testing images, then we should see the same pattern of recognition performance as that reported by DiPietro et al for both the wide-wall and narrow-wall stimuli: namely, better recognition of the erased and notched stimuli compared to the occluded and on-top stimuli. If the width of the wall does participate in pigeons' recognition of the testing images, then we should see a different pattern of recognition performance from that reported by DiPietro et al for the wide-wall and narrow-wall testing stimuli.

2.1 *Method*

2.1.1 *Subjects.* The subjects were four feral pigeons (*Columba livia*) maintained at 85% of their free-feeding weights by controlled daily feeding. Grit and water were available ad libitum in their home cages. All of the pigeons had previously participated in unrelated experiments.

2.1.2 *Apparatus.* The experiment used four operant conditioning chambers and four Macintosh computers (detailed by Wasserman et al 1995). One wall of each chamber contained a large opening with a frame attached to the outside that held a clear touch screen. An aluminum panel in front of the touch screen allowed the pigeons to access a circumscribed portion of a video monitor behind the touch screen. There were five openings or buttons in the panel: a 7 cm × 7 cm square central display area in which the stimuli appeared and four round report areas (1.9 cm diameter) located 2.3 cm from each of the four corners of the central opening. A food cup was centered on the rear wall level with the floor. A food dispenser delivered 45 mg food pellets through a vinyl tube into the cup. A house light mounted on the rear wall of the chamber provided illumination during sessions.

2.1.3 *Stimuli.* Figure 1 shows the gray-scale geon training stimuli: the arch, barrel, brick, and wedge (detailed by DiPietro et al 2002). The stimuli differed from one another by several non-accidental properties: curvature, collinearity, symmetry, parallelism, and cotermination (Biederman 1987).

Figure 1 illustrates that the training stimuli included a red-brick wall that could be located at the left, right, top, or bottom of the geons (or target stimuli); but the wall did not occlude the geons. The testing stimuli involved four different modifications of the target stimuli that either widened the wall so that it could occlude 25% of the target geon (wide-wall stimuli) or that displaced the same-width wall in order to occlude 25% of the target geon (narrow-wall stimuli).

The first column of figure 2 depicts a sampling of occlusions from both the wide-wall and narrow-wall conditions, in which the red-brick wall has occluded 25% of the target geon. The second column of figure 2 depicts a sampling of the erased stimuli that showed the same portion of the target geons as the occluded stimuli, but without the occluder touching the object; here, the wide-wall and narrow-wall conditions were identical. The third column of figure 2 depicts the notched stimuli that were created by pasting the target geon on top of the wall in the same location as it would have been if it were placed behind the wall in the occluded condition and by inserting a thin white gap between the target geon and the red-brick wall. Finally, the fourth column of figure 2 depicts the on-top stimuli that were created just as the notched stimuli, but without the white gap between the geon and the occluder. Stimuli in this last condition simply reversed the front–back locations of the target geons and the red-brick wall. All of the stimuli were prepared in Deneba artWORKS℗ (Deneba Software, Inc.) and were saved as PICT files.

2.1.4 *Procedure. Pretraining.* Following weight reduction, pigeons began pretraining, in which they were required to peck at the center button and at the four side buttons for food reinforcement.

Training. After pretraining, the birds entered the training phase, in which their task was four-alternative forced-choice 'naming' of the four geons that we had chosen for theoretical distinctiveness. At the beginning of a training trial, the pigeons were shown a black cross in the center of the white display screen. Following one peck anywhere on the screen, the training stimulus appeared and a series of pecks (observing responses) was required. The observing-response requirement varied from bird to bird and ranged from 15 to 53 pecks; this requirement was individually adjusted on the basis of the performance of the pigeon. If a bird failed to complete a session owing to a high fixed-ratio requirement, then the peck requirement was decreased. If the bird was pecking but not meeting criterion in a timely fashion, then the peck requirement was increased to make failures more punishing. After completing the observing-response requirement, four report buttons were illuminated and the pigeon was required to make a single report response to one of the four choice buttons. The assignment of four choice keys to each object was counterbalanced across the birds.

If the response was correct, then food was delivered and the intertrial interval (ITI) ensued, randomly ranging from 5 to 10 s. If the response was incorrect, then the house light and the screen darkened and a correction trial was given. On correction trials, the ITI randomly ranged from 25 to 35 s in duration. Correction trials continued to be given until the correct response was made. Only the first report response was scored in data analysis. During training, each session comprised 160 trials composed of 5 blocks of 32 trials; each of the 16 training stimuli in figure 1 was presented 10 times per session (total 160 trials per session).

The pigeons were required to meet an 85/80 criterion: 85% correct overall and 80% correct to each geon. The selected criterion had to be maintained during testing; if a bird's discrimination performance fell below criterion, then the bird was returned to training until it once again reached criterion.

Testing. During testing, we presented occluded, erased, notched, and on-top arches, barrels, bricks, and wedges (see figure 2) on a small number (32) of probe trials. Because there were 64 testing stimuli (4 geons $\times$ 4 wall locations $\times$ 4 stimulus types) with the wide-wall and another 64 testing stimuli with the narrow-wall, but only 32 testing stimuli could be presented each day, the test had to be given in four parts. Parts 1 and 2 involved wide-wall testing stimuli, whereas parts 3 and 4 involved narrow-wall testing stimuli. Testing lasted for 20 days in order for the pigeons to receive 5 exposures to each testing stimulus.

During testing sessions, the pigeons received 192 trials per day, composed of five blocks. The first block of 32 trials (warm-ups) comprised all 16 training stimuli, each seen twice. Warm-up trials were not included in the statistical analysis. The second through fifth blocks contained a mixture of training and testing stimuli. Each block included 32 training stimuli and 8 testing stimuli, so that the pigeons received 10 presentations of each training stimulus (figure 1) per day and 1 presentation of each testing stimulus (figure 2) per day (with only wide-wall or narrow-wall testing stimuli shown in any given session).

The pigeons reported the identity of the presented objects by pecking at one of the four choice buttons. For the training stimuli, the birds received reinforcement only for a correct response; incorrect responses led to one or more correction trials (differential reinforcement). For the testing stimuli, the birds received reinforcement for all responses (nondifferential reinforcement). α was set to 0.05 for all statistical tests.

2.2 *Results and discussion*

The birds took a mean of 23.3 days to reach the discrimination criterion, with a minimum of 6 days and a maximum of 51 days.[1] The testing results are shown in figure 3. We found the same pattern of test responding as had DiPietro et al: the pigeons most accurately discriminated the erased and notched stimuli, whereas they evidenced poorer discrimination of the occluded and on-top stimuli. The birds performed at levels reliably above chance to all of the testing images (two-tailed *t*-test, $t \geqslant 21.2$). More importantly, they responded virtually identically during the wide-wall tests and the narrow-wall tests.
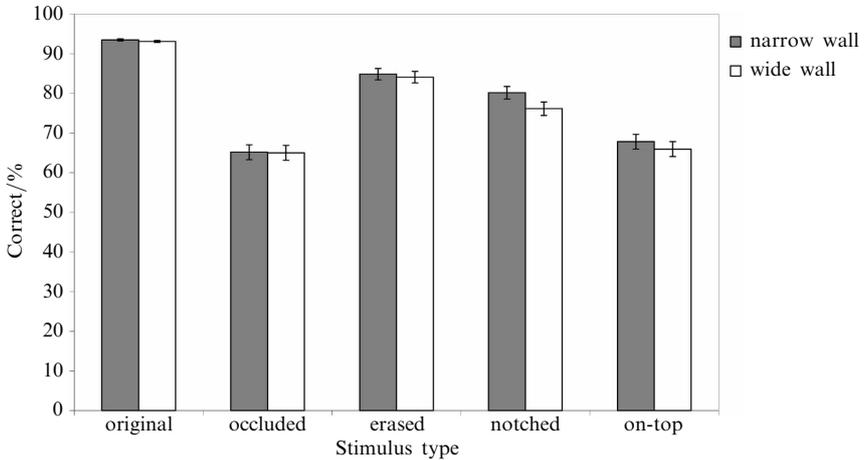

Figure 3. Results of experiment 1. Recognition of occluded, erased, notched, and on-top objects during narrow-wall and wide-wall tests. The bars represent ± 1 SEM for each stimulus condition.

A repeated-measures analysis of variance (ANOVA) with wall width (2) and stimulus type (5) as factors supported these observations. We found no significant main effect of wall width ($F_{1,3} = 1.28$, $p = 0.34$) nor a significant stimulus type × wall width interaction ($F < 1$), indicating that the birds' performance was not affected by the differences in wall width. We did find a significant main effect of stimulus type ($F_{4,12} = 31.86$), as we expected on the basis of our earlier experiments. Planned comparisons following this effect revealed that the birds discriminated the occluded and on-top stimuli at the same level ($t_3 < 1$) and they did so significantly less accurately than either the notched or erased stimuli ($t_3 \geqslant 2.33$), which did not differ ($t_3 = 1.31$, $p = 0.22$).

Experiment 1 thus provided strong evidence that any differential responding to the occluded, erased, notched, and on-top testing stimuli could not be explained by disparities in the width of the wall in the training and testing displays (compare the training stimuli shown in figure 1 with the testing stimuli shown in the upper and lower portions of figure 2). We also replicated the pattern of responding obtained by DiPietro et al, again finding that presenting full versions of the target geons was no guarantee of pigeons' accurately recognizing them. The on-top stimuli (which depicted the full geons) were as modestly recognized as the occluded stimuli (which removed 25% of the geons' area), and the notched stimuli (which depicted the full geons) were no better recognized than the erased stimuli (which removed 25% of the geons' area).

We next explored whether teaching the pigeons to attend to specific areas of the stimulus image could improve their recognition of the occluded stimuli.

[1] Because of an experimental error, the pigeons in this experiment continued to be trained after they reached criterion (a mean of 98.8 sessions, with a minimum of 93 sessions and a maximum of 106 sessions). However, this prolonged training did not appear to alter the pattern of responding to occluded, erased, notched, and on-top stimuli (see text).

3 Experiment 2

One might hypothesize that on-top training enhanced the recognition of partially occluded objects by teaching pigeons to ignore those portions of the target geons that were covered by the brick wall in the occluded testing stimuli and to attend selectively to those portions of the target geons that extended beyond the occluder and that were never covered in the occluded testing stimuli. Recall that the on-top images were created by placing the target geons in the same location as in the occluded images; thus, teaching pigeons to re-allocate their attention while recognizing the on-top images might improve their recognition of the occluded images. Indeed, because we used 25% occlusion, certain parts of the target shape were never occluded even though the brick wall could be placed on the top, on the bottom, on the left, or on the right portions of the target shapes.

Figure 4 shows the four training geons with the future occluded areas brightened; the central, darker areas are those portions of the target geons that were never occluded, placed on top of the brick wall, or erased. The darkened areas appear to reveal enough object-specific information to discriminate the four different target shapes from one another, suggesting that reallocation of attention is a plausible explanation for improved recognition of occluded objects by pigeons after on-top training.
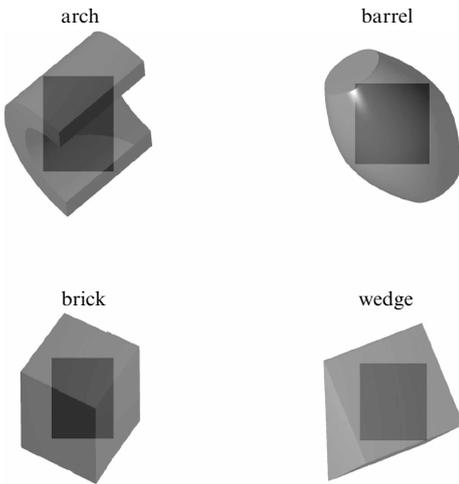

arch   barrel

brick   wedge

Figure 4. The four training shapes with the lightened regions representing those areas that could be covered by the brick wall, placed on top of the brick wall, or erased altogether. The darker central, rectangular areas are those portions of the target shapes that were available for viewing on all of the testing images.

If this attentional hypothesis were true, then we would expect erased training to improve recognition of occluded objects by pigeons in much the same way as had on-top training in DiPietro et al. Erased training ought to teach the pigeons to recognize the target shapes by attending to those central regions of the geons that were never erased. However, erased training cannot teach pigeons either to ignore the occluder or to segregate the target shape from the occluder when it is placed in close proximity to the target shape. By its very nature, an erased stimulus places the target geon at a considerable distance from the brick wall. Given this analysis, experiment 2 explored the effects, if any, of erased training on pigeons' object-recognition performance.

3.1 Method

3.1.1 *Subjects.* The subjects were four new feral pigeons housed and maintained as described above.

3.1.2 *Apparatus and stimuli.* The same apparatus and stimuli were used as in experiment 1.

3.1.3 *Procedure. Original training and testing.* The training and testing procedures were identical to those in experiment 1, except that only the wide-wall stimuli were used during testing (see the upper portion of figure 2).

Erased training. The procedure was similar to that of experiment 2 in DiPietro et al (2002), in which the pigeons were trained to discriminate the on-top stimuli. Here, however, we trained the pigeons to discriminate the erased stimuli by adding them to the set of original training stimuli.

Each training session included 3 blocks comprising 32 original training stimuli and 32 erased stimuli (total of 192 trials). All trials were differentially reinforced. Pigeons were required to meet the 80/85 criterion before they could proceed to the testing (85% overall percent correct on all of the training stimuli and 80% correct on each individual geon).

Testing. After reaching criterion, the pigeons proceeded to testing. Because the erased stimuli were included in the training set, the number of presentations of each training stimulus was reduced to five per day to keep the total number of trials the same as in experiment 1. Testing sessions comprised an initial block of 32 warm-up trials and four blocks of 16 training stimuli, 16 erased stimuli, and 8 nondifferentially reinforced testing trials. Each session contained one half of the complete collection of 64 testing stimuli. Testing lasted for 20 days.

3.2 *Results*

Acquisition of the original object 'naming' task took a mean of 21.5 sessions, with a minimum of 9 sessions and a maximum of 34 sessions. Additional training with the erased stimuli took a mean of 10.3 sessions (range: 1 to 20). It might appear that, because discrimination performance with the erased images was quite high even before erased training, erased training might have been too short to have any beneficial impact. However, some birds did take as many as 20 sessions to reach criterion during erased training. As well, the mean number of sessions to criterion in erased training was comparable to the other conditions (see, for example, section 4.2). We will return to this notion in section 5.

Figure 5 shows that the birds discriminated all of the testing stimuli at above chance levels (two-tailed *t*-test, $t \geqslant 13.16$) both before and after erased training. Not surprisingly, erased training led to improved discrimination of the erased stimuli by 6.5%. Given that performance to the on-top and notched stimuli before erased training was only 73.1% and 65.0%, respectively, any potential rise in discrimination performance
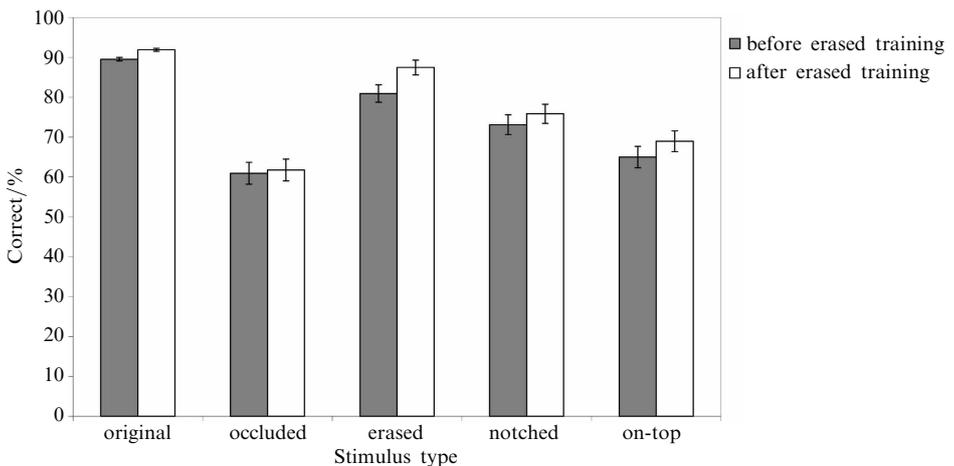

Figure 5. Results of experiment 2. Recognition of occluded, erased, notched, and on-top objects both before and after erased training. The bars represent ±1 SEM for each stimulus condition.

to these stimuli was unlikely to be limited by a ceiling effect. Nevertheless, discrimination of both the on-top and notched stimuli increased by less than 4%, suggesting that erased training truly had little or no effect on recognition of the notched geons or geons placed on top of the occluder. Recognition of the occluded stimuli remained essentially unchanged (a less than 1% increase) after erased training.

A repeated-measures ANOVA found a significant main effect of stimulus type ($F_{4, 12} = 24.09$), but no significant main effect of test ($F_{1, 3} = 1.77$, $p = 0.27$), and no significant stimulus type × test interaction ($F < 1$). These results suggest that the same pattern of responding to the different types of testing stimuli was observed both before and after erased training, a pattern of responding that closely resembled that in experiment 1 and in DiPietro et al. Planned comparisons following stimulus type × test interaction indicated that performance to the erased stimuli improved significantly after erased training ($t_3 = 2.24$, $p < 0.05$), but that performance to the occluded, notched (both ts < 1), and on-top stimuli ($t_3 = 1.36$, $p = 0.20$) remained unchanged.

Clearly, erased training did not generally enhance pigeons' recognition performance as did on-top training in DiPietro et al. Thus, on-top training probably did not teach the pigeons to reallocate their visual attention and to better recognize those parts of the target shapes that were never covered by or placed on top of the occluder.

4 Experiment 3

It is possible that on-top training teaches pigeons to ignore the brick wall when it is placed in close proximity to the target shape. If that were the case, then we would expect notched training to improve pigeons' recognition of occluded objects much as does on-top training. However, notched training cannot teach pigeons to better segregate the target shape from the occluder because here, unlike on-top training, the target shape and the occluder never meet, let alone overlap.

Experiment 3 explored this issue by giving pigeons notched training after first testing them after our standard training regimen.

4.1 Method

4.1.1 *Subjects.* The subjects were four new feral pigeons housed and maintained as described in the first two experiments.

4.1.2 *Apparatus and stimuli.* The same apparatus and stimuli as in experiment 1 were used. We also used a second set of target stimuli comprising four new geons: claw, cone, cylinder, and noodle (figure 6), each portrayed along with the same red-brick wall given with the previous set of target stimuli. The same two sets of stimuli had been used to assess the generality of geon recognition after on-top training by DiPietro et al.

4.1.3 *Procedure. Original training and testing.* The training and testing procedure was identical to that in experiment 2.
Notched training and testing. This procedure was similar to erased training and testing in experiment 2, except that the set of notched stimuli was added to the set of original training stimuli.
Novel-object training. The pigeons were trained to recognize four novel, full-view shapes (claw, cone, cylinder, and noodle) with the same training procedure as in experiment 1. Training continued until the birds reached the criterion of 85/80 (85% overall and 80% to each geon). Note that notched training was not conducted with these stimuli.
Novel object transfer testing. After reaching criterion, the birds progressed to testing. As in experiment 1, each day of testing involved 32 nondifferentially reinforced testing trials randomly interspersed among 160 training trials. The birds received 10 presentations each of 16 training stimuli per day. Because there were again 64 testing stimuli,
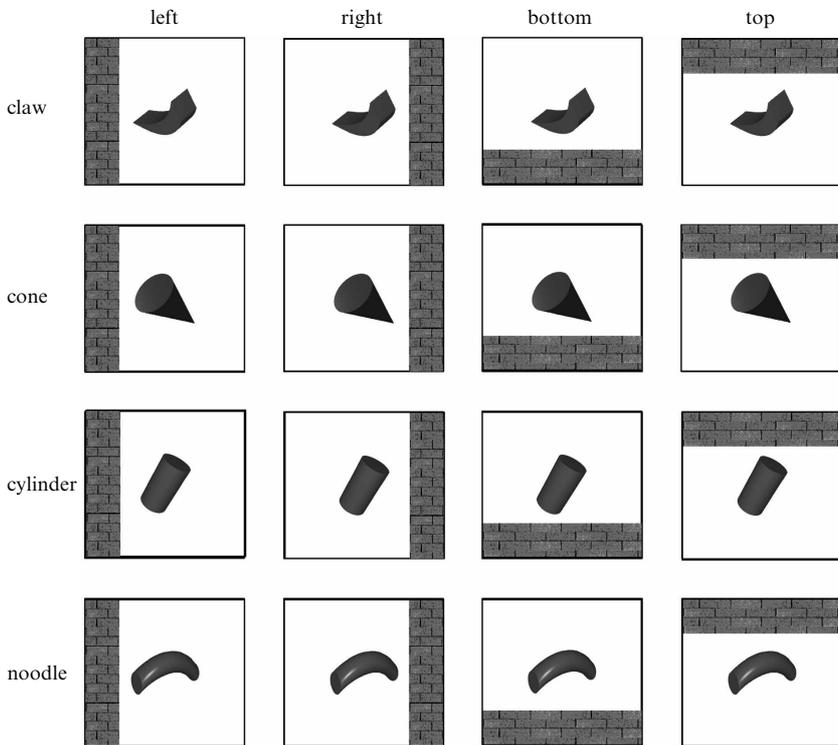
Figure 6. A subset of the novel shapes used in experiment 3. The four shapes are shown in the columns and the four wall locations are shown in the rows.

32 were presented on each day, so that half of a test was presented in each testing session; 10 such sessions were required to allow the pigeons to receive five presentations of each stimulus.

4.2 Results and discussion

Acquisition of the original 'naming' task required a mean of 8 sessions, with a minimum of 4 sessions and a maximum of 17 sessions. Additional training with the notched stimuli required a mean of 7 sessions (range: 2 to 15) and training with novel objects (cylinder, cone, claw, and noodle) took a mean of 5 sessions (range: 3 to 8).

Figure 7 depicts pigeons' performance before notched training, after notched training, and in the novel-object transfer test. Unlike erased training in experiment 2, notched training prompted a dramatic increase in pigeons' recognition of occluded objects (from 55.8% to 78.6%) and on-top objects (from 67.7% to 84.8%), reminiscent of the effect of on-top training reported by DiPietro et al. But, unlike on-top training, the benefits of notched training did not transfer to novel objects. Recognition of the novel occluded, notched, and on-top objects was virtually identical to pigeons' performance before notched training.

A repeated-measures ANOVA with stimulus type and test as factors found that both main effects and their interaction were significant ($Fs \geqslant 11.14$). Planned comparisons following stimulus type $\times$ test interaction confirmed that pigeons' recognition of notched, occluded, and on-top stimuli before notched training and in the novel-object transfer test did not differ significantly (all $ts < 1$). Pigeons' recognition of occluded, notched, and on-top stimuli was significantly higher after notched training than before notched training as well as in the novel-object transfer test ($t_3 \geqslant 4.59$); and pigeons' recognition of the erased stimuli did not differ in any of the tests (all $ts < 1$).
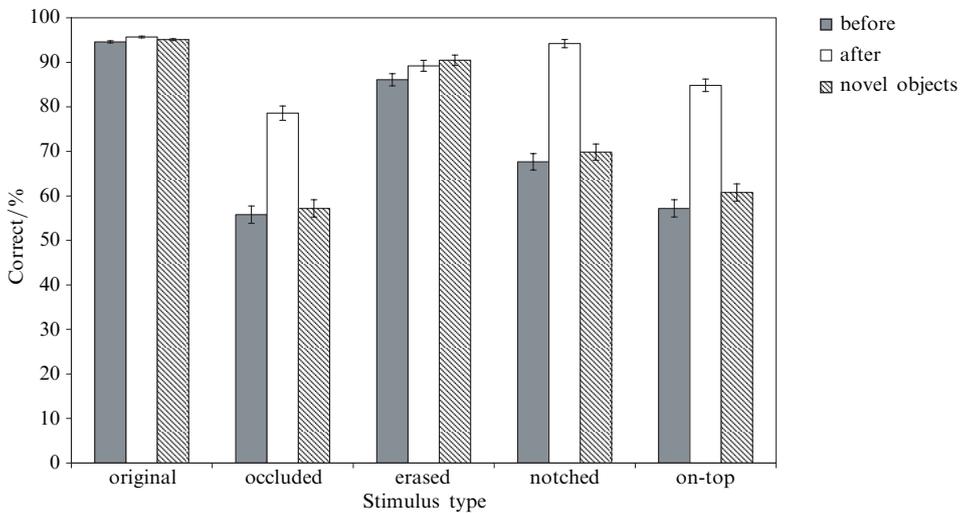
Figure 7. Results of experiment 3. Recognition of occluded, erased, notched, and on-top objects before and after erased training and transfer to novel objects. Note that the novel objects did not undergo the additional notched training. The bars represent ±1 SEM for each stimulus condition.

5 General discussion

In the present trio of experiments, we explored the role of several different factors on pigeons' recognition of partially occluded objects. The experiments were inspired by two earlier observations (DiPietro et al 2002). First, we previously found that on-top stimuli (which depicted complete geons) were as modestly recognized as occluded stimuli (which lacked 25% of the geons' area), whereas notched stimuli (which depicted complete geons) were no better recognized than erased stimuli (which lacked 25% of the geons' area). This pattern of performance suggests that pigeons' modest recognition of occluded images cannot be explained by the mere removal of 25% of the geons' area. Second, we previously found that, after they had been given discrimination training with the four target objects on top of the brick wall, pigeons' recognition performance improved dramatically to those target objects when they were partially occluded by the wall as well as to four other target objects that had not been used in on-top training, when they too were partially occluded by the wall. This pattern of performance suggests that specific prior experience with 2-D images may have a profound general effect on pigeons' later recognition of partially occluded objects. Still, several alternative explanations were available for these results, and our current experiments evaluated those explanations.

First, we examined whether the different widths of the occluding wall surface in the training and testing stimuli (cf figures 1 and 2) contributed to the pigeons' pattern of responding to the occluded, notched, on-top, and erased stimuli. But, we found that the width of the red-brick wall did not affect pigeons' superior recognition of erased stimuli compared to the occluded and notched stimuli.

In experiment 2, we examined whether teaching pigeons to reallocate their attention to specific portions of the geons (cf figure 4), by explicitly training them to recognize erased images of the target shapes, would enhance their recognition of occluded target shapes. We found that this attentional hypothesis was an unlikely explanation of the results of DiPietro et al, as erased training had no effect on pigeons' recognition of occluded target shapes.

It might be argued that, because discrimination accuracy to erased stimuli was quite high even before erased training, the birds might have reached criterion so quickly that any potential benefit of erased training did not have time to accumulate.

However, the mean number of sessions to criterion for erased (10.0 ± 4.9 sessions) and notched (7.0 ± 2.5 sessions) training suggests that this explanation is unlikely to be true, as erased training (which had no effect on pigeons' recognition of occluded stimuli) actually took longer on average than did notched training (which did improve pigeons' recognition of occluded stimuli). To pursue this point even farther, we computed the Spearman's correlation coefficient between the number of sessions to criterion and accuracy to occluded images for erased training, notched training, and on-top training reported in DiPietro et al. Although the resulting correlation was positive, it was quite small and it failed to reach statistical significance ($r_S = 0.11$, $n = 12$, $p = 0.74$), suggesting that the length of additional training did not contribute significantly to the recognition of occluded images. It appears, therefore, that the nature, rather than the length, of the additional training affected the birds' recognition of occluded images.

Finally, in experiment 3, we trained pigeons to recognize notched images of the target shapes. Notched training might effectively teach pigeons to ignore the brick wall when it is placed in close proximity to the target shape. However, notched training cannot teach pigeons to better segregate the target shape from the occluder because here, unlike on-top training, the target shape and the occluder never meet. We found that notched training did dramatically improve pigeons' recognition of the occluded target geons. Yet, this improvement did not transfer to a second set of geons that were not involved in notched training; such transfer had been obtained after on-top training by DiPietro et al. Apparently, on-top training has more profound effects on pigeons' recognition of occluded objects than does notched training (DiPietro et al 2002).

Clearly, erased training and notched training do not produce the same effects on pigeons' recognition of partially occluded objects as does on-top training (DiPietro et al 2002). Figure 8 graphically compares pigeons' performance in our present experiments with the data from DiPietro et al. As figure 8a demonstrates, all of our present experiments replicated the pattern found in the earlier report, the recognition of erased and notched stimuli being superior to that of occluded and on-top stimuli.

We next compared these data statistically; because of issues surrounding cross-experiment comparison, interpreting these analyses should be done with caution. An ANOVA with experiment (4, 4 birds in each experiment) and stimulus type (5) as factors found a significant main effect of stimulus type ($F_{4, 48} = 30.66$), but no significant main effect of experiment ($F_{3, 12} = 1.62$, $p = 0.19$) or stimulus type × experiment interaction ($F < 1$), confirming that the pattern of discrimination of occluded, erased, notched, and on-top images did not differ from experiment to experiment.

Figure 8b depicts the effects of additional on-top, erased, and notched training on pigeons' recognition of occluded stimuli. Unlike erased training, on-top training and notched training clearly improved recognition of occluded stimuli. Both main effects of stimulus type (5) and experiment (3) and their interaction were significant ($Fs \geqslant 2.98$), confirming this observation. Planned comparisons following stimulus type × experiment interaction revealed that performance to occluded, notched, and on-top stimuli after erased training (experiment 2) was significantly lower ($t_9 \geqslant -2.90$) than after on-top training (DiPietro et al) or notched training (experiment 3), whereas performance to erased stimuli did not differ in all three experiments (all $ts < 1$). Moreover, discrimination accuracy of occluded stimuli after on-top training and after notched training did not differ significantly ($t_9 = -1.57$, $p = 0.12$), indicating that on-top training and notched training had comparable beneficial effects on object recognition.

Figure 8c suggests that, unlike on-top training, the benefits of notched training did not transfer to novel stimuli. Here again, ANOVA found that main effects of stimulus type (5) and experiment (2) were significant ($Fs \geqslant 9.44$), indicating that, on average, pigeons responded less accurately after notched training than after on-top training.
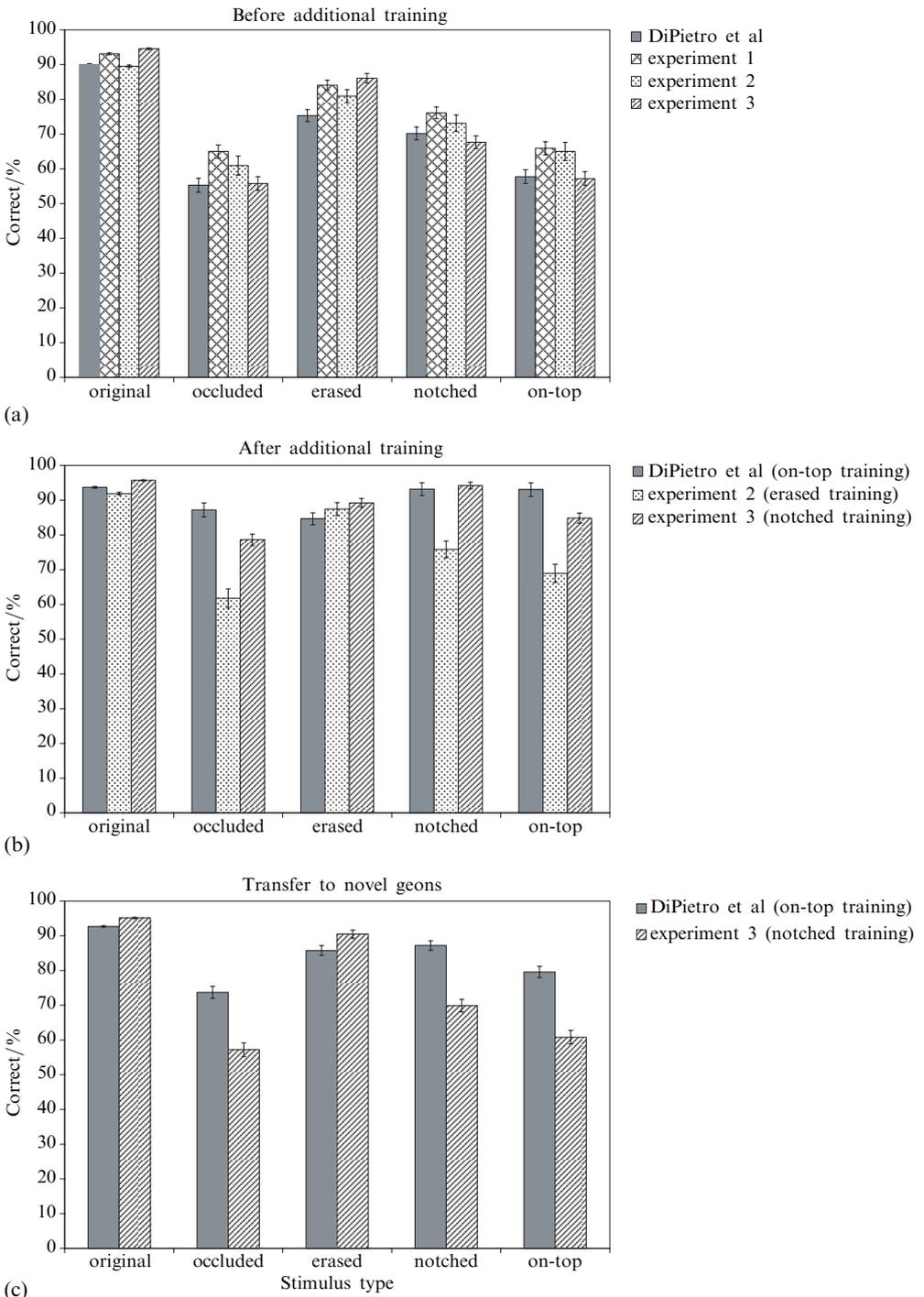
(a)

(b)

(c)

Figure 8. Effects of different types of additional training on pigeons' recognition of occluded, erased, on-top, and notched objects. Panel (a) shows pigeons' responding to the testing geons before any additional training has occurred. The experiment 1 data are from the wide-wall condition. Panel (b) shows pigeons' responding to the testing geons after on-top training (DiPietro et al 2002), erased training (experiment 2), and notched training (experiment 3). Panel (c) shows pigeons' transfer to the novel objects after on-top training (DiPietro et al 2002) and notched training (experiment 3).

The ANOVA also found a significant stimulus type × experiment interaction ($F_{4, 24} = 2.92$), revealing different patterns of performance after notched training and after on-top training. Planned comparisons indicated that transfer to novel occluded, notched, and on-top stimuli after on-top training was significantly higher than after notched training ($t_6 \geqslant 2.46$), whereas transfer to novel erased stimuli did not differ ($t_6 < 1$). This pattern of results is consistent with the suggestion made by DiPietro et al that on-top training enhances pigeons' discrimination of different types of testing stimuli, including those that were not involved in special training. In other words, training to recognize one set of objects placed on top of the occluder benefits recognition of other sets of objects as well. Our data suggest that notched training does not produce a comparable benefit.

What might be responsible for the particularly beneficial effects of on-top training? One good possibility is that on-top training teaches pigeons to better segregate the target objects from the occluding surface. If that is indeed the case, then we might expect other kinds of visual experiences—such as moving the occluder independently of the object or showing the target shape and the occluder on a background with depth cues—might be as beneficial as on-top training. Future experiments will explore these and other possibilities.

Whatever those investigations may yield, the present results and those of DiPietro et al suggest that pigeons can recognize partially occluded objects in a 2-D environment if they are given sufficient training to separate the prevailing foreground and background cues. Studies of infants' perception of partially occluded objects suggest that even humans may not immediately recognize partially occluded 2-D images; instead, this tendency may emerge during the first few months of life, possibly owing to multiple exposures to occluded stimuli and training to recognize the objects in question (Johnson 2003; Kellman and Spelke 1983; Slater et al 1990). Similarly, pigeons placed in the laboratory world of 2-D images may require additional experience before they can effectively cope with object occlusion.

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