

Effects of Varying Stimulus Size on Object Recognition in Pigeons

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The authors investigated the pigeon's ability to generalize object discrimination performance to smaller and larger versions of trained objects. In Experiment 1, they taught pigeons with line drawings of multipart objects and later tested the birds with both larger and smaller drawings. The pigeons exhibited significant generalization to new sizes, although they did show systematic performance decrements as the new size deviated from the original. In Experiment 2, the authors tested both linear and exponential size changes of computer-rendered basic shapes to determine which size transformation produced equivalent performance for size increases and decreases. Performance was more consistent with logarithmic than with linear scaling of size. This finding was supported in Experiment 3. Overall, the experiments suggest that the pigeon encodes size as a feature of objects and that the representation of size is most likely logarithmic.

Keywords: object recognition, size invariance, pigeon (*Columba livia*), vision, learning

The recognition of an object is a remarkable feat of the visual system. Objects must be recognized from different angles, at various positions in the visual field, under different lighting conditions, and from a considerable range of distances. Despite these many variations, a well-functioning visual system should be able to map the diverse retinal images created by any given object to the same neural representation.

The study of the mechanisms by which humans achieve shape equivalence over variations in size has yielded two rival hypotheses. The first is that the internal stored representations used for recognition include information encoding the absolute size properties of an object (Bundesen & Larsen, 1975; Larsen & Bundesen, 1978). Consequently, later encounters with the object projecting different retinal sizes should require some transformation for accurate recognition. Performing a transformation requires time;

therefore, recognition times should be longer when the object is viewed at a novel size than when it is viewed at a familiar size. To evaluate this hypothesis, Bundesen and Larsen required people to report whether two serially presented objects were the same as or different from one another; these researchers found longer reaction times when object size changed across the two presentations than when size was constant. Jolicoeur (1987) also reported increases in reaction times for size changes in an old–new task. For these studies, then, the results indicated that object representations encoded the size of the object; such encoding was true of both novel (Bundesen & Larsen, 1975) and familiar objects (Jolicoeur, 1987).

In contrast, Cooper, Biederman, and Hummel (1992) proposed that metric properties, such as size, are not encoded as a part of the representation used for the identification of objects; instead, they posited that an encounter with an object produces two types of representations. One is size invariant; this representation mediates perceptual facilitation, as indexed by name priming. The second is an episodic representation that binds the invariant representation of shape with view variables, such as the object's size, position, and orientation, to form an episode; this representation mediates old–new judgments on the basis of familiarity. Consistent with this view, when Cooper et al. used a name priming task, they found no effect of size changes.

How do we reconcile these conflicting results? Biederman and Cooper (1992) proposed that the costs from size changes in object matching observed in the Bundesen and Larsen (1975) same–different matching experiment, in which there was a short (100-ms) interval between the stimuli, could have been a consequence of attentional adjustments to a particular scale rather than a result of a transformation of the shape itself. Larsen and Bundesen

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(1978) themselves allowed for this possibility. Consistent with this interpretation is the fact that, at a longer (2-s) interstimulus interval, there were no longer any effects of size changes. Fiser, Subramaniam, and Biederman (2001) added evidence to this perspective by showing that attentional adjustments to different sizes could be accomplished in (well) under 576 ms. These data suggest that, for normal recognition tasks, size is not encoded.

Ashbridge, Perrett, Oram, and Jellema (2000) tested for size invariance in single cells of the object recognition area of rhesus macaques. They first recorded from 16 cells in the anterior part of the superior temporal sulcus that responded selectively to images of human forms; they later presented these images at several different sizes. Of the 16 cells tested, 3 exhibited the same level of activity to all four stimulus sizes. The remaining 13 cells showed the highest activity to the largest size and a systematically decreasing rate of activity as size was decreased. All four sizes evoked higher firing rates than control stimuli (random objects for which the cells were not selective). These results show that, at the level of a single cell, monkeys exhibited some size specificity, although there was considerable cellular responding to even the smallest stimuli. Still, these data do not address how a neuronal population might encode object shape under conditions in which the size of the object changes.

Sawamura, Georgieva, Vogels, Vanduffel, and Orban (2005) examined the functional MRI response for size changes in humans and monkeys, bridging the gap between human and animal studies. Using a functional MRI adaptation paradigm, they did not find complete size invariance for either humans or monkeys. However, they did find graded adaptation, which was greatest for the same size, intermediate for size changes, and lowest for different objects. These results indicate that the response rate of a cell population may specify a change in the shape's size. Sawamura et al.'s data also suggest that, except for extreme size changes, the response pattern of the neuronal population should still allow for object discrimination, even when the size of the object varies. Thus, these results suggest that, at the neural level, general changes in object size are encoded. Nevertheless, this encoding of object size may not be evidenced by costs in recognition performance.

Research with human and nonhuman primates therefore indicates that object size may be encoded at the neural level but that differences in neural activity need not eventuate in behavioral costs. Less is known about the object recognition behavior of other species. The present study thus focuses on the ability of pigeons to generalize their recognition behavior to new stimulus sizes. A thorough study of how pigeons respond to size changes may suggest evolutionary disparities between primates and avians. Likewise, similarities would suggest a common recognition mechanism shared by a number of species. In addition, we seek to determine what size transformations yield psychologically equivalent increases and decreases. These data may guide future studies testing neurally plausible algorithms. Although some previous research has examined size invariance in pigeons, these studies have been confined to simple stimuli that lack internal structure.

Size Invariance Studies in Pigeons

Several studies have explored the pigeon's visual recognition behavior as a function of stimulus size. Towe (1954) used a simultaneous discrimination task in which pigeons were shown a

square and a triangle. The birds were required to peck the triangle to receive reinforcement. The pigeons were then tested with several stimulus manipulations, including variations in size. Both the absolute and the relative sizes of the target and nontarget stimuli were manipulated, so that either the triangle and the square were both shown at large or small sizes or one shape was small and the other was large. The pigeons exhibited significant generalization of the discrimination despite size changes, but they also showed a preference for pecking at the larger stimulus, regardless of shape.

Jenkins, Pascal, and Walker (1958) trained pigeons using a 12-min aperiodic reinforcement schedule during which a 1.4-cm spot was projected onto the pecking window. The size changes consisted of three increases and three decreases in the sizes of the spots, yielding diameters of 0.2, 0.6, 1.0, 1.8, 2.2, and 2.6 cm (linear scaling with increments of 0.4 cm). The pigeons exhibited significant generalization over size changes, although there was a systematic decrease in the rate of pecking as testing size varied from training size. In addition, some pigeons exhibited better generalization to the largest size than to the smallest size.

Wildemann and Holland (1973) trained pigeons to peck a key whenever a spot of light 0.360 in. (0.914 cm) in diameter was shown. One group received training with the positive stimulus (S+) alone, two groups also received training with the S+ and a 0.290-in. (0.737-cm) spot of light as a negative stimulus (S-), and a fourth group received the S+ and a blackout procedure as an S-. Once the pigeons met criterion (responses to the S+ were 10 times greater than to the S-), they were shown 10 stimuli with various diameters, including the S+ and the S-: 0.185 (0.470 cm), 0.220 (0.559 cm), 0.255 (0.648 cm), 0.290 (0.737 cm), 0.325 (0.826 cm), 0.360 (0.914 cm), 0.395 (1.003 cm), 0.430 (1.092 cm), 0.465 (1.181), and 0.500 in. (1.270 cm; these were linearly scaled with an increment of 0.035 in. [0.089 cm]). No reinforcement was given during testing with novel sizes. All four groups of birds showed reliable generalization to untrained sizes, and the groups with S- training exhibited a peak shift, with most subjects exhibiting a higher level of generalization to size increases.

Pisacreta, Potter, and Lefave (1984) used a matching-to-sample task to test the pigeons' generalization performance across size changes. Initially, the pigeons learned to match the shape (either a circle, a cross, or a triangle) with sample and comparison stimuli that were shown at the same size (5, 8, or 12 mm across). Next, the pigeons were given trials in which the sample and comparison stimuli were not a consistent size (only the 12-mm and 8-mm sizes were used); for example, the sample might be shown at 12 mm and the comparison stimuli shown at 8 mm. For sessions in which the sizes of the sample and comparisons did not match, the accuracy scores were only slightly lower than for sessions in which the sizes matched (matched: 81%, mismatched: 73%).

Lombardi and Delius (1990) explored the pigeon's generalization performance to size changes using novel silhouette stimuli (uniform white, two-dimensional objects shown on a black background). The researchers used a nonmatching-to-sample task in which a sample shape was presented to the pigeons on the center key and the two comparison shapes were presented on the side keys: one different from the center shape, and one identical to the center shape. Pigeons were trained to peck the nonmatching stimulus. The birds were shown shapes in three sizes: 5, 10, and 20 mm. During training, on a single trial, the sizes of all three objects were uniform. During a transfer phase, the sample shape was a

different size than the comparison shapes. Overall, the pigeons responded at above chance levels on trials in which the sample and comparisons were of different sizes, which suggests that they were able to generalize discriminative performance to different sizes. It is interesting that the pigeons were more accurate when the comparisons were smaller than the sample.

Summary of Previous Results

Similar to human and nonhuman primates, pigeons show significant generalization of discriminative performance to the same stimuli presented at novel sizes. However, in accord with the results reported by Jolicoeur (1987), pigeons generally exhibit some performance decrement when size is changed. It is important to note that prior pigeon studies have used very simple stimuli, such as circles, triangles, spots of light, and object silhouettes. Also, most of the tasks given to pigeons were quite different from the tasks used to test humans. Biederman and Cooper (1992) showed with human research participants that the nature of the task can significantly affect the outcome of the experiment. Consequently, it is not clear how pigeons would generalize discriminative responding in an experiment using complex stimuli and a task that should encourage the pigeons to discriminate among the multiple stimuli.

The Present Study

We sought to extend previous pigeon research by testing birds with visual stimuli that implied three-dimensionality. Prior pigeon studies used two-dimensional shapes or spots of light that lacked internal structural information. Our experiment also explored whether birds store metric information as part of the object representation; if so, then recognition performance ought to be reliably affected by changes in object size. Alternatively, if pigeons exhibit invariance to size changes, then this result would suggest that pigeons store metric information separately from the object representations used for recognition. In pursuit of these aims, we used line drawings of multipart objects (Experiment 1) and shaded images of single-geon objects (Experiments 2 and 3).

In Experiment 1, we found that pigeons generalized discriminative responding to size changes of line drawings of complex objects. This generalization was not invariant, however. The pigeons showed a systematic decrease in accuracy as the size changes deviated further from the original size, although the generalization gradient was somewhat asymmetrical. In Experiment 2, we compared a linear size transformation to an exponential size transformation¹ using shaded images of single-geon objects to determine which transformation yielded the most symmetrical gradient for increases and decreases in object size. In previous studies, these two transformations were not directly compared, so it was unclear which transformation would yield more equivalent performance changes. Pigeon studies have generally used linear transformations (Jenkins et al., 1958; Wildemann & Holland, 1973), whereas human studies have generally used exponential size transformations (Bundesen & Larsen, 1975; Jolicoeur, 1987; Larsen & Bundesen, 1978). We found that generalization performance was symmetrical across the logarithm (base 2) of object size, consistent with Fechner's (1860/1966) law. Finally, in Experiment 3, we explored whether the asymmetry found for linear

transformations in Experiment 2 might be due to an acuity problem with small-sized stimuli. The results did not support this interpretation.

Experiment 1

In Experiment 1, we sought to extend the findings of previous studies of stimulus control by size by testing pigeons with size changes in line drawings of complex, multipart stimuli. We used a four-alternative forced-choice task in which the pigeons had to peck four different report keys in the presence of four different line drawings. This task differs from previous studies (Jenkins et al., 1958; Lombardi & Delius, 1990; Pisacreta et al., 1984; Towe, 1954; Wildemann & Holland, 1973) in that it uses complex stimuli with an implied three-dimensionality and tests a large number of size increases and decreases. We used six size transformations (three smaller and three larger) to see whether pigeons would exhibit a generalization gradient that decreased systematically as the testing size differed from the original training size or whether they would show similar generalization to all size changes. In addition, the stimuli used in Experiment 1 were very similar to those used in some human studies of size changes (e.g., Biederman & Cooper, 1992; Cooper et al., 1992). Consequently, we could more confidently compare the results of this study with those reported in humans.

Method

Pigeons. Four feral pigeons (*Columba livia*) served as experimental animals. They were housed individually in a colony room on a 14:10 light-dark cycle, with lights on at 7 a.m. The birds were given free access to grit and water plus a daily ration that consisted of 45-mg P. J. Noyes (Lancaster, NH) pigeon pellets in the experimental sessions and an additional quantity of mixed grain given shortly after each experimental session to maintain the birds at 85% of free-feeding weight. The pigeons had previously experienced the present training stimuli as well as versions that were spatially reorganized, moved to new positions on the viewing screen, or missing components (see Kirkpatrick-Steger, Wasserman, & Biederman, 1998). However, all of the intact stimulus presentations were the same size as the training stimuli used in the present experiment.

Apparatus. The pigeons were trained in four specially constructed plywood chambers. One side of each chamber consisted of a large opening with an aluminum frame attached to the outside of the box. Inside the frame was a clear touch screen (Accutouch Model No. 002744-FTM-K1; Elographics, Oak Ridge, TN) that was coated with Mylar for durability. The birds' pecks to the touch screen were processed by a serial controller board (Model No. E271-2210, Elographics). A brushed aluminum panel was placed directly in front of the screen to allow the pigeons access to limited portions of the video monitor. There were five openings in the aluminum panel. The center opening was a 7 cm × 7 cm square opening in which the object stimuli appeared. The remaining four openings were circular, 1.9 cm in diameter, and located 2.3 cm from each corner of the center display opening. The four corner keys served as report keys. In the rear of the chamber, a clear Plexiglas food container was placed level with a wire

¹ In the linear size transformations, the measurements of the stimuli were changed by 25% for successive size increases and decreases from the original. In the exponential transformations, the measurements of the stimuli were multiplied by 1.41 to increase the size and by 0.71 to decrease the size (this is equivalent to adding or subtracting 0.5 on a log base 2 scale).

mesh floor to prevent pigeons from perching on the food cup. P. J. Noyes 45-mg pigeon pellets were delivered through a vinyl tube into the food cup via a rotary pellet dispenser (Model No. ENV-203M; MED Associates, Lafayette, IN). During experimental sessions, constant illumination was provided by a houselight mounted on the upper rear wall of the chamber. A digital input/output (I/O) interface board (Model No. NB-DIO-24; National Instruments, Austin, TX) controlled the pellet dispenser and the houselight.

Control of peripheral stimuli (via the I/O interface) and recording of pigeons' responses (via serial controller board) were accomplished by four Apple Macintosh 7100/66 Power PCs equipped with 15-in. (38-cm) monitors set at 640×480 resolution. The pigeon's monitor and an identical monitor in an adjacent room were connected by a distribution amplifier (Model NO MAC/2 DA2; Extron Electronic, Santa Fe Springs, CA). Programs were developed in Hypercard 2.3 (Apple Computing, Cupertino, CA).

Stimuli. The stimuli consisted of line drawings of four familiar objects: a watering can, an iron, a desk lamp, and a sailboat. The training drawings were standardized in size, so that the maximum dimension was 2.79 cm. The original training size was designated as 100%. These original images were then transformed, so that there were three size decreases (75%, 50%, and 25%) and three size increases (150%, 200%, and 250%). We determined the sizes by subtracting 25% from each successive size decrease and by adding 50% to each successive size increase. The scaling was relative, so that the aspect ratio of the altered stimuli remained the same as the original size. Specifications of the area of each stimulus can be found in Table 1.

Procedure. The birds had been trained to discriminate among the stimuli according to a four-alternative forced-choice procedure (Kirkpatrick-Steger et al., 1998). The training drawings had appeared in four different locations on the screen. As the present experiment involves manipulations in size, it was necessary to present all of the stimuli in a single central location on the viewing screen. The birds were given additional training with the centrally located line drawings. Each trial involved the presentation of one of the training drawings (see 100% size in Figure 1) on the viewing screen. The pigeon had to peck the image 30 times to obtain access to four differently colored report keys. The report keys were situated diagonally from each corner of the viewing screen. Each object was associated with a different report key. For example, one pigeon might have to peck the red key in the presence of the watering can, the green key in the presence of the iron, the blue key in the presence of the desk lamp, and the violet key in the presence of the sailboat; key color was redundant with position (e.g., the red key always appeared in the upper left). Different birds received different visual object-report key assignments. If the pigeon pecked the correct report key, then food reinforcement was dispensed into the food tray located on the back wall of the chamber. If the pigeon pecked the incorrect report key, then the trial was repeated until a correct choice was made, resulting in the delivery of food. Only the first choice attempt of a trial was scored; correction trials were omitted from all data analyses. An interval varying randomly from 5 to 15 s ($M = 10$ s) separated trials. The birds were given a minimum of 10 training sessions. Individual

training sessions entailed 40 trials of each of the four training drawings, resulting in a total of 160 trials. Following the minimum number of sessions, individual birds were advanced into the testing phase once they exceeded 70% correct for each object on 2 consecutive sessions.

Testing stimuli were presented relatively rarely (17.5% of the trials) in testing sessions along with normal training trials. Testing sessions involved an initial block of 16 training trials, followed by seven 20-trial blocks that consisted of 16 training stimuli and 4 randomly selected testing stimuli, resulting in a total of 156 trials. On training trials, the normal contingencies of food reinforcement were in place (food following a correct response and one or more correction trials following an incorrect response). On testing trials, pigeons' pecks were nondifferentially reinforced; that is, food was delivered regardless of the pigeon's choice response. If performance on the training trials fell below criterion, then one or more retraining sessions were administered to reestablish accurate performance on the original discrimination. There were 7 testing stimuli for each of the four objects given in each testing session: 3 smaller, 3 larger, and 1 original size (see Figure 1). Each testing size of each of the four objects was shown once during a testing session; all other aspects of the procedure were the same as during the training sessions. A total of 20 testing sessions were conducted.

Results and Discussion

Figure 2 displays the percentage of correct responses as a function of stimulus size, collapsed across the four birds. Discrimination performance to the training objects was uniformly high to all four drawing types (watering can = 100% correct, iron = 92.5%, desk lamp = 90.0%, and sailboat = 96.2%). There was a progressive drop in discrimination performance as size increased or decreased relative to the training size. All sizes except for the smallest were discriminated above the chance level of 25% correct, as assessed by one-tailed binomial tests ($ps < .01$). A repeated-measures analysis of variance (ANOVA) of size (25%, 50%, 75%, 100%, 150%, 200%, and 250%) and object type (watering can, iron, desk lamp, and sailboat) revealed a significant effect of size on choice accuracy, $F(6, 18) = 31.80, p < .001$. Tukey's post hoc analyses indicated that all of the sizes differed significantly from the training size except the 75% value. There was no main effect of object type, $F(3, 9) = 0.94, p > .05$, but there was a significant interaction between size and object type, $F(18, 54) = 2.42, p < .01$, as one can see by examining the gradients of the individual objects depicted in Figure 2. The sailboat gradient was more asymmetrical than those of the other three objects, with high levels of accuracy to the large-sized stimuli. In addition, the iron gradient was more symmetrical than the other three gradients. The shapes of the desk lamp and watering can gradients most closely approximated the mean gradient. These differences in generalization performance across the four objects were not the result of variations in the areas of the stimuli. The sailboat and the watering can have similar areas (see Table 1), yet the generalization gradients of these two stimuli were quite different from one another (see Figure 2).

In summary, pigeons exhibited significant generalization of discriminative responding to size changes in a recognition task using line drawings of complex objects. Previous studies of size invariance in pigeons have used simple, two-dimensional images (Lombardi & Delius, 1990; Pisacreta et al., 1984; Towe, 1954) or circles of light (Jenkins et al., 1958; Wildemann & Holland, 1973). In this experiment, we used more complex images with implied three-dimensionality.

Table 1
Areas of the Differently Sized Testing Stimuli for the Images

Image	25%	50%	75%	100%	150%	200%	250%
Watering can	0.47	1.87	4.20	7.47	16.81	29.88	46.69
Iron	0.19	0.76	1.72	3.05	6.86	12.20	19.06
Desk lamp	0.26	1.06	2.38	4.23	9.52	16.92	26.44
Sailboat	0.42	1.67	3.76	6.69	15.05	26.76	41.81

Note. The 100% sizes served as the training stimuli. Values are areas (cm^2).

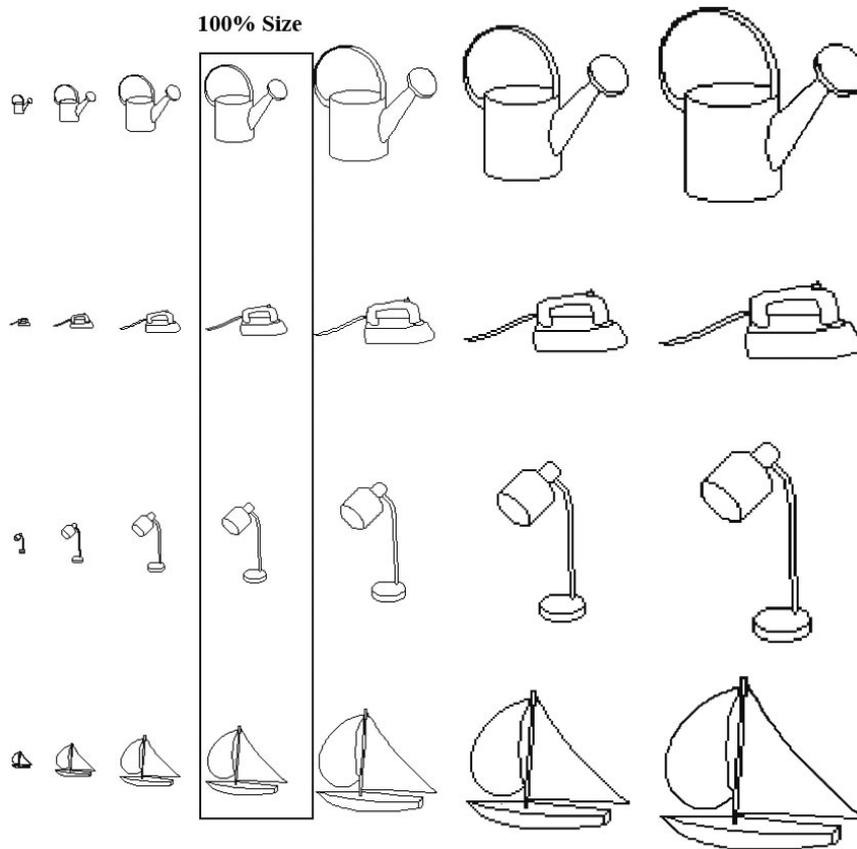


Figure 1. The full set of line drawings administered during testing in Experiment 1. The objects were a watering can, an iron, a desk lamp, and a sailboat. The 100% stimulus size (in the box) served as both the training drawing and one of the tested sizes. The drawings have been reduced in size for presentation purposes. The area of each of the drawings can be found in Table 1.

In Experiment 1, we used a task that required the pigeons to compare novel-sized stimuli with memory representations of a single training size. In similar studies with humans, Biederman and Cooper (1992) found that people exhibited the same amount of priming for objects that were the same size and that were changed in size. In contrast, we found that pigeons showed progressive performance decrements as the testing size deviated from that of the original objects. Thus, our data show that pigeons exhibit a systematic generalization gradient around the trained stimulus, which may indicate the use of a process that is different from primate visual recognition.

The apparent asymmetry in object recognition (greater decrements to smaller than to larger objects) may be because object size obeyed Fechner's (1860/1966) power law: Halving the size of an object may be equivalent to doubling its size. Thus, the expected recognition of a 50%-sized object may be better equated to the recognition of a 200%-sized object than to the recognition of a 150%-sized object. We more fully discuss this issue in the General Discussion.

Finally, there is evidence that pigeons may not process line drawings in the same way as they process fully shaded, three-dimensional images (Peissig, Young, Wasserman, & Biederman, 2005; Young, Peissig, Wasserman, & Biederman, 2001). It is

possible that more fully featured stimuli would allow for a better assessment of size effects on recognition. Therefore, in Experiment 2, we trained pigeons using the same task as in Experiment 1, but now with shaded images of simple single-geon objects. We also explicitly tested two methods of creating the different stimulus sizes to see whether the pigeon's object recognition behavior is more consistent with aligning size along a linear or a logarithmic dimension.

Experiment 2

In Experiment 1, we found that pigeons exhibited a systematic performance decline for changes in size of line drawings of three-dimensional objects. Although these objects were similar to those used in human experiments, they were not well controlled for area. In Experiment 2, we used shaded images of simple, three-dimensional objects; this allowed us to better control for overall area as well as to determine whether pigeons show similar generalization performance to size changes of shaded images.

In addition, we sought to determine what types of size transformations yield psychologically equivalent increases and decreases. Many studies exploring size changes in humans have used exponential transformations (Besner, 1983; Howard & Kerst, 1978;

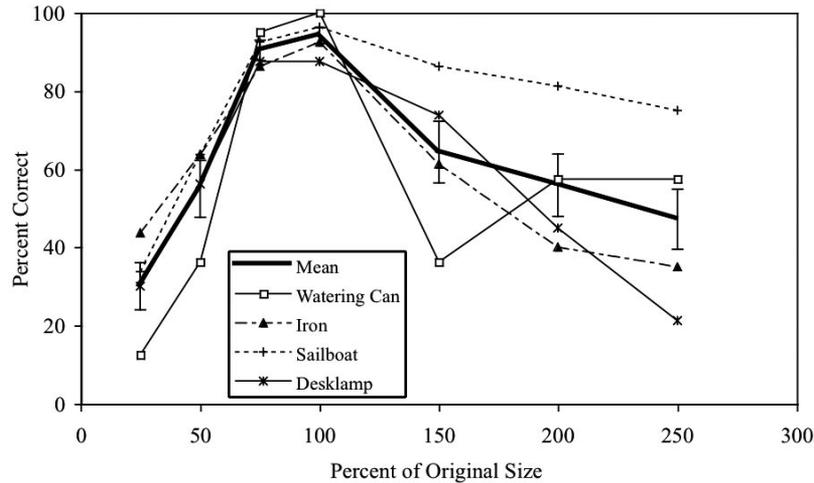


Figure 2. Percentage correct responding across the 4 birds as a function of relative size. The mean scores are shown across all four objects (\pm SEM) and for each individual object.

Larsen & Bundesen, 1978). In these studies, participants were shown two objects at a variety of size ratios, such as 1:1, 1:2, 1:3, 1:4, and 1:5. For example, Larsen and Bundesen (1978) used a sequential matching task and explicitly compared size increases with size decreases. Participants responded to indicate whether two objects were the same or different, regardless of size; the objects were novel, two-dimensional geometric shapes that were rotated within the picture plane on *same* trials. Larsen and Bundesen found that a size increase resulted in a smaller reaction time cost than an analogous size decrease, suggesting that an exponential size transformation may not result in equivalent performance for size increases and decreases. It is unclear, however, whether these findings generalize to other paradigms that require long-term memory recognition.

In studies with pigeons, both linear (Jenkins et al., 1958; Wildemann & Holland, 1973) and logarithmic (Lombardi & Delius, 1990) size transformations have been used. Jenkins et al. (1958) tested a linear size transformation using spots of light; they found that 15 of 16 pigeons exhibited better generalization to size increases than to size decreases, suggesting that a logarithmic size transformation would yield a symmetrical generalization gradient. However, this result may also suggest that pigeons have more difficulty discriminating smaller spots of light. Lombardi and Delius (1990) found a linear trend for logarithmic size transformations in the range of 1:2 to 1:4 size ratios; however, they found no performance decrement from the 1:1 to the 1:2 ratio. Thus, these results do not clearly indicate that a logarithmic scale affords the best fit, and it is unclear whether a logarithmic or a linear size transformation would lead to symmetrical gradients in pigeons. Therefore, in Experiment 2, we explicitly compared a linear with a logarithmic size transformation to see which method would yield psychologically equivalent performance for increases and decreases in size for pigeons.

Method

Pigeons. The data are reported from 3 feral pigeons; a 4th bird had to be dropped from the study because of its failure to learn the initial task. The

birds were individually housed in a colony room on a 14:10 light–dark cycle, with lights on at 7 a.m.; they were given free access to grit and water plus a daily ration that consisted of 45-mg P. J. Noyes pigeon pellets. An additional quantity of mixed grain was given immediately following each experimental session to maintain the birds at 85% of their free-feeding weight. Prior to the present experiment, the pigeons had participated in unrelated studies.

Apparatus. The apparatus was identical to that used in Experiment 1.

Stimuli. The stimuli consisted of an arch, a barrel, a brick, and a wedge that differed from each other by a variety of nonaccidental properties (Biederman, 1987; see Figure 3, top row). The training stimuli were designated as 100% and ranged from 2 to 4 cm in height and in width. For the testing stimuli, we scaled the four objects for the linear transformations by increasing or decreasing size by 25% steps (see Figure 3, Rows 3 and 4), which thereby produced values of 25%, 50%, 75%, 100%, 125%, 150%, and 175% (log transform noted in the parentheses of Figure 3). We scaled the exponential transformations by adding or subtracting 0.5 on a log (base 2) scale (see Figure 3, Rows 5 and 6), which resulted in the transformations of -1.5 , -1.0 , -0.5 , 0.0 , 0.5 , 1.0 , and 1.5 . To directly compare the exponential transformations with the linear proportions, we refer to the exponential transformations by the equivalent percentages (35%, 50%, 71%, 100%, 141%, 200%, and 283%, respectively). The scaling was relative, so that the aspect ratio of the altered stimuli remained the same as the original size. Table 2 gives the area of each stimulus for each size and for each of the transformations.

Procedure. At the beginning of a trial, the central display area was illuminated with a black cross centered on a white background. A single peck anywhere within that display area turned on a stimulus in the central display area. The pigeons were required to peck the center area a fixed number of times (observing responses). The fixed ratio varied from 5 to 30 pecks for different birds, depending on what level they would tolerate. After the final peck, the four corner report keys were illuminated. The pigeons were trained to peck one of the four corner keys to report each of the four single-geon objects (see Figure 3). The assignment of the correct report keys to the four different geons was partially counterbalanced according to a Latin-square design. After a correct choice, a food pellet was delivered. After an incorrect choice, the houselight was turned off for 4 to 6 s ($M = 5$ s)—during which the stimulus was present—and one or more correction trials began (repeating the incorrect trial until a correct choice was made). Correction trials were not scored for analysis. After a correct response was produced and food was delivered (whether that response was

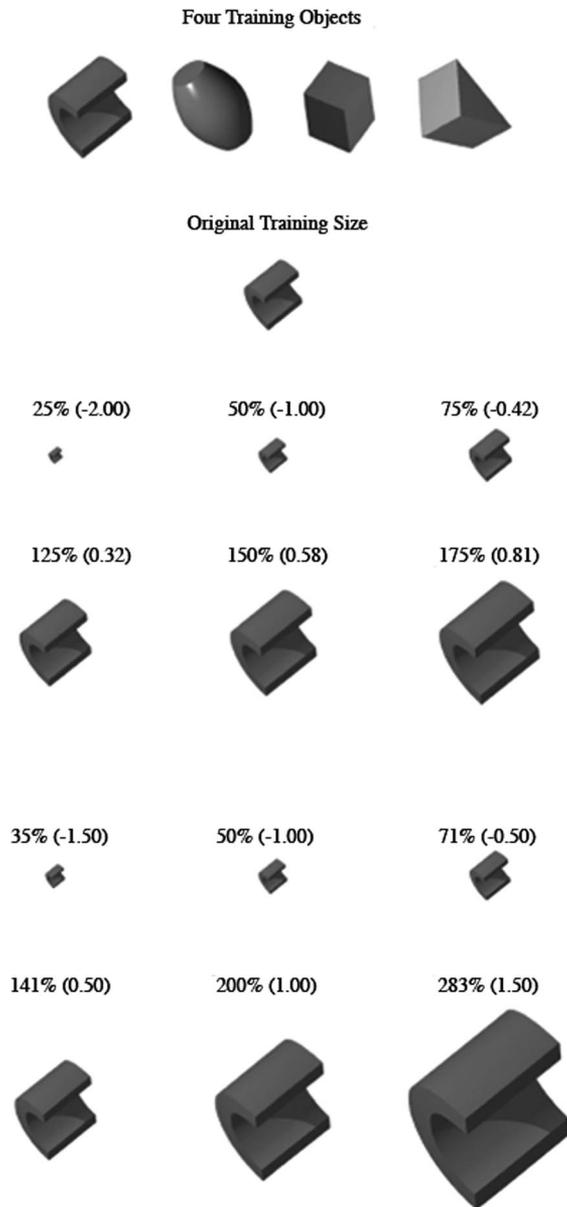


Figure 3. The four single-geon objects used in Experiments 2 and 3. The geons were an arch, barrel, brick, and wedge (top row). The original training size (Row 2) served as both the training stimulus and one of the tested sizes. The linear (Rows 3 and 4) and exponential (Rows 5 and 6) size transformations of the arch were used in Experiments 2 and 3. The drawings have been reduced in size for presentation purposes. The area of each of the geons can be found in Table 2.

the first or followed a number of incorrect responses), there was an intertrial interval ranging from 6 to 10 s ($M = 8$ s), during which the houselight remained on and the display was dark. Each block of 20 trials consisted of five presentations of each of the four objects. There were 10 blocks in each daily session, for a total of 200 trials per day. Each bird was required to meet a session criterion of 85% correct overall and 80% correct for each of the four geons (85/80 criterion) before it could proceed to testing.

Testing stimuli composed a small percentage of trials (14.9%), which were intermingled with normal training trials. Trials on which testing

stimuli were given were nondifferentially reinforced. If a pigeon failed to meet the 85/80 criterion on the normal training trials, then it was returned to training until it again met the 85/80 criterion. Testing sessions began with 20 warm-up trials (4 different stimuli, each shown five times). In the remainder of the testing session, each block consisted of 24 trials, with 20 of the trials involving the original training stimuli (4 different stimuli, each shown five times) and the remaining 4 trials involving testing stimuli. The 4 testing stimuli were chosen randomly from the pool of 28 testing stimuli. There were seven blocks in each daily session, for a total of 188 trials (20 differentially reinforced warm-up trials, 140 differentially reinforced training trials, and 28 nondifferentially reinforced testing trials).

In a given testing session, the pigeons were shown stimuli that corresponded to either a linear or an exponential size transformation. There were 7 testing stimuli for each of the four objects delivered in each testing session: 3 smaller, 3 larger, and 1 original size (see Figure 3 and Table 2). Each of the 28 testing stimuli for one type of transformation was shown once within a single session. Each pigeon remained in testing until it had completed a total of 20 sessions with each type of transformation (40 sessions total).

Results and Discussion

The pigeons exhibited systematic performance decrements as testing size varied from the original training size (see Figure 4). We analyzed the data from the linear and exponential transformations separately using Geon (arch, barrel, brick, and wedge) \times Size (linear: 25%, 50%, 75%, 100%, 125%, 150%, and 175%; exponential: 35%, 50%, 71%, 100%, 141%, 200%, and 283%) ANOVAs.

For the linear size transformation, there was no significant main effect of geon, $F(3, 6) = 0.51$, $p > .05$, indicating that, overall, there were no significant performance differences among the four geons. The main effect of size was statistically significant, $F(6, 12) = 27.87$, $p < .0001$, as was the interaction of geon and size, $F(18, 36) = 2.07$, $p < .05$. These data suggest that the pigeons exhibited a significant decrement in performance to changes in size and that this decrement was not equivalent for all of the geons. In Figure 4a, it is clear that the pigeons did not exhibit uniform generalization across geons, with the wedge differing notably from the other three geons. To explore this possibility, we performed a Tukey's honestly significant difference (HSD) analysis for each geon, comparing the training size (100%) with the six size transformations. For the arch, there was no significant difference at the 125% and 75% sizes compared with the original. All other size transformations were significantly different from the training value ($p < .05$). For the barrel and the brick, there was no significant difference at the 125% and 150% size increases and at the 75% size decrease compared with the original. For the wedge, there was no significant difference at the 125% size increase or at the 75% and 50% size decreases. We also analyzed whether the mean percentage of correct responses was above chance at each of the linear size transformations. All but the smallest size, the 25% transformation, were significantly above chance across all four geons (one-tailed binomial; $p < .05$).

For the exponential size transformation, there was no significant main effect of geon, $F(3, 6) = 0.78$, $p > .05$. There was a significant main effect of size, $F(6, 12) = 45.74$, $p < .0001$, indicating that the pigeons exhibited a significant performance decrement to changes in size. The interaction between geon and size was not significant, $F(18, 36) = 1.58$, $p > .05$, which suggests that for the exponential size transformations, the pigeons exhibited

Table 2
Areas of the Differently Sized Testing Stimuli for the Single-Geon Objects

Object	Linear size transformations							Exponential size transformations						
	25%	50%	75%	100%	125%	150%	175%	35%	50%	71%	100%	141%	200%	283%
Arch	0.22	0.87	1.95	3.47	5.42	7.81	10.63	0.43	0.87	1.75	3.47	6.90	13.88	27.79
Barrel	0.19	0.77	1.73	3.08	4.81	6.93	9.43	0.38	0.77	1.55	3.08	6.12	12.32	24.67
Brick	0.20	0.81	1.83	3.25	5.08	7.31	9.95	0.40	0.81	1.64	3.25	6.46	13.00	26.03
Wedge	0.21	0.85	1.90	3.38	5.28	7.61	10.35	0.41	0.85	1.70	3.38	6.72	13.52	27.07

Note. The 100% sizes served as the training stimuli. Values are areas (cm²).

a more consistent pattern of generalization across all four geons. Tukey's HSD post hoc analyses indicated that, across all four geons, all of the size transformations differed significantly from the training size ($p < .05$). We also analyzed whether the pigeons

responded significantly above chance at all of the exponential size transformations. Neither the smallest nor the largest stimuli (-1.5 and 1.5) was significantly above chance across all four geons (one-tailed binomial; $p > .05$).

It is evident from Figure 4 that, for linear size transformations, decreases in size produced more pronounced decrements in accuracy than did increases in size. To determine whether the exponential or the linear size transformation produced more psychologically equivalent performance, we examined paired increases and decreases in size. For linear transformations, the 125% and 75% transformations were not significantly different (Tukey's HSD; $p > .05$); for both of the other pairs (150% and 50%, 175% and 25%) there was a significant difference (Tukey's HSD; $ps < .05$). In each case, pigeons were significantly less accurate at the size decrease than at the corresponding size increase. For the exponential size transformations shown in Figure 4b, there were no significant differences at any of the corresponding pairs of exponential increases and decreases (141% and 71%, 200% and 50%, 283% and 35%; Tukey's HSD; $ps > .05$).

In addition to accuracy, we also explored the time it took for pigeons to peck the correct button (measured from the time the corner buttons appeared after completion of the observing response). The pigeons' response times were less sensitive to size changes than were their accuracy scores (see the Appendix). To assess this observation, we tested the data from both sets of transformations, using a geon (arch, barrel, brick, and wedge) \times size (25%, 35%, 50%, 71%, 75%, 100%, 125%, 141%, 150%, 175%, 200%, and 283%) ANOVA. There was no significant main effect of geon, $F(3, 6) = 0.45, p > .05$, or size, $F(11, 22) = 1.36, p > .05$, nor was there any interaction, $F(33, 66) = 1.45, p > .05$. These data suggest that response times are not a particularly sensitive measure for pigeons in our task (see the Appendix).

In summary, in Experiment 2, the pigeons better generalized their visual discrimination behavior to increases than to decreases along the linear size continuum (see Figure 4a). Therefore, these data suggest that exponential size scaling provides the most psychologically equivalent increases and decreases (see Figure 4b). The possibility remains, however, that these results were influenced by the pigeons' inability to discriminate the smallest stimuli. The pigeons did not respond at above chance levels of accuracy to the smallest stimuli (nor did they do so in Experiment 1), so we do not know whether the pigeons could discern enough of the features in the smallest size to discriminate one geon from another. In Experiment 3, we trained pigeons with all of the sizes used in Experiment 2 to test this possibility.

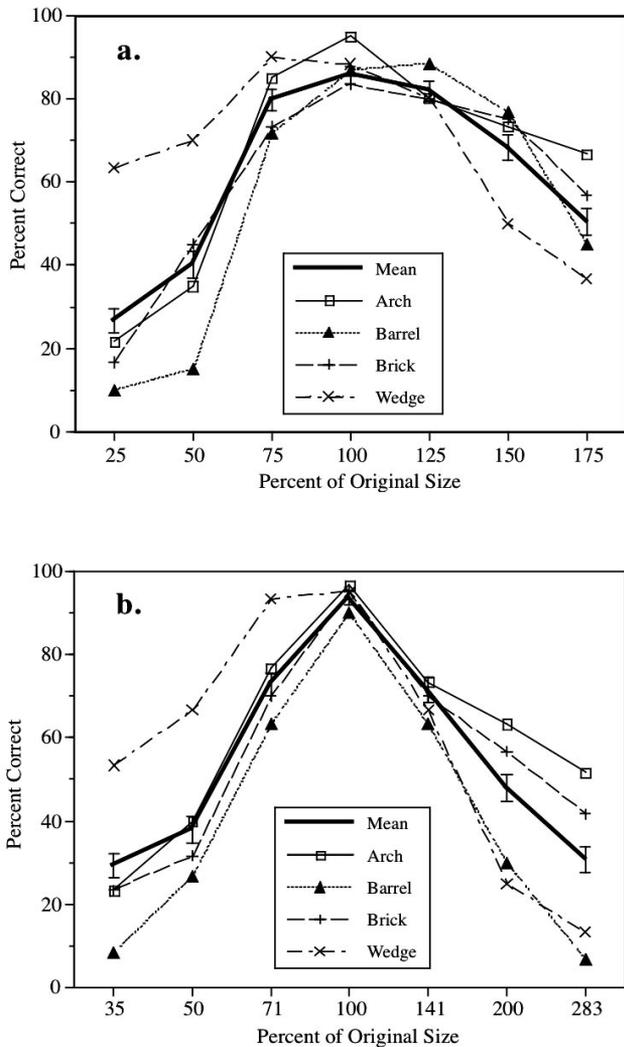


Figure 4. Percentage correct across the 4 birds as a function of relative size for the linear size transformations (a) and exponential size transformations (b). The mean scores are shown across all four objects ($\pm SEM$) and for each individual object.

Experiment 3

In Experiments 1 and 2, we found an asymmetry in pigeons' recognition performance when size changes were scaled linearly. However, in Experiment 2, the recognition gradients were fairly symmetrical when size changes were scaled exponentially. Pigeons were significantly less accurate at decreases in size than at increases in size when the transformations were linear rather than exponential. One possible explanation for this asymmetry is that pigeons have poor acuity for stimuli presented at the smallest size. Because the linear transformation yielded a greater size decrease than the exponential size transformation (see Table 2), it might have been differentially affected by visual acuity.

In Experiment 3, we explicitly tested the pigeon's acuity for these visual stimuli by training birds with all of the size changes used for testing in Experiment 2 (see Figure 3, Rows 3 to 6). If the pigeons were unable to learn the discrimination with the smallest stimulus, then this would suggest that the asymmetry for linear size changes was at least partly due to pigeons' difficulty in seeing enough detail in the smallest stimuli to discriminate among them.

Method

Pigeons. The animals were the same 3 feral pigeons that had been studied in Experiment 2. In Experiment 2, the birds had been tested with both increases and decreases in stimulus size via nondifferential reinforcement; thus, before the beginning of Experiment 3, these pigeons had not received any explicit training with differently sized stimuli.

Apparatus. The apparatus was identical to that used in Experiments 1 and 2.

Stimuli. The stimuli were identical to those used in Experiment 2 (see Figure 3). The area of the stimuli can be found in Table 2.

Procedure. Individual trials proceeded identically to those in Experiment 2. In the present experiment, the pigeons were trained to peck one of the four corner keys to report each of the four single-geon objects at seven different sizes (see Figure 3, top row). The pigeons were trained with differential reinforcement of both exponential and linear size changes in alternating sessions; the two types of transformations were not intermingled at any time during the experiment. The training stimuli were identical to the testing stimuli used in Experiment 2 (see Figure 3, Rows 3 to 6, and Table 2).

During each session, there were seven different sizes (either linear or exponential) of each of the four objects, which yielded a total of 28 different stimuli for training with the linear transformation and another 28 stimuli for training with the exponential transformation. Within each of six blocks, these 28 stimuli were repeated once each, for a total of 168 trials in a single daily session (28×6). Each pigeon was trained for 56 daily sessions, 28 with each transformation type.

Results and Discussion

Figure 5a shows data from the first training session with the size changes. From this figure, it is evident that the pigeons were less accurate for extreme size increases and decreases compared with the original image size. Although the pigeons were less accurate at both increases and decreases, the size decreases generally yielded poorer performance. Consequently, we did not directly compare learning rates; the size increases started training closer to asymptote than did the size decreases, so any learning effects would be obscured by this initial bias. Instead, we looked at the final session of each transformation at the end of several weeks of training, which should better indicate whether the pigeons were capable of

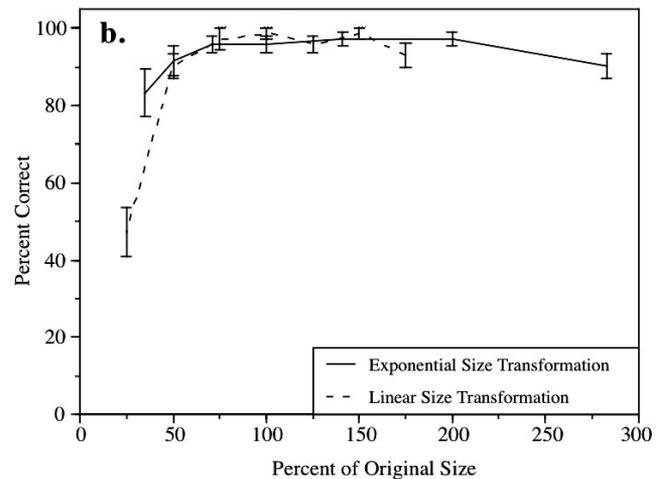
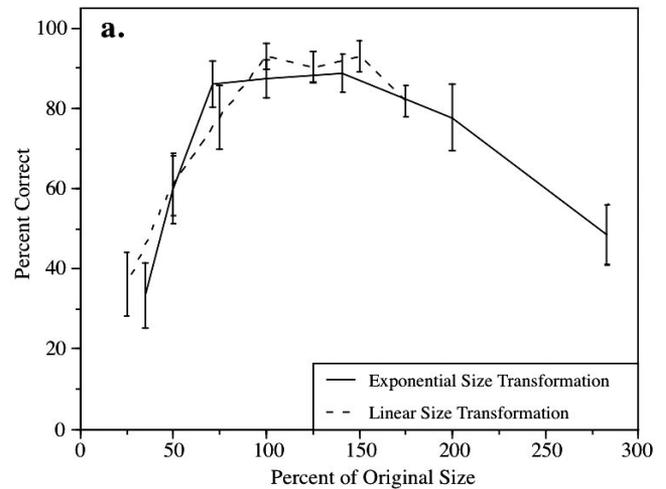


Figure 5. Percentage correct (\pm SEM) for training with all sizes in Experiment 3 as a function of transformation type. Data are shown for the first session of the experiment (Session 1; a) and the last session of the experiment (Session 28; b).

responding at above-chance levels for all the size variations. Figure 5b shows the data for the final training session to parallel the data for the first training session depicted in Figure 5a. This figure shows that, by the end of the experiment, the pigeons were performing at ceiling levels for most of the size variations, with the exception of the two smallest sizes. Thus, the pigeons were able to learn all of the size increases and most of the size decreases. However, the birds continued to have difficulty with the smallest sizes (25% and 35% of the original size) even after 28 training sessions, which equals a total of 168 repetitions for each stimulus. In particular, the pigeons attained over 90% accuracy at all of the sizes except the two smallest by the last session of training. At the 25% linear size transformation, mean response accuracy was 47%; at the 35% exponential size transformation, response accuracy was 83%. These scores were both significantly above the chance level of 25% (one-tailed binomial, $p < .05$).

The data from the linear and exponential transformations were analyzed separately, across the last four training sessions. We used a repeated-measures ANOVA with accuracy as the dependent measure and with linear size (25%, 50%, 75%, 100%, 125%, 150%, and 175%) and geon (arch, barrel, brick and wedge) as the independent variables. The main effect of size was significant, $F(6, 12) = 25.12, p < .0001$, which indicated that the pigeons did not exhibit the same level of accuracy at all of the size transformations; the pigeons' discrimination performance was poorest at the smallest size. The main effect of geon was not significant, $F(3, 6) = 1.06, p > .05$, which indicated that there were no overall differences in performance among the four geons. The interaction between size and geon was not significant, $F(18, 36) = 1.36, p > .05$, which suggested that the pigeons responded similarly to the different sizes of the four geons.

We also analyzed the exponential size transformation training data for the last four training sessions, using a repeated-measures ANOVA with accuracy as the dependent measure and size (exponential: 35%, 50%, 71%, 100%, 141%, 200%, and 250%) and geon (arch, barrel, brick, and wedge) as the independent variables. The main effect of size was statistically significant, $F(6, 12) = 5.21, p < .01$, which indicated that, for exponential transformations, the pigeons did not exhibit the same level of accuracy at all size changes; discrimination performance was poorest at the smallest size. The main effect of geon was not significant, $F(3, 6) = 0.08, p > .05$, indicating no differences in performance for the four geons overall. The Geon \times Size interaction was not significant, $F(18, 36) = 0.24, p > .05$.

These results suggest that the asymmetry reported in Experiments 1 and 2 can be explained in part by the pigeons' difficulty discriminating among stimuli at the smallest sizes, although we did not test equivalently extreme increases in stimulus size (e.g., 400% to match 25%) because of limitations in the size of the viewing area. The results of Experiment 3 indicate that the pigeons were less accurate with the smallest stimulus sizes than with any other sizes. Because these pigeons were the same birds trained in Experiment 2 (see Figure 3), we were unable to directly compare learning rates for the differently sized stimuli. As Figure 4 shows, the pigeons were performing above chance for most size changes prior to the start of the Experiment 3, and in the case of the linear size transformation, they were significantly more accurate for size increases. Thus, with pigeons starting at different levels of accuracy for differently sized stimuli, exploring the learning rates is not a useful comparison, and additional studies using naive pigeons are necessary to completely address the acuity issue. It is critical that the pigeons were able to achieve above chance performance by the last four sessions with all of the trained sizes. Thus, it is unlikely that the asymmetry we found for linear transformations in Experiment 2 can be explained entirely by the pigeons' inability to discriminate the stimuli at the smallest size. In addition, in Experiment 2, the pigeons did not respond equally well to all of the size increases, as might be expected if the generalization gradient were driven entirely by acuity. For the exponential transformation, the pigeons did not show significant generalization to the largest size (283%), even though they were able to learn the correct response to this size in Experiment 3. These results suggest that the recognition decrements found in Experiments 1 and 2 reflect a generalization gradient that better accords with a logarithmic transformation than with visual acuity deficits.

General Discussion

In three experiments, we explored the pigeon's generalization of object recognition performance to different object sizes using both line drawings and shaded images as discriminative stimuli. In primates, evidence suggests that, at least for behavioral performance in naming tasks, object recognition is invariant to changes in size (Biederman & Cooper, 1992; Cooper et al., 1992; see also Grill-Spector et al., 1999). It is less clear, however, how changes in size might affect object recognition in nonprimates, such as pigeons.

Prior studies have reported that pigeons generalized their discrimination performance to size changes of simple, two-dimensional objects (Lombardi & Delius, 1990; Towe, 1954) or to spots of light (Jenkins et al., 1958). However, these studies did not test more complicated representations of three-dimensional objects, nor did they explicitly test the types of size transformations that would produce equivalent performance for both increases and decreases in size. The current study addresses these issues. In the present study, we were unable to directly test whether the pigeons used the entire stimulus or just a portion of the image to solve the task. The images maintained a constant location during the experiment, a necessary constraint because of the small size of the viewing area and the broad range of size increases we tested. However, the orderly results we obtained in all three experiments suggest that the size scaling process might have worked similarly regardless of whether the pigeons were using local features or the entire object.

First, we found that pigeons generalized their discriminative responding to both smaller and larger versions of line drawings of multipart objects (Experiment 1) as well as to shaded images of single-part objects with implied three-dimensionality (Experiment 2). Although we cannot be certain that the pigeons perceived these objects as three-dimensional, our stimuli were composed of more complex features than previously used stimuli. In particular, in contrast to the stimuli used in prior pigeon studies, these stimuli contained internal structural information that could guide recognition performance. Generalization was similar for both line drawings and shaded images, which suggests that pigeons process size changes similarly for both types of stimuli. By testing more complex stimuli, we have thereby extended our knowledge of how size changes affect recognition in pigeons.

Second, we tested pigeons using a recognition task to determine whether they exhibited invariant responding to size changes. Previous studies of pigeon behavior entailed either matching-to-sample tasks (Lombardi & Delius, 1990; Pisacreta et al., 1984) or tasks in which the birds learned to peck at a single stimulus and to withhold pecks to other stimuli (Jenkins et al., 1958; Towe, 1954; Wildemann & Holland, 1973). These tasks are quite different from the recognition tasks used to test humans (Biederman & Cooper, 1992). Our birds showed significant decrements in recognition accuracy. In contrast, Biederman and Cooper reported size invariance in humans in a similar task. These data suggest that pigeons form object representations that are not size invariant and that pigeons may use a recognition process for dealing with size changes that differs from that used by humans.

Third, we directly compared linear and exponential size transformations to determine which would yield equivalent performance at size increases and decreases. In humans, an exponential

transformation is nearly always used (Besner, 1983; Bundesen & Larsen, 1975; Jolicoeur, 1987); however, very few studies have explicitly compared size increases and decreases. In pigeons, both linear and exponential transformations have been used. These different transformations have yielded mixed results for generalization to increases and decreases in size. The nature of the stimuli might have contributed to the mixed findings. A size transformation for a spot of light may be very different from the size transformation for a representation of a three-dimensional object.

In Experiment 2, we directly compared a linear size transformation with an exponential size transformation. We found a large asymmetry for the linear transformation, in which pigeons generalized better to size increases than to size decreases. The exponential transformation, however, yielded more equivalent performance for size increases and decreases.

In Experiment 3, we tested whether poor acuity for the smallest stimulus sizes might have contributed to the asymmetry found for the linear transformation. Despite poorer performance with the smallest sizes of the linear and exponential transformations than with the other size transformations, the pigeons were able to respond at above chance levels to all of the size changes. This result suggests that the pigeons were able to see the stimuli in enough detail to perform the discrimination task. On the basis of these findings, we concluded that an exponential series supports more behaviorally equivalent size functions.

The results of Experiment 3 are surprising, considering that pigeons are capable of discriminating among different types of seeds, which are quite small, to choose their favorites. However, the pigeon's ability to select among seeds may be aided by visual cues other than shape, such as color and brightness. There may be haptic or olfactory cues as well, which may contribute to the birds' discriminative feeding behavior. Furthermore, the pigeons were able to perform this discrimination at above chance levels to all of the stimulus sizes. Thus, it is clear that they were able to see enough detail to perform the task, just not at the same level of accuracy as with larger stimuli.

The asymmetry in the linear generalization gradient implies that visual size may conform to Fechner's (1860/1966) law, with accuracy being a logarithmic function of the change in size of the object. Thus, halving the size of an object is functionally equivalent to doubling its size. To illustrate the degree of conformity of the data from Experiments 1 and 2 to Fechner's law, Figure 6 shows the superposition of the data on a logarithmic size scale and the best fit Gaussian generalization curves. The data from Experiment 2 include both linear and exponential size transformations. It is apparent that the generalization gradients were quite symmetrical for both experiments and that the gradient for Experiment 1 (line drawings) was slightly broader than that for Experiment 2 (shaded geons). Given that the line drawing data and the geon data are from different experiments, comparison of these generalization gradients is merely suggestive. Yet the symmetrical Gaussians provided excellent models of the generalization data, accounting for 93% of the variance in average responding for Experiment 1 and 99% of the variance in average responding for Experiment 2. We observed these excellent fits without making any adjustments for the possibility of poorer visual acuity of the smaller items.

In these experiments, we showed that pigeons do not respond invariantly to size changes in a visual recognition task. One possible explanation for this finding is that the pigeons might have

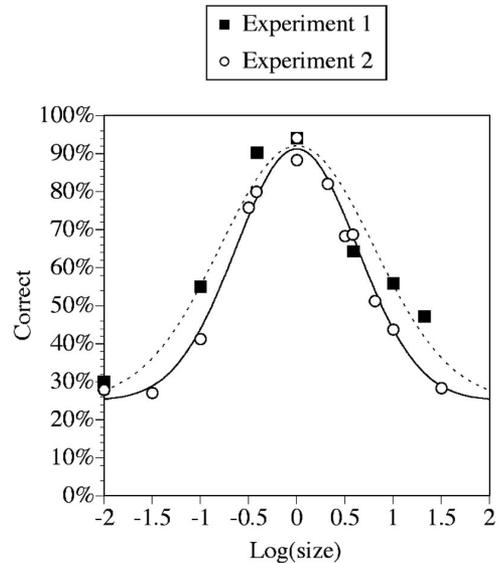


Figure 6. The data from Experiments 1 and 2 plotted on a logarithmic scale. The data from Experiment 2 include both the linear and exponential size transformations. The curves indicate the best fitting Gaussian generalization gradients for each experiment.

attended to metric properties, such as the relative size of the objects, rather than their general shapes to solve the discrimination task. In Experiment 1 the stimuli were quite varied in their total area (see Table 1), so using relative size might have provided a useful strategy. Nevertheless, the pigeons did not show similar gradients for objects with similar areas (e.g., the sailboat and watering can). In Experiment 2, we used objects that were better controlled for overall area. In this experiment, using metric properties, such as relative size, would have been less diagnostic. In addition, if pigeons were relying on metric properties, then we might have expected them to show poor generalization to size changes. It is possible, however, that extensive training to provide the same label for an object shown at a number of different sizes would result in flatter generalization gradients with a new set of stimuli (DiPietro, Wasserman, & Young, 2002). Additional studies are necessary to explore the extent of the pigeon's flexibility for recognizing objects that vary in size.

In conclusion, we have explored the role of size changes on the visual recognition ability of the pigeon. Prior studies have found that pigeons are able to generalize discriminative responding to a variety of object transformations (e.g., Kirkpatrick-Steger & Wasserman, 1996; Kirkpatrick-Steger et al., 1998; Kirkpatrick-Steger, Wasserman, & Biederman, 2000; Peissig, Wasserman, Young, & Biederman, 2002; Young et al., 2001). However, it is also clear that there are performance costs when pigeons respond to those transformations. For example, pigeons exhibit systematic decrements in accuracy for rotations in depth (Peissig, Young, Wasserman & Biederman, 1999, 2000; Wasserman et al., 1996). Our findings for size changes are similar to those reported for depth rotations: Pigeons generally perform at above chance levels, but they nevertheless exhibit a systematic decrease in accuracy as the testing size deviates from the original. A model of avian object recognition must account for these consistent patterns of responding to object changes.

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Appendix

Response Times for the Choice Response in Experiment 2

% of original	Response time (ms)			
	Linear size transformation	SEM	Exponential size transformation	SEM
25	91	3.6		
35			94	4.1
50	96	3.6	109	5.4
71			98	4.4
75	103	4.6		
100	92	3.6	92	3.9
125	93	4.1		
141			91	4.7
150	104	4.9		
175	122	7.3		
200			103	6.2
283			95	10.6

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