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USE OF NUMBER BY CROWS: INVESTIGATION BY MATCHING AND ODDITY LEARNING

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Hooded crows were trained in two-alternative simultaneous matching and oddity tasks with stimulus sets of three different categories: color (black and white), shape (Arabic Numerals 1 and 2, which were used as visual shapes only), and number of elements (arrays of one and two items). These three sets were used for training successively and repeatedly; the stimulus set was changed to the next one after the criterion (80% correct or better over 30 consecutive trials) was reached with the previous one. Training was continued until the criterion could be reached within the first 30 to 50 trials for each of the three training sets. During partial transfer tests, familiar stimuli (numerals and arrays in the range from 1 to 2) were paired with novel ones (numerals and arrays in the range from 3 to 4). At the final stage of testing only novel stimuli were presented (numerals and arrays in the range from 5 to 8). Four of 6 birds were able to transfer in these tests, and their performance was significantly above chance. Moreover, performance of the birds on the array stimuli did not differ from their performance on the color or shape stimuli. They were capable of recognizing the number of elements in arrays and comparing the stimuli by this attribute. It was concluded that crows were able to apply the matching (or oddity) concept to stimuli of numerical category.

Key words: numerical competence, concept formation, matching to sample, oddity from sample, crows

The question of how and to what degree animals can distinguish numerical attributes is a point of interest to many researchers. The study of numerical competence is directly connected with the problem of animal cognition and, in particular, constitutes one of the models for the investigation of concept formation. Birds might be promising subjects for the investigation of these questions, as has been shown earlier (Koehler, 1950; Pepperberg, 1987; Wilson, Mackintosh, & Boakes, 1985).

Birds are known to possess a specific type of brain structure characterized by progressive development of the hyper- and neostriatum nuclei instead of the neocortex in mammals. Nevertheless, the mammalian neocortex is not only a functional analogue but is also a homologue of the birds' hyperstriatum (Karten, 1991), and, accordingly, some cognitive abilities were found to be similar between the representatives of these two taxonomic groups.

Corvids were subjects of the present investigation. They are characterized by one of the highest degrees of brain structure complexity among birds (Stingelin, 1958) and can perform various types of complex cognitive test successfully (Kamil, 1987; Koehler, 1950; Mackintosh, 1988; Wilson et al., 1985; Zorina, 1997). It has been shown that their cognitive abilities are comparable to those of monkeys in a number of characteristics (Kamil, 1987; Krushinsky, 1990; Zorina, 1997). On the other hand, pigeons, which are among the most typical laboratory subjects, are not able to solve a number of complex cognitive tests that corvids can perform successfully or can solve on the basis of simpler mechanisms (Krushinsky, 1990; Wilson et al., 1985; Zorina, 1997). In this connection, hooded crows are, in our opinion, of great interest as subjects for the investigation of animal cognition.

Recently we have been investigating nu-

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merical competence in hooded crows and in pigeons using the relative numerousness judgment paradigm (Zorina & Smirnova, 1994, 1996a, 1996b). This term is usually employed to mean the process of approximate comparison of arrays markedly differing in the number of elements (Davis & Perusse, 1988).

First, we used a free-feeding situation in which two cups with sets of food items were presented simultaneously, and on every trial the bird could eat the food only from the cup chosen by it. In this task crows, as well as pigeons, preferred a food cup that contained a larger number of food items. However, the performance accuracy in crows was not a function of the difference between the number of items in the stimuli across a range of 1 to 12, whereas pigeons chose greater arrays only when sets differed by three elements or more (Zorina & Smirnova, 1994).

Next, crows were trained to choose the greater array from pairs of numerousness discriminanda in the range of 1 to 25 (the difference between number of stimuli was varied from 1 to 24). These birds perceived and exactly estimated graphic arrays containing up to 20 items (but not 25). They also acquired the concept ''larger than'' based on numerical rather than other quantitative attributes of arrays (Zorina & Smirnova, 1996a, 1996b). The latter inference could be made because we varied the ratio of cumulative area of elements to their number: In half of the trials the greater array consisted of bigger elements and the lesser array consisted of smaller elements and vice versa in the other half of the presentations.

Another experimental paradigm in numerical competence investigation is number concept formation by matching and oddity learning. The most convincing evidence of the birds' ability to form a matching concept comes from studies by Koehler (1950) and Wilson et al. (1985). Koehler demonstrated that a raven can perform both matching and oddity tasks with the array stimuli in the range from three to seven and transfer to new items of various colors and sizes, displaying concept learning by the number itself. Wilson et al. found that European jays are capable of transfer of the matching or oddity rule from color stimuli to line orientation stimuli (i.e., from stimuli of one category to stimuli of another one).

Several criteria for the presence of a number concept in animals have been suggested (e.g., Davis & Perusse, 1988; Gallistel, 1993; Koehler, 1956). In the present article, we study whether crows' numerical competence satisfies one such criterion, namely, a transfer to numerical stimuli of a new range. For this purpose, we trained the birds on matching to sample and oddity from sample with stimuli of three different categories: color, shape, and number of elements.

It has been demonstrated that subjects performing in matching-to-sample or in oddity-from-sample tasks may solve them on the basis of two different mechanisms (Farthing & Opuda, 1974; Oden, Thompson, & Premack, 1988; Pack, Herman, & Roitblat, 1991; Wilson et al., 1985; Wright, Cook, Rivera, Sands, & Delius, 1988). These mechanisms are referred to as ''if . . . then'' rules (''if see Stimulus A, choose Stimulus B''), which allow one to solve a task with a restricted set of familiar stimuli, and a general rule (''choose a stimulus corresponding to a sample''), which allows one to solve a task with any new stimuli (Carter & Werner, 1978). It has also been suggested that a subject has a tendency to form ''if . . . then'' rules if during training it was presented with a limited set of stimuli. On the other hand, when subjects are trained with a large set of various stimuli or even with unique ones, the general rule is often acquired (Wright et al., 1988). The question is what type of rule will be used by crows trained with a limited number of stimuli of three different categories?

The goals of this study were (a) to investigate matching-to-sample and oddity-from-sample acquisition in crows using physical similarity and number of elements in arrays; (b) to study a shift from ''if . . . then'' rules to a general matching rule; and (c) to evaluate whether crows are able to transfer to numerical stimuli of a new range.

METHOD

Subjects

Six hooded crows (*Corvus cornix* L.) older than 2 years were used in these experiments. Crows were caught at the age of about 1 year and were housed in outdoor aviaries in small groups (2 to 3 birds). One of them (Crow

250) was previously used as a subject in a series of two-choice object-discrimination tasks (Zorina & Smirnova, 1996a, 1996b); the others were experimentally naive. Crow 250 did not participate in Phases 10 and 11 because it was shot by an unknown hooligan in the outdoor aviaries.

Throughout the experiment the birds had free access to water. Mealworms were used as reinforcers, two worms on each trial up to a daily maximum of 120. In our experience mealworms are crows' favorite food, and are attractive at any food-deprivation level (Zorina & Smirnova, 1994, 1996a, 1996b). Therefore, chronic food deprivation was not necessary, although sometimes it was used at the beginning of training. If the crows refused to work during training, they received food without animal proteins for 1 or 2 days.

Apparatus

An experimental wire mesh cage (70 cm by 35 cm by 35 cm; mesh dimension 4 cm by 4 cm) and a plastic tray (20 cm by 30 cm) with a handle (30 cm) were used. Figure 1A shows a schematic of the setting of the experiment. Two cups (3.7 cm high and 5.0 cm in diameter) were placed on the tray. One of them contained two mealworms as a reinforcer. The cups were covered with cardboard cards (comparison stimuli). A sample card was placed between the cups.

The tray was prepared for the trial out of the scope of bird's vision. An opaque plastic screen (70 cm by 40 cm) was between the experimental cage and the experimenter, minimizing the chance of unintentional cues from the experimenter. Figure 1B shows the arrangement of the experimenter and the subject in relation to each other at the moment when the bird made its choice. The bird could not see the experimenter at the moment of choice and the experimenter could not see the bird. This precluded the possibility of a "clever Hans" effect. Note that because the experimenter could not see the bird, she could judge the outcome of each trial only by sounds made by the bird. If she heard a sound of a card falling from the cup and after that a sound of the bird picking the cup with mealworms, then the choice was correct. If she did not hear a sound of picking the cup with mealworms, then the choice was incorrect and the experimenter removed the tray quickly to prevent the bird from opening the second cup.

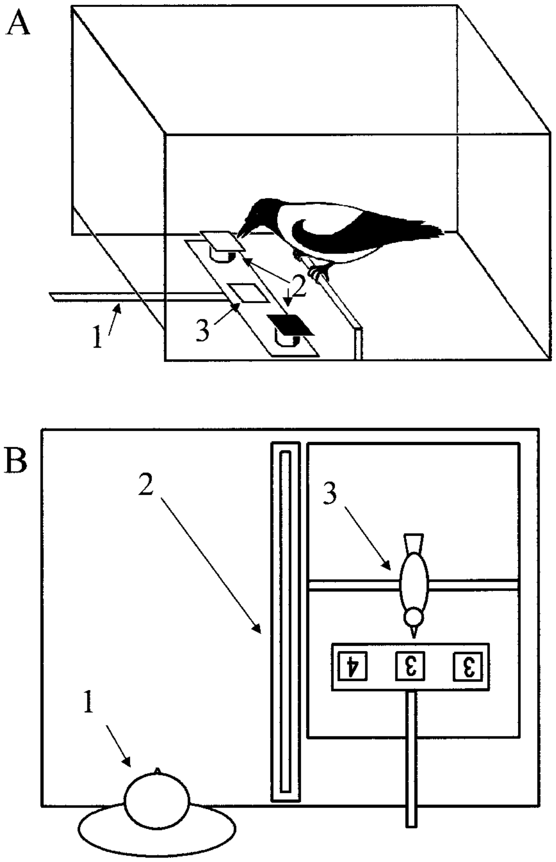


Fig. 1. Diagrams of the test apparatus. A: the stimulus presentation tray (1), the two cups covered by the stimulus cards (2), and a sample card (3) between them. B: the experimenter at the moment of the bird's choice (1), the opaque screen (2), and the crow (3).

Stimuli

The stimuli were cardboard cards measuring 7 cm by 7 cm. The stimuli were drawn from three categories: black and white, black Arabic Numerals 1 through 8 on a white background, and heterogeneous graphic arrays of one to eight elements of various colors and shapes on a white background. The latter set included two different cards for each number of elements. These cards differed in their elements' shape, color, and disposition. Elements were always standard and included uniform black dots, red squares, blue rectangles, and green triangles. For example, arrays of three elements consisted of a blue rectangle, a red square, and a black dot or a blue rectangle, a red square, and a green triangle (see Figure 2, Phases 6 and 8).

General Procedure

A two-alternative simultaneous matching-to-sample procedure was used. Three crows (207, 208, 251) were trained in a matching-to-sample paradigm; the others (250, 203, 297) were trained in an oddity-from-sample paradigm.

During the experiment a bird was placed into the experimental cage. A trial began when the tray with the cups covered with the cards was slid into the cage. To give the crow an opportunity to get acquainted with the stimuli, the tray was first placed for 2 to 3 s in front of the bird so that it could see the cards but could not open the cups. Then, after the tray was moved further into the cage, the crow opened one of the cups and, if the choice was correct, received the reinforcer. In the event of the wrong choice, the tray was quickly removed from the cage to prevent the crow from opening the other cup. If the bird did not choose any cup during 2 min, the tray was removed from the cage.

The type of the sample stimulus was determined by a quasirandom schedule under the restrictions that the same card not be used as a sample more than two times successively, and that the positive stimulus (S+) not appear in the right or left location on more than two successive trials. A permanent sequence of 10 trials was used in Phases 1 through 8 (Table 1), and a sequence of 48 unique trials was used in Phases 9 and 10 (Table 2).

During Phases 1 through 4 a correction procedure (repeated presentations of the same combination of stimuli) was used in the event of perseveration (repeated choices of the left or the right stimulus only). During the test phases (Phases 5 through 10), this procedure was not employed.

The training and testing in Phases 1 through 8 continued until a criterion of 80% correct or better over 30 consecutive trials was reached ($p < .001$; binomial probability test); thus, 30 trials were the minimum duration of any phase excluding Phases 9 and 10. Phases 9 and 10 consisted of a fixed number of trials (96 and 48 trials, respectively).

Daily experimental sessions were conduct-

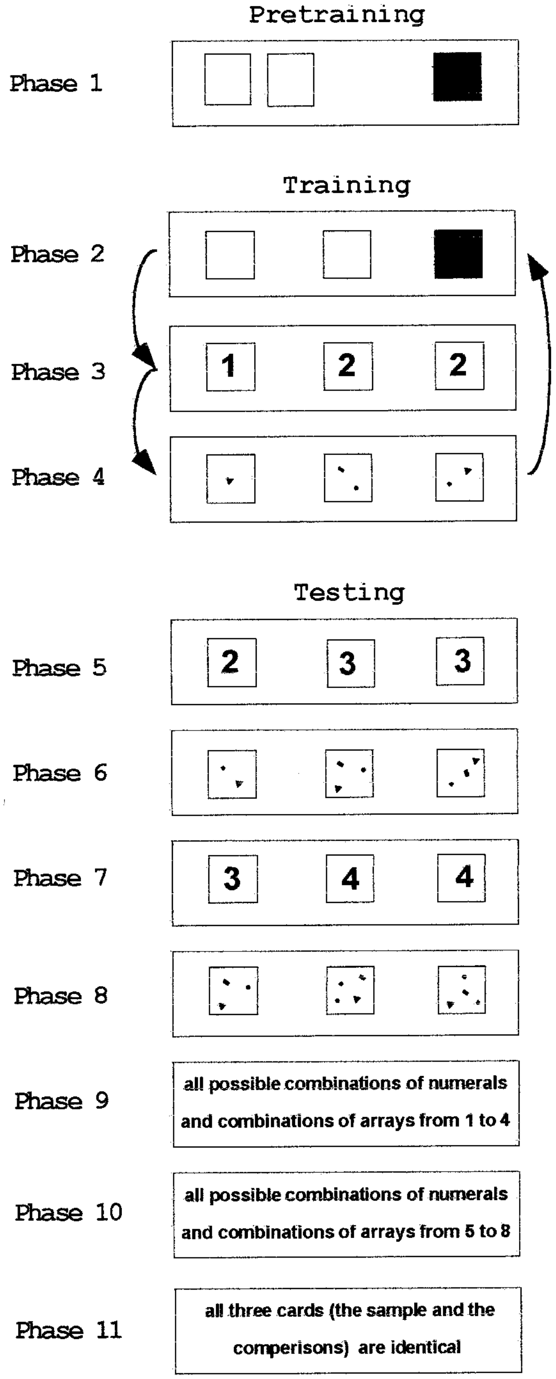


Fig. 2. Design of the experiment. Arrows indicate that Phases 2, 3, and 4 were repeated cyclically until a criterion was met in the first trials of each of the phases (see text for details).

Table 1

The sequence of trials presented in Phases 1 and 2. Analogous sequences were used in Phases 3 through 8, produced from the one shown by replacing "black" and "white" with other types of stimulus cards.

Trial number	Left card	Sample	Right card
1	Black	Black	White
2	White	White	Black
3	Black	White	White
4	Black	Black	White
5	Black	White	White
6	White	Black	Black
7	White	White	Black
8	White	Black	Black
9	Black	Black	White
10	Black	White	White

Table 2

Types of trials presented in Phase 9 (48 unique trials). The same sequence of combinations was used in Phase 10 with the difference that Arabic numeral 1 and array of 1 element were replaced by numeral 5 and array of 5 elements; 2 was replaced by 6, 3 by 7, and 4 by 8. Dots indicate arrays, the number of dots equaling the number of elements.

Trial number	Left card	Sample	Right card
1	2	3	3
2	4	4	1
3	●●●●	●●●●	●●
4	3	1	1
5	●	●	●●●●
6	●●●●	●●●	●●●
7	3	4	4
8	●●●	●●●	●●●●
9	1	1	4
10	●	●●●	●●●
11	4	4	2
12	4	3	3
13	●●	●●	●
14	3	2	2
15	●●	●●●	●●●
16	●	●	●●
17	●	●●	●●
18	1	1	3
19	●●●●	●	●
20	3	3	1
21	●	●	●●●
22	4	2	2
23	3	3	2
24	●	●●●●	●●●●
25	●●●●	●●●●	●
26	●●	●●	●●●
27	1	4	4
28	●●	●●	●●●●
29	2	4	4
30	●●	●	●
31	4	4	3
32	2	1	1
33	●●●	●	●
34	●●●	●●●	●
35	●●●	●●●●	●●●●
36	4	1	1
37	2	2	3
38	●●	●●●●	●●●●
39	1	1	2
40	2	2	1
41	●●●	●●	●●
42	1	3	3
43	●●●	●●●	●●
44	●●●●	●●	●●
45	3	3	4
46	●●●●	●●●●	●●●
47	1	2	2
48	2	2	4

ed 6 days each week and consisted of 40 to 60 trials. The exact number of trials per day depended on a bird's willingness to work on each particular day.

Training

Figure 2 shows the design of the experiment. The types of the trials presented during Phases 1 through 8 are shown in Tables 1 and 3.

Phase 1 (pretraining). During this phase the subjects were habituated to the experimental situation and the experimenter and learned to open the cups. For this purpose the experimenter placed mealworms into the cup within the bird's field of vision and covered it. After that the bird usually opened the cup quickly and ate worms without further training.

A set of black and white cards was used (Figure 2, Table 3). The sample was placed next to the cup with the comparison card of the same color (if the bird was trained in matching to sample) or vice versa (if it was trained in oddity from sample). Therefore, during this phase birds could also solve this task by the position of the sample without comparing the stimuli themselves.

Starting with Phase 2 the sample card was always placed exactly in the middle of the tray. Thus, birds could solve this task only by comparing the stimuli.

Phase 2. The same a set of black and white cards was used as in Phase 1, with the only difference that the sample card was placed at

Table 3

Types of trials presented in Phases 1 through 8. The alternation of the right and left locations of the comparison stimuli is not shown, so for each phase four combinations of the stimuli were possible. Dots indicate arrays, the number of dots equaling the number of elements.

Phase	Type of matching	Sample	Comparisons	
			S+	S−
1, 2	MTS	White card	White card	Black card
		Black card	Black card	White card
	OFS	White card	Black card	White card
		Black card	White card	Black card
3	MTS	1	1	2
		2	2	1
	OFS	1	2	1
		2	1	2
4	MTS	●	●	●●
		●●	●●	●
	OFS	●	●●	●
		●●	●	●●
5	MTS	2	2	3
		3	3	2
	OFS	2	3	2
		3	2	3
6	MTS	●●	●●	●●●
		●●●	●●●	●●
	OFS	●●	●●●	●●
		●●●	●●	●●●
7	MTS	3	3	4
		4	4	3
	OFS	3	4	3
		4	3	4
8	MTS	●●●	●●●	●●●●
		●●●●	●●●●	●●●
	OFS	●●●	●●●●	●●●
		●●●●	●●●	●●●●

equal distance from both cups (Figure 2, Table 3).

Phase 3. A set of novel cards (black Arabic Numerals 1 and 2 on white backgrounds) was used (Figure 2, Table 3).

Phase 4. Cards with graphic arrays consisting of one element (a green triangle or a black dot) and two elements (a green triangle and a red square or a blue rectangle and a black dot) on white backgrounds were used (Figure 2, Table 3). So, a sample stimulus and S+ had only one common feature during this phase, namely the number of elements.

To establish matching (or oddity), Phases 2 through 4 were cyclically repeated until the criterion was reached in the first 30 to 50 trials of each of the phases (Figure 2). Because the criterion was calculated across the first 30 trials, 30 trials were the minimum duration of any phase. Hereafter we will refer to the successive repetition of the three training sets of the stimuli (black and white cards, Arabic Numerals 1 and 2, arrays consisting of one and two elements) as a *cycle*.

Testing

Sets of novel stimuli were used to examine the transfer from training stimuli to novel ones (Figure 2). The first five tests (Phases 5 through 9) constituted partial transfer, during which new stimuli (Arabic Numerals 3 and 4 and arrays of three and four elements) were paired with the stimuli used in training (Arabic Numerals 1 and 2 and arrays of one and two elements). In the subsequent transfer test (Phase 10) only novel stimuli were presented (Arabic Numerals 5 through 8 and arrays of five to eight elements).

Phase 5. A novel stimulus (Arabic Numeral 3) was paired with the familiar one (Arabic Numeral 2).

Phase 6. A novel stimulus (arrays of three elements) was paired with the familiar one (array of two elements).

Phase 7. The stimulus used in Phase 5 (Arabic Numeral 3) was paired with an absolutely novel one (Arabic Numeral 4).

Phase 8. The stimulus used in Phase 6 (array of three elements) was paired with an absolutely novel one (array of four elements).

Phase 9. All six possible combinations of numerals and combinations of arrays, three of which had been used during training (1 and 2, 2 and 3, 3 and 4) and three of which had not (1 and 4, 2 and 4, 1 and 3), were mixed quasirandomly to yield 48 unique combinations (Table 2). This sequence of combinations was repeated twice for each bird (96 trials).

Phase 10. A set of absolutely novel stimuli (Arabic Numerals 5 to 8 and arrays of the same range) was used to investigate the transfer of matching (or oddity). As in the previous stage, all six possible combinations of numerals and arrays were alternated according to the pseudorandom schedule (48 unique trials altogether; see Table 2).

Phase 11. A specially designed test of 32 trials was used to rule out possible artifacts (such as the rustling of worms in the cup or their odor). During this test all three cards (the sample and the comparisons) were identical. Thus, both left and right comparisons were correct and matched the sample, but only one cup (sometimes left, sometimes right quasirandomly) was baited with mealworms. Therefore, this task does not have any logical solution. If such artifacts affect birds' choice, their performance will differ from chance.

RESULTS

Acquisition

Matching-to-sample and oddity-from-sample acquisition (Phases 1 through 4) and testing (Phases 5 through 10) for all 6 crows are shown in Figure 3. The number of trials to criterion during training and testing for the 4 successful birds is shown in Table 4. The performance of Crow 250, which had a previous experimental history involving conditional discrimination, did not significantly differ from the performance of other birds [Mann-Whitney *U* test, $U(1, 78) = 258$, $p = .41$]. A Mann-Whitney *U* test also failed to detect any difference between oddity and matching groups, $U(1, 78) = 697$, $p = .64$.

These data contrast with earlier works (Wilson et al., 1985) demonstrating that jays and jackdaws learned the oddity task more rapidly than matching. On the other hand, the differences between matching and oddity acquisition may be ambiguous, as Carter and Werner (1978) demonstrated in their review of such data in pigeons. We suppose that the difference between our data and the data of Wilson et al. can be explained by considerable individual variation among the birds: In 4 birds learning took from 1,780 to 5,260 trials, whereas 1 of the birds (Crow 203) did not learn after more than 6,000 trials. This individual variability is common and is revealed in many forms of complex cognitive abilities and logical problem solving (Zorina, 1997).

During the first phases of the experiment acquisition was slow (Table 4, Figure 3), with some rare exceptions. For example, Crow 203 met criterion during Phase 2 of the first cycle after 50 trials. Moreover, the performance of this crow in the first 30 trials was significantly above chance ($p \leq .05$, binomial probability test). Rapid acquisition to the criterion by this bird suggests that during pretraining it may have solved this task both by the position of the sample and by the comparison of the color of the stimuli (i.e., it acquired information that was not necessary for the solution of this particular task).

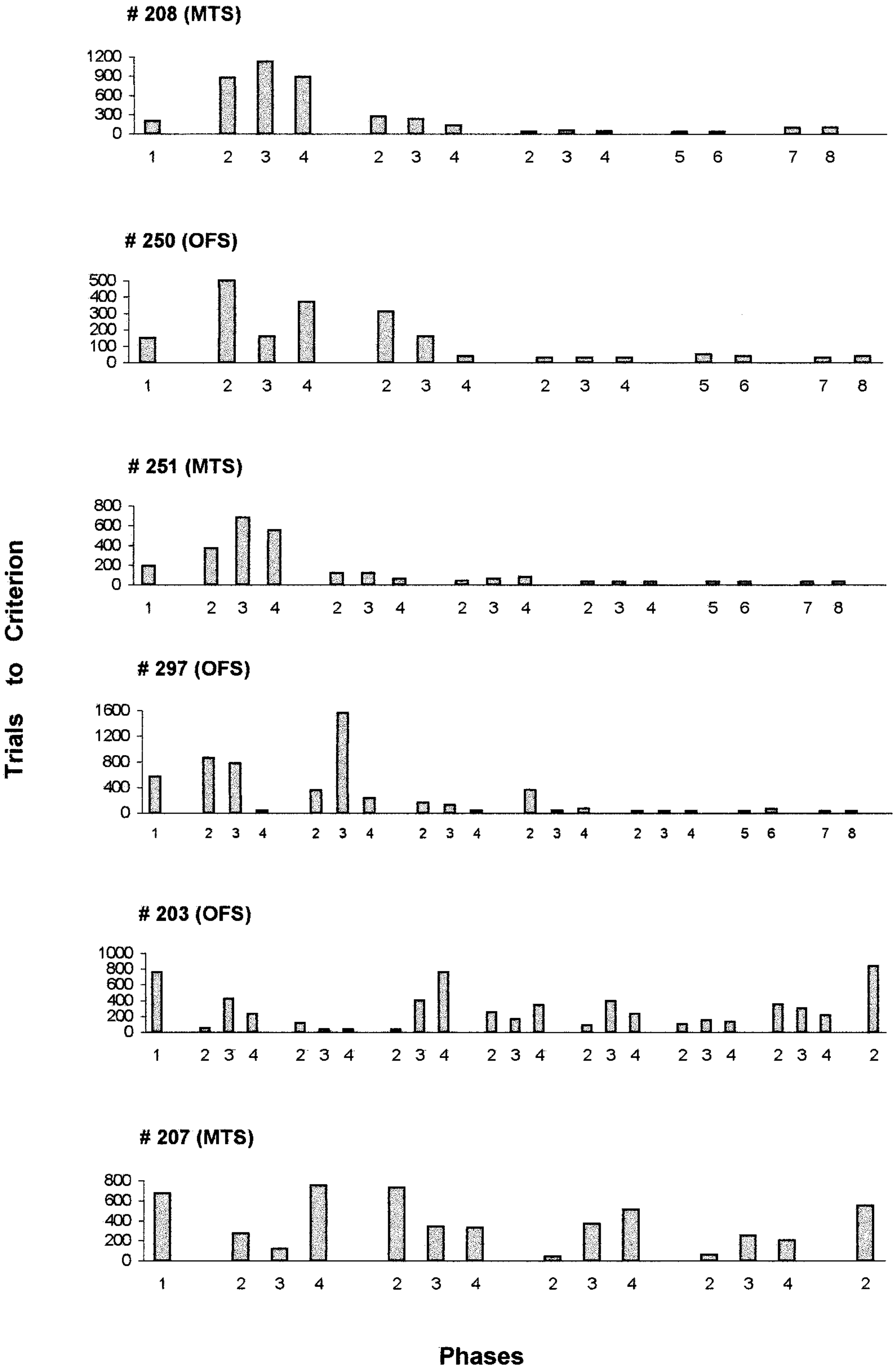
During Phase 4 of the first cycle, Crow 297 met criterion after only 40 trials, and the performance of another crow (207) during the first 30 trials of this phase was above chance (70.0%, $p < .03$, binomial probability test), although acquisition of the criterion (80%) took 750 trials (Figure 3). Moreover, a Mann-Whitney *U* test of the pooled data from all subjects did not reveal any difference between the crows' performance on the array stimuli and on the shape or color stimuli during the first three cycles, $U(1, 78) = 611$, $p = .49$. Thus, we may suppose that for the birds numerousness was as obvious an attribute as color or shape (see also Discussion).

The number of cycles before the completion of learning varied considerably among subjects (Figure 3, Table 4). Crow 297, which solved the task during Phase 4 of the first cycle (arrays of one and two elements) after only 40 trials, met criterion during Phase 2 of the second cycle (black and white cards) after 380 trials, and during Phase 3 of the second cycle (Arabic Numerals 1 and 2) after 1,560 trials (instead of 860 and 770 trials, respectively, required at the first cycle).

Two crows (203 and 207) failed to learn (Figure 3), and experiments with them were discontinued. Only the other 4 birds (250, 208, 251, and 297) participated in further phases with new sets of stimuli.

Testing

As noted above, the first five tests (Phases 5 through 9) evaluated a partial transfer, in which new stimuli (Arabic Numerals 3 or 4 and an array of three or four elements) were paired with familiar ones (Arabic Numerals 1 or 2 and an array of one or two elements). Figure 4 shows the percentage of correct responses on the first 30 trials of each of the training and testing phases. In general, all 4 birds transferred the matching rule to the combination of the familiar and novel stimuli successfully: Their performance in the first 30 trials was significantly above chance. The only exception was the failure of Crow 208 during Phase 8 (66.7% correct trials, $p > .05$, bino-


208 (MTS)
1200
900
600
300
0
1 2 3 4 2 3 4 2 3 4 5 6 7 8
250 (OFS)
500
400
300
200
100
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1 2 3 4 2 3 4 2 3 4 5 6 7 8
251 (MTS)
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1 2 3 4 2 3 4 2 3 4 2 3 4 5 6 7 8
297 (OFS)
1600
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1 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 5 6 7 8
203 (OFS)
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1 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2
207 (MTS)
800
600
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1 2 3 4 2 3 4 2 3 4 2 3 4 2
Trials to Criterion
Phases

mial probability test). All cases of failure of immediate transfer (the performance in the first 30 trials below 80%) appear in Table 5. In several failures the birds' performance in the first 30 trials was only a little below 80% (Table 5).

The performance during Phase 9 when all (new and familiar) combinations of the stimuli were alternated is similar to that in the previous phases of the test. Performances on the novel combination transfer task (Phase 9) and on the novel transfer task (Phase 10) are shown in Table 6. The performance of all 4 birds was good both during the first 30 unique trials and during the 96 trials taken together (Table 6, Figure 4). The possibility of retraining at Phase 9 was analyzed with a Kruskal-Wallis analysis of variance (ANOVA). For this analysis we used four 10-trial blocks as an independent factor (each of the first 10 trials was assigned Number 1, the next 10 trials were Number 2, etc.; four blocks altogether). A single-trial performance (correct or incorrect) was used as a dependent factor. The statistical analysis did not reveal any significant effect, $H(3, 160) = 4.5$, $p = .21$.

Only for 1 crow (251) was performance during the first 30 trials a little below 80% (73.3%, $p = .01$, binomial probability test, Table 6).

None of the subjects' performances with the familiar combinations was significantly different from performance with novel combinations (t test for difference between two percentages, $p > .05$). Moreover, performance with the array stimuli did not differ significantly from their performance with Arabic numerals (t test for difference between two percentages, $p = .85$). Therefore, it can be concluded that the crows successfully transferred the matching and oddity rule to the novel combinations of the stimuli.

Table 4

Number of trials to criterion (80% correct or better over 30 consecutive trials, $p < .001$, binomial probability test) during training (1–4) and testing (5–8) phases for the 4 successful birds.

	Crow			
Phase	208	250	251	297
1	200	150	190	570
2	870	500	370	860
3	1,120	160	680	770
4	890	370	550	40
2	270	310	120	350
3	230	160	120	1,560
4	130	40	60	230
2	30	30	40	160
3	50	30	60	120
4	40	30	80	40
2			30	360
3			30	40
4			30	70
2				30
3				30
4				30
5	30	50	30	30
6	30	40	30	60
7	90	30	30	30
8	100	40	30	30

The final test (Phase 10) evaluated a novel transfer. Only novel stimuli were presented during this test (Arabic Numerals 5 to 8 and graphic arrays of five to eight elements). All possible combinations of these stimuli were alternated quasirandomly (48 unique trials altogether). In our opinion, this procedure completely excluded the possibility of retraining during the test although reinforcement was used. This assumption was examined with a Kruskal-Wallis ANOVA. For this analysis we used four 10-trial blocks as an independent factor (each of the first 10 trials was assigned Number 1, the next 10 trials were Number 2, etc.; four blocks altogether). A single-trial performance (correct or incorrect) was used as a dependent factor. Statistical analysis did not reveal any significant effect, $H(3, 120) = 0.83$, $p = .84$.

In the first 30 unique trials, performance of all 3 birds (Crow 250 did not participate in Phase 10) was significantly above chance (Table 6): Crow 208 at 83.3% ($p < .0001$), Crow 251 at 73.3% ($p = .01$), Crow 297 at 80.0% ($p = .0001$, binomial probability test). The performance during this phase was as

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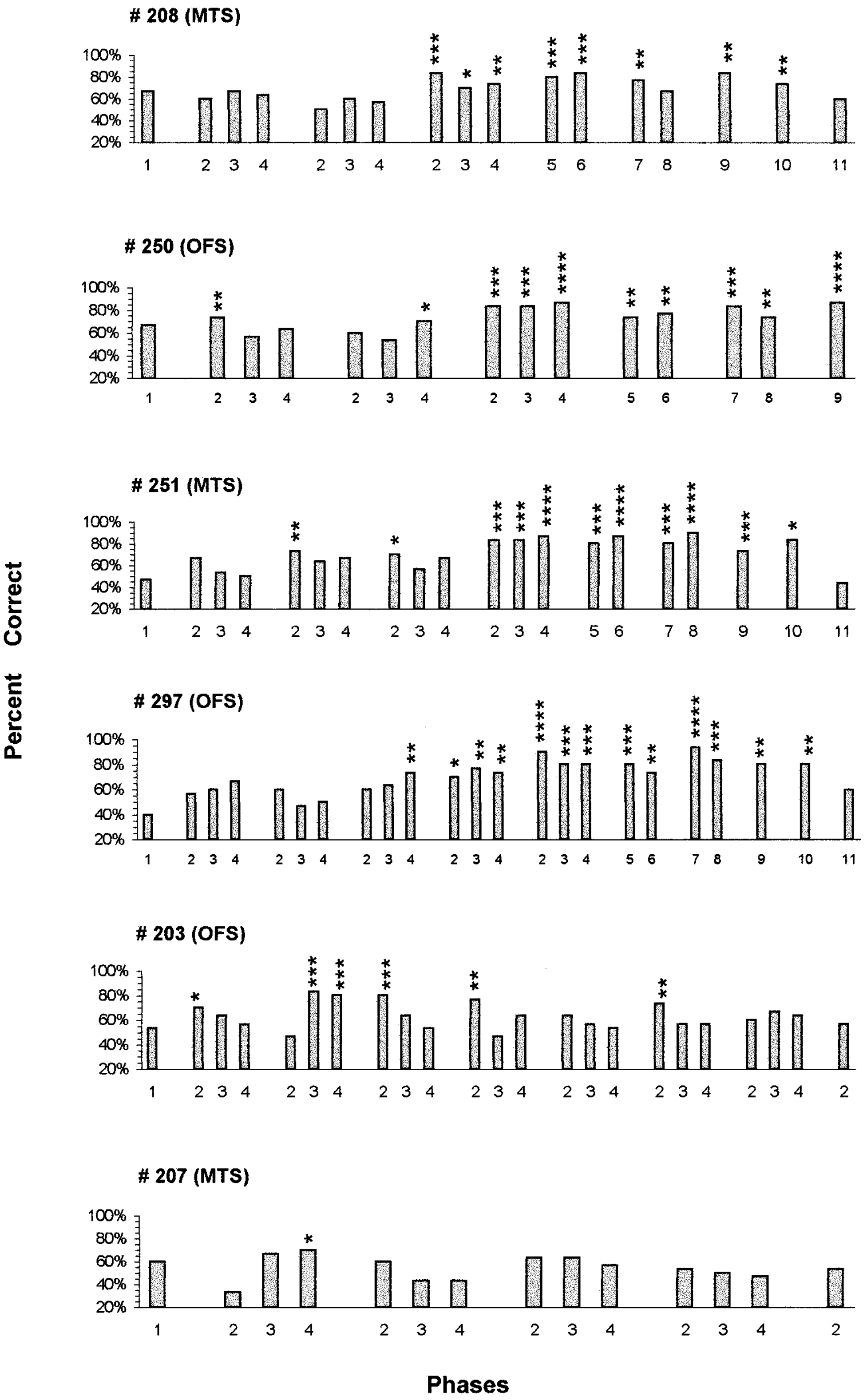
Fig. 3. Matching-to-sample and oddity-from-sample acquisition (Phases 1 through 4) and testing (Phases 5 through 8). Performance is shown as the number of trials to criterion. MTS and OFS indicate that either a matching-to-sample or an oddity-from-sample procedure, respectively, was used for a particular bird.


208 (MTS)
250 (OFS)
251 (MTS)
297 (OFS)
203 (OFS)
207 (MTS)
100%
80%
60%
40%
20%
1 2 3 4 2 3 4 2 3 4 5 6 7 8 9 10 11
1 2 3 4 2 3 4 2 3 4 5 6 7 8 9
1 2 3 4 2 3 4 2 3 4 2 3 4 5 6 7 8 9 10 11
1 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 5 6 7 8 9 10 11
1 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2 3 4 2
1 2 3 4 2 3 4 2 3 4 2 3 4 2
Percent Correct
Phases

good as that in Phase 9 for all 3 subjects ($p > .05$, t test for difference between two percentages). Moreover, performance with the array stimuli did not differ significantly from their performance with Arabic numerals (t test for difference between two percentages, $p = .91$).

The test (Phase 11) that was conducted to rule out artifacts (such as the crows hearing the worms stirring) demonstrated that such artifacts did not affect choice performance (Figure 4). The crows' performance did not significantly differ from the chance level (Crow 208 at 59.4%, Crow 251 at 43.8%, and Crow 297 at 59.5%, $p > .05$, binomial probability test).

Hence, all 3 birds actually transferred the matching rule not only to novel combinations of the familiar stimuli but also to novel unfamiliar stimuli.

Analysis of Possible Effects of Difference Between Two Arrays and Their Size on Performance

Possible effects of difference between two arrays and their size were analyzed with a Kruskal-Wallis ANOVA. For this analysis as independent factors we used the indices of absolute and relative difference. The term *relative difference* refers to the ratio of the absolute difference between the arrays ($\Delta = \max - \min$) to the size of the larger of them (max): $\Delta/\max$ (Zorina & Smirnova, 1994). Single-trial performance (correct or incorrect) in Phases 9 and 10 was used as the dependent variable. The statistical analysis did not reveal any significant effect: for relative difference, $H(6, 264) = 5.5$, $p = .48$; for absolute difference, $H(2, 264) = 3.3$, $p = .19$. The absence of a significant effect may be due to the lack of experimental data, because the study of such a relation was not our goal. A thorough analysis had been conducted earlier (Zorina & Smirnova, 1994), and it also did not reveal any significant relation between the accuracy and the absolute and relative differences in crows, although in pigeons such an effect was found.

Table 5

Cases of failure of immediate transfer (the performance in the first 30 trials below 80%). Transfer performance was calculated as the percentage of correct trials in the first 30 trials of the test. None of these cases of transfer performance was significantly different from 80% (t test for fractions). Values of p indicate probability according to a binomial test.

Crow	Phase	Transfer performance %	Transfer performance p
208	7	76.7	<.01
	8	66.7	>.05
	10	73.3	.01
250	5	73.3	.01
	6	76.7	<.01
	8	73.3	.01
251	9	73.3	.01
297	6	73.3	.01

DISCUSSION

Our results demonstrate that hooded crows are capable of matching and oddity from sample both by physical resemblance (color, shape) and by the number of elements in heterogeneous graphic arrays.

We used a new training technique—a successive repetition of stimuli of three different categories (color, shape, and number of elements). This technique allowed us to observe the shift from the ''if . . . then'' associations, applied only to the familiar stimuli, to a general rule, applied to any novel stimuli (Carter & Werner, 1978).

It has been demonstrated previously that animals frequently show little or no transfer when they learn matching to sample with a limited set of training stimuli (Wright et al., 1988). The exception is chimpanzees, which are capable of applying the matching concept to novel items following training with only two stimuli (Oden et al., 1988). If the number

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←

Fig. 4. Percentage of correct responses in the first 30 trials of each of the phases. Performance is shown as a percentage of correct trials. The number of asterisks indicates significance level: $*p \leq .05$, $**p \leq .01$, $***p \leq .001$, $****p \leq .0001$ (binomial probability test). MTS and OFS indicate that either a matching-to-sample or an oddity-from-sample procedure, respectively, was used for a particular bird.

Table 6

Performance on the novel combination transfer task (Phase 9) and on the novel transfer task (Phase 10). The performance was calculated as a percentage of correct trials during each phase.

	Performance (%)					
	Phase 9				Phase 10	
Crow	On the first 30 trials	On the 48 familiar combinations	On the 48 novel combinations	On the 96 trials altogether	On the first 30 trials	On the 48 trials altogether
250[a]	86.7***	87.5***	87.5***	87.4***		
297	80.0**	85.4***	83.3***	84.4***	80.0**	83.3***
251	73.3*	68.7*	85.4***	77.0***	83.3**	75.0**
208	83.3**	75.0**	81.3***	78.1***	73.3*	83.3***

[a] Crow 250 did not participate in Phase 10.

* $p \leq .01$, ** $p \leq .001$, *** $p \leq .0001$ (binomial probability test).

of training stimuli is limited, subjects can acquire item-specific associations or ''if . . . then'' rules (Carter & Werner, 1978; Wright et al., 1988). Such strategies might allow a subject to respond correctly to familiar stimuli, but they do not require abstract concept formation and thus will fail with novel unfamiliar stimuli.

In our experiment, during the first training phases crows presumably used separate sets of ''if . . . then'' rules for each of the training sets. We concluded so because the level of correct choices decreased to chance after presentation of stimuli of other categories (Figure 4). As cycles were repeated, the number of trials to criterion with these same sets gradually decreased. At last, the birds began to reach the criterion with every training set after almost a minimum number of trials (30 to 50 trials; see Figure 3). However, it was not clear without additional testing procedures whether the birds used the general rule or three separate sets of ''if . . . then'' ones at the end of training.

Transfer of the matching rule by applying it to new items can be used as the measure of abstractness of the matching (or oddity) concept (Mackintosh, 1988). To evaluate the level of transfer in crows, we applied two types of transfer tests: partial transfer tests (Phases 5 through 9) that consisted of either new combinations of familiar stimuli or combinations of novel stimuli with familiar ones, and a novel transfer test (Phase 10) that included only novel stimuli. Partial transfer, as demonstrated earlier (Farthing & Opuda, 1974; Pack et al., 1991), is a considerably simpler task because of the possibility of responding on the basis of the stimulus relations that were either reinforced or nonreinforced during training. For example, a bird tested with a set of Arabic Numerals 2 and 3 (Phase 5) could use an ''if see 2, then choose 2'' rule elaborated in previous training.

At least 3 crows successfully solved both types of tests without any significant difference between their performances. Note that Crow 208, which demonstrated lack of transfer only during Phase 8 (Table 2), transferred the matching rule both to new pairs of the familiar stimuli during Phase 9 and to absolutely novel stimuli (Phase 10). Thus, after several (three to five) cyclical repetitions of the three sets of stimuli from three different categories, all 4 crows acquired the abstract concept of matching (or oddity).

It should be emphasized that these birds were able to apply the matching and oddity rules not only to stimuli identical to each other (by color or shape) but also to stimuli corresponding to each other only by the number of elements in arrays. All the arrays used in our experiments differed in the shape, color, or disposition of elements. Thus, the birds could select a card with an array that consisted of a blue rectangle and a black dot if the sample was a card with an array that consisted of a red square and a green triangle, and vice versa. To solve this task, a crow had to determine the number of elements on the sample and compare it with the number of elements on the comparison cards.

The arrays of items were used as stimuli for the first time during Phase 4. This task (comparison of the stimuli by the number of the elements regardless of such attributes as color, shape, and disposition) seemed to us to be more complex than the two previous ones, during which the sample was always identical to one of the comparison stimuli. Nevertheless, performance of Crows 297 and 207 on the first 30 trials with array stimuli presented for the first time (Phase 4; Figure 4) was well above chance. These facts may indicate some transfer of the matching rule to the stimuli of another category, that is, from matching (or oddity) by physical appearance of the stimuli to matching by the corresponding (or noncorresponding) number of elements. Moreover, we did not detect any difference between the crows' performance on the array stimuli and on the shape or color stimuli. In other words, we may suggest that numerousness was not a more complex attribute of stimuli than color or shape.

One of the important criteria of number concept in animals is the transfer to numerical stimuli of a new range (Davis & Perusse, 1988; Koehler, 1956). In the novel test (Phase 10) we used heterogeneous graphic arrays consisting of five to eight elements of different shape, color, and disposition. Therefore, birds' performance could not be based on pattern recognition because the arrays were from a new range that was too great for this mechanism (Davis & Perusse, 1988). Note that pattern recognition of simultaneous visual stimuli has typically been confined to arrays with no more than five items (Mandler & Shebo, 1982). Miller argues that ''for random arrays of more than 4 objects, there are simply too many possible resulting configurations, making discrimination based on pattern difficult, if not impossible'' (1993, p. 161). It seems likely that crows are, indeed, capable of recognizing heterogeneous graphic arrays by the number of elements itself and can apply the matching (or oddity) concept to the novel stimuli of numerical category.

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