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Relational thinking in animals and humans: From percepts to concepts

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"The power of abstraction has its germ in sense-experience (1894, p. 264)." So wrote the famous comparative psychologist C. Lloyd Morgan well over a century ago. At issue was how we progress from direct sense impressions to more abstract conceptual thoughts, a matter which still intrigues psychological scientists and about which we are concerned in the present chapter.

Morgan was especially interested in the abstract idea of sameness. He believed that the perception of similarity was basic to relational and conceptual thought—even to our appreciation of higher-order relations between relations. Morgan invites us into the realm of relational thinking in the following way: "Suppose that we are looking over a series of coins or other similar objects. As we pass from one impression to another, we sense, or are marginally aware of, the similarity of each to each. We may then make the likeness of any two focal in consciousness and perceive the relation of similarity. We may go [even] further and perceive that the relation of this to that is similar to the relation of that to the other—we may perceive the similarity of the relations. But the relations that we perceive to be similar are particular relations. Not until the particular fades from view, and the relationship, as common to all the particular instances, becomes focal, do we reach the conception properly so-called (pp. 263-264)."

Based on the extremely limited evidence that was available to him, Morgan concluded that only adults are capable of such conceptual or abstract thought. He further proposed that young children are initially incapable of abstract thought and that animals altogether lack this advanced cognitive capacity.

Morgan's views on the abstract idea of sameness were strongly shaped by the relationship between language and conceptualization. "Our conception of similarity is indefinite from its very generality, and the moment we try and make it clear and precise to our mind's eye, we make it particular by thinking of an illustrative example. We exemplify the conception by reference to a particular perception. The symbolic name, however, serves to fix the general conception without particularizing it (pp. 264-265)." Hence, Morgan deemed the final step in the process of abstraction to be the complete uncoupling of perception and conception through analysis and synthesis. "We find in a great number of particular cases, with which reflection presents us, the relation of similarity, and submitting these cases to analysis, we detach the relation from the related terms. But the relation is given in experience as a similarity now of colour, now of musical notes, now of pressures, now of tastes, now of scents, and so forth. Fusing these together, we reach the synthetic general conception of this relation as of universal application, and label it "similarity" (p. 265)." So, despite the fact that abstraction may have its germ in sense-experience, by virtue of symbolic labeling, Morgan proposed that perception and conception might no longer be coextensive.

Even today, we find Morgan's rich observations and incisive speculations to be particularly interesting and relevant. They serve as a fitting introduction to a view of cognitive processing which effectively encompasses an exciting realm of contemporary psychological science: namely, the development and evolution of relational cognition.

Chapter Overview

In the present chapter, we explore the possible continuity in relational and analogical cognition between humans and nonhuman animals. Relational reasoning—particularly appreciating the relation between relations, as in analogies—represents what many theorists believe to be the pinnacle of human cognition. Nevertheless, recent evidence suggests that such abstract relational thought does not arise *de novo*; rather, it develops in humans and its evolutionary roots can be observed in the behavior of animals.

To embrace these exciting research discoveries, we outline an emerging theoretical perspective on the development and evolution of relational thinking, which proposes that perceptual and relational processes are intimately interrelated in both humans and animals. The ultimate uncoupling that Morgan hypothesized may prove to be unattainable, as Goldstone and Barsalou (1998) suggest: “Concepts usually stem from perception, and active vestiges of these perceptual origins exist for the vast majority of concepts (p. 232).”

Specifically, our review will consider mounting research in the realm of animal cognition which undermines the common belief that same-different conceptualization is uniquely human. Considerable evidence indicates that many species can master (first-order) same-different relations. Even more challenging tasks requiring appreciation of the relation between relations (second-order relations) can be mastered by (possibly fewer) animal species.

Evidence also suggests that relational control in animals does not emerge distinct from perceptual control: the processing of individual stimuli is foundational to and continuous with the processing that occurs between or among stimuli. This finding holds true for animals’ processing of both first-order and second-order relations.

Critical to the comparative analysis of relational cognition, we further ask: Are these findings peculiar to animals? Here, the answer appears to be: “No.” Although animals may not achieve relational thinking of the same versatility and complexity as do humans, striking behavioral similarities nevertheless emerge. Especially important is the observation that, during development, children too move from perceptually-based to relationally-based processing, owing to innumerable relevant experiences. Human adults can go even further and solve third-order relational tasks (judging the relation between relations of relations; Kroger, Holyoak, & Hummel, 2004). Yet, here too, perceptual processes still seem to be intimately involved.

Finally, although both animals and humans engage in perceptually- and relationally-based processing in complex judgment tasks, the role of symbolic language cannot be ignored. In this connection, we observe that linguistic encoding of higher-order judgment tasks may ease and promote relational thinking in children; nevertheless, language appears not to be mandatory for relational thought, as demonstrated by the success of nonverbal animals in mastering advanced relational tasks. We suggest that the contribution of language to relational thinking might best be seen to provide abstract symbols for humans to re-encode and simplify complex stimulus relations, thereby permitting us to solve higher-order relational problems that may be beyond the cognitive reach of animals which lack symbolic language.

Item vs. Relation Control in Animal First-Order Same-Different Discrimination

Basic to all studies of first-order same-different discrimination learning in animals is that arrays of two or more items must in some way be reported as involving same or different interstimulus relations. This requirement holds across a wide range of discrimination learning procedures with pigeons, a key species in the experimental investigation of same-different conceptual behavior: two-alternative forced-choice training displaying a single array of items (e.g., Wasserman, Hugart, & Kirkpatrick-Steger, 1995); two-alternative forced-choice training displaying two or more successively presented arrays of items (e.g., Young, Wasserman, & Dalrymple, 1997); conditional same-different discrimination training displaying two or more simultaneously presented arrays of items (e.g., Castro, Kennedy, & Wasserman, 2010); and, go/no-go same-different discrimination training displaying a single array of items (e.g., Wasserman, Frank, & Young, 2002). We will further describe these and other discrimination methods as we consider a series of important substantive issues.

Influence of item information and number of items on generalization performance

It has become standard practice in the study of pigeons' same-different discrimination learning to begin an experiment by creating two sets of individual items from a common pool of visual stimuli: one set containing all possible *training* items and a second set containing all possible *testing* items. After discrimination mastery, a generalization test must be conducted in order to confirm that discriminative control by the familiar items in the training set effectively transfers to the novel items in the testing set. Successful transfer is the indisputable empirical hallmark of a same-different concept, because it requires relational control by untrained items.

No matter how many items are contained in each visual display—from 2 (the smallest possible number) to 16 items is typical—these items are customarily selected from a single training or testing set in order to create displays of identical items (same displays) and nonidentical items (different displays). This selection method guarantees that each individual item has an equivalent likelihood of appearing in both same and different displays, thereby encouraging behavioral control by the same-different *relations* and discouraging behavioral control by the identities of the individual *items*. Figure 1 depicts a small sampling of such multi-item arrays originally used by Wasserman et al. (1995). Note that the individual items in the same and different arrays in Set 1 do not overlap with the items in Set 2. Also note that the individual items in the same arrays can also appear in the different arrays in Set 1 (the locomotive and the compass) and Set 2 (the brain and the music notes).

The effectiveness of these particular procedural practices is confirmed by effective behavioral transfer from the training displays to the testing displays in most published reports of same-different discrimination behavior in both pigeons and humans (reviewed by Wasserman & Young, 2010). Notwithstanding such successful behavioral transfer, discriminative performance to the novel testing displays frequently falls below that to the familiar training displays. This *generalization decrement* is believed to be due to the animals' remembering the individual training items during acquisition, despite the utter irrelevance of those individual items to the programmed demands of the discrimination task. Clearly, item and relation processing can co-occur in the mastery of basic same-different discrimination learning tasks.

To take just one example of such joint item and relation processing, consider the study by Young and Wasserman (1997, Experiment 1). These researchers first taught pigeons to peck one report button when they viewed a stimulus array comprising 16 copies of the same computer icon and to peck a second report button when they viewed a stimulus array comprising 16 different computer icons. Correct button responses produced food reinforcement; incorrect button responses failed to do so and led to one or more correction trials. Rather than placing the 16 icons of the same and different displays into a *completely* filled 4 × 4 grid (Figure 1), these investigators placed the 16 icons into an *incompletely* filled 5 × 5 grid (Figure 2) in order to weaken the role of stimulus "orderliness" in the pigeons' discrimination behavior, because arrays of identical items may appear to be more orderly than arrays of nonidentical items.

Despite deploying this method of upsetting the orderliness of the stimulus arrays, the pigeons' acquisition of discriminative responding was quite rapid and they showed strong transfer to displays of novel items. Over the course of post-acquisition testing, discriminative performance to displays created from the training icons averaged 93% correct and discriminative performance to displays created from the untrained testing icons averaged 79% correct. Choice accuracy was much higher than chance to both the training displays and to the testing displays, but accuracy was nevertheless lower to the testing displays than to the training displays.

Considerable research has explored the nature of this generalization decrement. A key determinant of the disparity between training and testing performance is the number of items in the training set. Increasing that number progressively improves the accuracy of performance to the novel testing displays, thereby decreasing the disparity in discrimination performance between the training and testing displays (e.g., Castro et al., 2010; Young et al., 1997); in fact, with a sufficiently large set of training items, nearly complete generalization to novel testing displays has been documented (e.g., Castro et al., 2010). Such robust transfer testifies to the strength of behavioral control by the same-different relations at the possible expense of control by the identity of the individual training items.

To illustrate the role of the number of training items on same-different discrimination behavior, consider the study by Castro et al. (2010, Experiment 1). That project used a conditional discrimination task—introduced by Flemming, Beran, and Washburn (2007)—in which arrays of 16 identical and 16 nonidentical items were simultaneously presented on the pigeon's touchscreen (Figure 3). The birds had to learn a same-different discrimination *conditional* on the color of the background screen; each bird had to peck either the same array or the different array depending on whether the background color was pink or black. Two groups of pigeons were given this task: for one group the items came from a 24-item pool (Group 24), whereas for the other group the items came from a 72-item pool (Group 72). After training, all of the birds were tested with a common set of novel same and different stimulus arrays.

Initial acquisition proved to be faster for pigeons trained with stimuli from a 24-item pool than for pigeons trained with stimuli from a 72-item pool. However, transfer to arrays composed of novel stimuli showed the opposite trend. In Group 24, accuracy on transfer testing trials (70%) was decidedly lower than on training trials (94%); yet, in Group 72, accuracy on transfer testing trials (87%) was almost as high as accuracy on training trials (91%).

Prior basic-level object categorization studies with human adults (Homa, Cross, Cornell, Goldman, & Schwartz, 1973), human infants (Hayne, 1996), and pigeons (Wasserman & Bhatt, 1992) have also found that the number of exemplars in a category during initial learning strongly affects later transfer performance; the more exemplars presented during the learning phase, the better the classification of novel exemplars during the transfer phase. Presumably, a large number of training stimuli enhances categorical control by increasing information about the generic features of the category and/or by reducing the salience of those features that are specific to each of the exemplars (Soto & Wasserman, 2010). This overall pattern of results is clearly consistent with the idea that pigeons are initially attentive to both item and relational information, with more and more items increasingly taxing the birds’ capacity for memorization. This idea is also consistent with the supposition that item control is foundational to relation control; items should have to be processed before relations can be discerned, as Morgan suggested.

Relative contributions of item and relation information to same-different learning

Several additional tasks have now been devised to assess the relative strength and speed of emergence of item and relation control in the course of same-different discrimination learning

(Gibson & Wasserman, 2003, 2004; Wasserman & Frank, 2007; Wasserman et al., 2002). The invention of these tasks has been expressly guided by the plausible suspicion that item control might be stronger and emerge sooner than relation control.

For example, in Gibson and Wasserman (2003, 2004), both item and relation information was arranged to provide *redundant* cues for discrimination mastery; this redundancy was accomplished by composing all of the same training displays from one set of 16 items (Set A) and by composing all of the different training displays from a second set of 16 items (Set B) (see Figure 4, top row, which further jittered the position of the items in the arrays to disrupt the pigeons' discrimination of item orderliness). Specifically, Gibson and Wasserman (2004) adapted the earlier methods of Gibson and Wasserman (2003) to train pigeons to discriminate displays of 16 same items from displays of 16 different items. Both the specific features of the items and the relations among the items could serve as discriminative features of the displays during training. Pecks to one report button were reinforced with food reinforcement in the presence of identical visual items from Set A (same displays), whereas pecks to a second button were reinforced in the presence of nonidentical visual items from Set B (different displays).

Gibson and Wasserman monitored item and relation control "on-line" with a low frequency of probe tests as the birds were acquiring the same-different discrimination. To assess the development of stimulus control by the relations among the icons, they tested the pigeons with displays of identical and nonidentical stimuli from a third set of 16 items (Set C) during each session. They also tested the pigeons with displays of identical items from Set B and with displays of nonidentical items from Set A during each session; these "reversed" displays pitted relational control and item control against each other. This on-line monitoring procedure allows one to examine possible differences in the time-course of item and relation control during same-different discrimination learning.

The results of the Gibson and Wasserman study suggested that both specific stimulus features and relational cues exerted equivalent behavioral control over the pigeons' initial choice behavior, with the specific stimulus features exerting stronger control during the final three-fourths of same-different learning. These findings thus replicated earlier research suggesting that pigeons encode both the specific stimulus features and relational cues to which they were exposed, and for the first time documented the time-course of control by each kind of cue. The weaker relational control than item control in this study may be attributable to the fact that only 16 items were contained in each of training Sets A and B.

All of the research discussed so far suggests that, when they must do so to earn food reinforcement, pigeons learn to make discriminative responses to arrays of pictures that are either the same as or different from one another. But, is explicit training the only way for organisms to exhibit relational discrimination behavior? Or might other behavioral methods, that do not demand explicit same-different discrimination, disclose this cognitive capacity for abstraction? These questions inspired Wasserman et al. (2002) to devise another kind of discrimination learning method that might shed fresh light on same-different discrimination learning, in general, and on the interrelation between item and relation control, in particular. Figure 5 illustrates a small sampling of the many thousands of actual pictorial displays that they showed their pigeons. Pigeons saw stimulus arrays comprising 16 icons that were either the same as or different from one another. The stimuli for both same and different arrays were selected from one of two sets of computer icons. Thus, there were four kinds of stimulus displays—Same 1, Different 1, Same 2, Different 2—where 1 and 2 refer, respectively, to two sets of computer icons.

Initially, the pigeons' pecks to all *four* kinds of displays produced food reinforcement.

Later, pecks to only *one* of the four kinds of displays produced food reinforcement. For one illustrative pigeon (whose reinforcement contingencies are illustrated in Figure 5), Same 1 arrays were positive discriminative stimuli or S+s; hence, pecks to Same 1 displays produced food reinforcement. Pecks to Different 1, Same 2, and Different 2 arrays were negative discriminative stimuli or S-s; so, pecks by this pigeon to any of these three displays did not produce food reinforcement. For different pigeons, other S+s and S-s were arranged, so that pecks to only one type of display produced food reinforcement, whereas pecks to all three of the other types of displays did not. All four types of displays—Same 1, Different 1, Same 2, Different 2—served as the S+ for different pigeons in the full experimental design.

Although the design of this study *allowed* pigeons to report same versus different relations among the items in visual arrays, it did not *require* the birds to do so for the receipt of food reinforcement. Nevertheless, pigeons did attend to and discriminate the relations among the 16 items as well as the individual items themselves. This conclusion is supported by the pigeons' pattern of responding to the four categories of stimulus arrays. Responding to the S+ category was the highest of all four categories; here, the items came from the reinforced set and they exemplified the reinforced relation among those items (I+/R+). Responding to the I-/R- stimuli was the lowest of all four categories; here, both the items and the relation among the items differed from the S+ category. And, responding was intermediate to the category containing items from the reinforced set, but exemplifying the nonreinforced relation among the items (I+/R-) and from the category containing items from the nonreinforced set, but exemplifying the reinforced relation among the items (I-/R+).

It is important to note that responding to arrays of items from a different set of icons that exemplified the same relation (I-/R+) as the reinforced arrays and responding to arrays of items from the same set of icons that exemplified a different relation (I+/R-) from the reinforced arrays each exceeded responding to arrays of items from a different set of icons that exemplified a different relation (I-/R-) from the reinforced arrays. The pigeons appear to have *concurrently* attended to *both* the item and relational properties of these complex visual arrays on I-/R- trials. This finding suggests that the *absolute* salience of each of these different stimulus properties was high. Also note that by comparing the pigeons' responding to arrays of items from a different set of icons that exemplified the same relation (I-R+) as the reinforced arrays to their responding to arrays of items from the same set of icons that exemplified a different relation (I+R-) from the reinforced arrays, one can quantify the relative strength of item and relation control. As was true in Gibson and Wasserman (2003; 2004), the stimulus control exerted by the relation among the items or by the items themselves was similar in Wasserman et al. (2002).

We thus see that the two previous studies were quite successful in quantifying both the strength and speed of learning about item and relation information. Clearly, pigeons do exhibit strong stimulus control by item and relation information even when they need not do so.

First-order same-different discrimination with trial-unique stimuli

Finally, at what must surely be the set size limit, one can arrange for training arrays *never* to be repeated; each trial involves brand-new same or different items. This arrangement effectively means that each training display is also a testing display. Any learning must therefore go beyond the past training items, because those items never recur. Brooks and Wasserman (2008) reported pigeons' successful same-different discrimination learning under just these conditions using 4 ×□4 arrays of trial-unique black-and-white mosaics, as shown in Figure 6. Each of four pigeons reached 80% correct choice responses on both same and different trials under this two-alternative forced-choice training task involving single arrays of items that were never repeated, making every training trial also a transfer trial.

Of course, this impressive demonstration of relational learning in pigeons is likely to be limited to members of the single training class: 4 ×□4 arrays of black-and-white mosaics. Shifting from these stimuli to others might very well prove to transfer little if at all, again implicating a perceptual basis to the pigeon's same-different conceptual behavior.

Second-order relational processing in animals

Initial studies of second-order relational processing in animals

Gillan, Premack, and Woodruff (1981) published the first paper on second-order relational processing in animals. This seminal study tested a single chimpanzee (Sarah) in a task which had the following conceptual structure: A is to A' as B is to which of these two alternatives B' or C? In practice, Sarah saw three objects on a tray. The A-A' pair of objects was presented on the left side of a tray and the B object was shown on the right side. Two other objects were presented below the tray and Sarah had to select the choice object (B') that completed the analogy. Sarah was successful in a first version of this task (figural analogy), in which the objects were pieces of plastic varying in shape, color, and marking. She could also solve a more conceptual version of the task in which the objects were household objects and the relations were either spatial or functional.

Of critical importance, Sarah was not naïve at the start of the experiment. She had initially learned the symbolic meaning of pieces of plastic; she had also acquired the ability to communicate complex meanings by combining strings of plastic symbols in sentence-like structures (Premack, 1976). For that reason, Premack argued that language training was a prerequisite for Sarah's analogical reasoning; this language training may have provided the scaffolding for Sarah's symbolic encoding of the relation between relations (Premack, 1983).

Most later research on second-order relational processing in animals has used the relational matching-to-sample task (RMTS, e.g., Thompson; Oden, & Boysen, 1997; Fagot & Thompson, 2011), which can be more easily implemented with animals than Premack's analogical reasoning procedure. Figure 7 illustrates the general design of the RMTS task, which has become the gold standard in this literature. In this task, the subject initially sees a sample display composed of a pair of either same or different objects. Two comparison pairs are then presented after the sample display: one pair exemplifies the same relation as the sample pair, whereas the other pair exemplifies the alternative relation. Critically, these two comparison pairs are composed of items that are not common to the sample pair, thereby preventing correct relational matching responses from being based on perceptual similarity (in some studies, there is no perceptual similarity between the correct and incorrect comparison pairs either). The animal receives reward if it chooses the comparison pair instantiating the same relation as the items in the sample pair; the animal receives no reward if it chooses the comparison pair instantiating the different relation. In other words, the task can be conceptualized as "if AA then BB and if AB then CD." Success on this task has been taken to prove that the animal can reason about the relation between relations, because this task requires the processing of two sets of abstract relations and a comparison between these relations.

Thompson et al. (1997) employed the RMTS task to reconsider Premack's original idea that language training is required for second-order relational processing in animals. The authors compared the performance of five chimpanzees on the RMTS task. Three of the chimpanzees had never received any form of language training, but had simply learned in a preliminary training phase to select a heart shape when they saw two identical objects in the trial, and to select an oblique line when they saw two different shapes. In other words, these "token-trained" chimpanzees had learned the meaning of two symbols: one for the identity relation and the other one for the nonidentity relation, but they never learned to combine these symbols in discursive sentences. Sarah, the “language-trained” chimpanzee, was also included as a subject in this study, as was another chimpanzee which had no preliminary token or language training and served as a control subject.

Thompson et al. (1997) found no reliable difference between Sarah and the other three token-trained chimpanzees, all of which were successful in the RMTS task, in sharp contrast with the fully naïve chimpanzee which remained at chance level in this task. Thompson et al. concluded that experience with discursive string symbols is not required for solving second-order relational tasks. What might then be required for successful RMTS performance is a form of token training, in which such tokens could serve much like “words” in human language. These tokens might then promote a “concrete” encoding of the abstract relations of sameness and differentness, and further serve as anchors to retrieve and compare these relations, thereby providing the representational scaffolding for processing second-order relations.

Thompson and his collaborators wondered whether old world monkeys might also benefit from token (symbolic) training in the RMTS task, as these researchers had found was true for apes. Earlier studies had suggested that monkeys fail in the RMTS task without symbolic training. So, the RMTS task was given to rhesus monkeys (*Macaca mulatta*) which had previously been trained to associate geometrical symbols (circle or triangle shapes) with identity and nonidentity relations. In sharp contrast with the token-trained chimpanzees (Thompson et al., 1997), these token-trained macaques were unable to learn the RMTS task (results published only in a summarized form in Washburn, Thompson, & Oden, 1997; Thompson & Oden, 2000).

Confirmation that symbol training is of no help for monkeys was later provided by

Flemming, Beran, Thompson, Kleider, and Washburn (2008), who compared humans (*Homo sapiens*), chimpanzees (*Pan troglodytes*), and rhesus monkeys (*Macaca mulatta*) given two versions of the RMTS tasks. The first version used non-meaningful shapes; the second version presented Arabic numerals as stimuli. Importantly, chimpanzee and rhesus (and humans of course) had learned the meaning of the numerals in previous studies.

Meaningfulness facilitated the acquisition of analogical matching for humans and to a more limited extent (in some subjects only) in chimpanzees. By contrast, the rhesus monkeys completely failed in the two versions of the RMTS task, suggesting that the symbolic meaning of the stimuli had no influence on their performance. Thompson and Oden (1996) concluded on that basis that a “profound disparity” exists between “analogical” apes and “paleological” monkeys. In their view, only the apes and humans would be capable of solving the RMTS task, albeit after symbolic training. Monkeys by contrast would be unable to do so, regardless of the form of prior training they received. More recent investigations of this issue in monkeys suggest that this idea should be reconsidered (see ahead).

Relational matching with arrays of same and different icons

Earlier in the chapter, we noted that abstract same-different discriminations can be established in pigeons (as well as baboons and humans) when *arrays* of several same and different icons, rather than *pairs* of same and different icons, are used as training and testing stimuli. Increasing the number of items in the training and testing arrays can decidedly enhance first-order same-different performance (e.g., Wasserman, Fagot & Young, 2001; Wasserman & Young, 2010). Second-order relational processing has also been studied in the RMTS task with *arrays* of sample and comparison stimuli rather than with *pairs* of sample and comparison stimuli (Fagot, Wasserman & Young, 2001).

Fagot et al. (2001) studied two Guinea baboons that had earlier received first-order same-different discrimination problems with arrays of 16 icons (e.g., Wasserman et al., 2001), but were initially naïve with respect to second-order relational problems. These animals were tested in a computerized version of the RMTS task (see Figure 8), in which the relations of sameness and differentness were instantiated by arrays of icons. At the beginning of the study, the baboons were repeatedly trained with 16-icon sample and comparison arrays drawn from two independent sets of 24 icons, thereby eliminating the repetition of any items in the sample and comparison arrays on any given trial. Learning occurred slowly, but the two baboons eventually responded in excess of 80% correct after 4,992 and 7,104 training trials, respectively.

After learning, the first critical test was to assess the generalization of RMTS performance to novel testing stimuli; here, the two baboons continued to perform at above chance levels (70% correct) with sample arrays drawn from a third pool of 24 icons that had never before been seen. Such reliable transfer across stimulus sets suggests that the baboons had indeed learned an abstract and generalizable concept. As in the case of first-order relational learning, the lower level of testing performance compared to training performance (84% correct) can be taken to reflect the baboons' effective processing and memory of individual stimuli despite the irrelevance of such information for solution of the RMTS problem. Fagot et al. (2001) concluded from their study that language or symbol training is not necessary for nonhuman primates to appreciate higher-order relations between relations, contrary to Thompson and Oden's (1996) initial theoretical position.

The possibly surprising success of the baboons in the RMTS task with arrays rather than pairs of sample and comparison items prompted Cook and Wasserman (2007) to replicate that procedure with a different animal species. Cook and Wasserman trained four pigeons with the same general training procedure using 16-icon arrays as in Fagot et al. (2001). As was true for baboons, the pigeons' performance improved during training. After a great many training trials (range 6,400-8,320), the birds performed above 70% correct and transferred this discrimination to brand-new sets of stimuli, although at a slightly lower level of accuracy. Later tests further showed that perceptual changes in the sample displays—including, for instance, alterations in icon alignment, size, or orientation—produced little disruption in pigeons' RMTS performance, suggesting considerable robustness of the pigeons' RMTS behavior.

Two-item RMTS task: Positive consequences of "dogged training" in monkeys

We noted above that initial attempts to teach monkeys RMTS with pairs of items were utter failures, in sharp contrast to the studies with token- and language-trained chimpanzees (Thompson & Oden, 2000). We further noted that baboons and pigeons can solve RMTS tasks when same and different arrays containing several items, rather than stimulus pairs, are used as sample and comparison stimuli (Fagot et al., 2001, Cook & Wasserman, 2007). One interesting feature of the work of Fagot et al. (2001) and Cook and Wasserman (2007) is that success with the multi-element RMTS task only emerged after what Premack (1988) labeled "dogged training" involving thousands of training trials. Later research explored the possibility that "dogged training" might promote the appreciation of relations between relations in baboons, even in the original version of the RMTS task involving pairs of stimuli as sample and comparison stimuli.

Extensive "dogged training" was made possible by the deployment of a new automated test system (ALDM test systems, see Fagot & Paleressompoulle, 2009; Fagot & Bonté, 2010), in which the test stations are available ad lib to a social group of monkeys for self-testing on a 24 hour schedule. This paradigmatic shift has had numerous positive consequences in comparative cognition studies, among them improved animal welfare (Fagot, Gullstrand, Kemp, Defilles, & Mekaouch, 2013) and the possibility of testing a large number of subjects voluntarily performing a massive number of trials (Fagot & Paleressompoulle, 2009; Fagot & Bonté, 2010).

Using this system, Fagot and Thompson (2011) tested a large number of guinea baboons (*Papio papio*, N = 29) of various ages with a computerized version of the task shown in Figure 7. Continuous training was conducted over approximately 4 weeks. Many baboons did not learn, which is unsurprising given prior failures to teach RMTS to language-naïve and even token-trained rhesus monkeys (Thompson & Oden, 2000). Nevertheless, six baboons ultimately did learn the RMTS task; their accuracy progressively rose, reaching or exceeding 80% correct after 17,000 to 30,000 training trials. Note that this number of trials is far larger than ever given to rhesus monkeys (e.g., 1,000 in Flemming et al., 2008; 10,000 in Flemming, Beran, & Washburn, 2007), which could explain why the baboons succeeded in learning this task. In addition, the gradual increase in accuracy suggests that no baboon suddenly comprehended the relational nature of the task. Such progressive learning implicates associative learning mechanisms and calls for additional tests to confirm the relational nature of the cognitive processes at work.

Two transfer tests were subsequently administered by Fagot and Thompson (2011) to investigate the nature of the cognitive processes used by the baboons. First, the animals were tested with stimulus pairs created from a pool of 90 novel stimuli. All of the baboons except one (incidentally, the oldest: B15) continued to perform at above chance levels of accuracy with these novel stimuli, albeit at a lower level (65%) than with the original training stimuli. The second transfer test used a cross-mapping procedure. Cross-mapped trials followed the same design as in Figure 7, except that one of the stimuli of the sample pair was also used to create the nonmatching (incorrect) comparison pair. For example, if the sample pair was AA, then the correct comparison pair might be BB and the incorrect comparison pair might be AC. We reasoned that the baboons would (erroneously) select the nonmatching pair on cross-mapped trials if they gave priority to processing the items over the relations instantiated by the items. By contrast, the baboons should give priority to the matching pair if they attended to the relations shown by the stimulus pairs. The results were clear-cut. All five of the baboons that had demonstrated positive transfer to the new testing stimuli reliably selected the relational matching pair on 72% of the cross-mapped trials, thus confirming that their cognitive strategy was not strongly based on correspondence of individual items in the sample and comparison stimuli.

Truppa, Mortari, Garofoli, Privitera, and Visalberghi (2011) published confirmatory data attesting to the fact that "dogged-training" can support learning of the RMTS task. These authors studied capuchin monkeys (*Cebus appela*) which were trained with the RMTS procedure shown in Figure 7. One of the five capuchins learned the task and later showed positive transfer to new stimuli. This performance required a very substantial number of training trials (21,888), in the same range as the baboons in Fagot and Thompson (2011).

The studies presented so far have used pairs (Fagot & Thompson, 211; Truppa et al., 2011) or arrays of shapes (Fagot et al., 2001; Flemming et al., 2007) as the sample and comparison stimuli in RMTS. Admittedly, this task has a conceptual structure which resides at a lower level of complexity than the gold standard of second-order relational processing: analogies in humans. Consider, for instance, the following verbal analogy: "I am to dancing what Roseanne is to singing." Here, the relation between the speaker and dancing remains unspecified until we have processed the relation between Roseanne and singing. Clearly, this task is different from the RMTS task, because the presentation of the sample in the RMTS task suffices to determine the relation (sameness or differentness) to be processed in comparison step of the trial.

Fagot and Maugard (2013) devised a *bidimensional* version of the RMTS task to more closely approximate for baboons the complexity of human verbal analogies. In this research, the baboons first saw a pair of objects which were defined along *two* dimensions: color and shape. The sample pair could, for instance, comprise one yellow and one red object of the same shape or a square and a circle of the same color. These bidimensional stimulus pairs were presented as samples on two kinds of trials. On “color” trials, the comparison pairs comprised vertical bars of identical shapes, but whose colors could vary. Because the shape of the bars was not a discriminative cue on the color trials, the baboons had to pay attention to the relations expressed by the color cues, and match the sample and comparison pairs accordingly. The same logic was followed for the second type of trials; on “shape” trials, the comparison pairs comprised stimuli of the same (white) color, but whose shapes could vary. Because the color of the comparison pairs conveyed no useful information on the shape trials, the baboons had to match the sample and comparison pairs in accord with the relations expressed by the shape dimension.

Fagot and Maugard (2013) observed accurate performance in this task by a total of four baboons. These animals achieved 80% correct or higher performance after training on both color and shape trials. Moreover, one baboon’s performance remained above chance when the two relations expressed by the sample were inconsistent, for instance when the sample pair contained two different shapes (expressing the different relation) both drawn with the same color (expressing the same relation). Finally, scores obtained on cross-mapped trials, in which the foil pair nevertheless shared one item with the sample pair, averaged well above chance (77% correct), but was slightly lower than on normal (non cross-mapped trials (79%). These two results suggest that the baboons processed both the relations and the items in this task, with priority given to relational cues when perceptual and relational cues conflicted. Note that this level of performance could only be achieved after an average of 58,541 trials per monkey, and was therefore obtained after decidedly “dogged-training.”

All of the above studies underscore the importance of dogged-training on animals’ mastering the RMTS task. Two additional studies should be discussed for a balanced presentation of the literature. First, Vonk (2003) trained and tested four orangutans and one gorilla in a computerized version of the delayed RMTS task. These apes had earlier received identity matching-to-sample training with single stimuli, but they were initially naïve with regard to the processing of relations between relations with pairs of stimuli. Four of the five apes demonstrated an immediate understanding of second-order relations; they could match, for instance, two blue shapes with two red shapes. Above-chance performance required only minimal training and was sometimes obtained in the first testing session.

Second, in a more recent project, Smirnova, Zorina, Obozova, and Wasserman (2015) tested RMTS performance in two hooded crows (*Corvus corone*). Initial training with identity matching trials had already suggested that these animals might have acquired a general identity concept, but neither of the crows had been given the RMTS task. In sharp contrast with earlier reports (e.g., Fagot & Thompson, 2011; Truppa et al., 2011), but consistent with Vonk’s (2003) ape work, the crows spontaneously displayed high levels of relational responding, and did so in several versions of the RMTS task requiring an appreciation of the relations expressed by stimulus size, shape, and color. This documentation of RMTS behavior is particularly noteworthy because the crows exhibited relational matching behavior (averaging 78% correct) that was as accurate as their identity matching behavior (averaging 73%) on trials in which one of the comparison pairs was identical to the sample pair. Although physical identity could have guided the crows’ choice behavior on identity matching trials, physical identity could not have done so on relational matching trials, because no physical matches were possible between the sample pairs and the correct comparison pairs. These results suggest that physical identity contributed little or nothing to the crows' RMTS performance; relational processing seems to have been of prime importance to controlling the birds' choice behavior.

Why apes and crows were immediately successful in these latter two studies (Vonk, 2003; Smirnova et al., 2015) remains a matter for future research. At least part of the explanation is likely to be due to the fact that all of these subjects had received extensive identity matching-to-sample training prior to RMTS testing. Such identity training may have enabled these animals to grasp a broadly applicable concept of sameness that could later be applied to RMTS testing.

Two-item RMTS task in monkeys: Perceptual, relational processing, or both?

Evidence thus suggests that language-naïve baboons, rhesus monkeys, and capuchin monkeys all can achieve high levels of performance on the RMTS task after extensive training. Evidence further suggests the involvement of an abstract cognitive capacity, revealed by accurate responding even on cross-mapped testing trials (Fagot & Thompson, 2011; Fagot & Maugard, 2013), where stimulus identity should lead baboons to choose the incorrect comparison stimulus.

Are an animal's representational structures in RMTS purely abstract or are they also grounded on perceptual features, as already documented for first-order same-different discrimination tasks using visual arrays as stimuli (e.g., Young & Wasserman, 1997; Fagot et al., 2001)? The following results suggest that both perceptual and relational processing contribute to performance on the RMTS task.

The first data on this issue come from the cross-mapped trials of Fagot and Thompson (2011). As noted earlier, the baboons achieved above-chance performance on these trials, thus implicating relational processing; however, a close look at the data divulged that accuracy on cross-mapped trials (72% correct) was lower than on normal (non-cross-mapped) trials (77% correct). This small, but statistically reliable disparity indicates that the sharing of stimulus features between the sample pair and the incorrect comparison pair deleteriously affected the baboons' RMTS performance, suggesting that the processing of same-different relations is not completely independent of the processing of stimulus features.

Flemming, Thompson, and Fagot (2013) published even stronger documentation of the interaction between perceptual and relational processes. These authors tested both baboons and humans with a version of the RMTS task involving arrays of 4 items as the sample and comparison stimuli. The subjects from both species were initially trained with arrays containing either four identical items (same relation) or four different items (different relation). After training with all same and all different displays, transfer was assessed using different *mixtures* of stimuli as samples (the comparison arrays continued to be composed of all identical or all nonidentical items). On probe trials, one of the shapes in the sample arrays was either repeated three times (e.g., AAAB or ABAA), two times (e.g., ABAB or AABB), or only one time (e.g., ABCD). The authors reasoned that the subjects should match all three of these types of sample arrays with the "different" comparison arrays, if the subjects based their responding on the abstract relations of sameness and differentness. By contrast, the subjects might match the sample mixtures depicting mostly same items (e.g., BAAA) with the all same comparison arrays (e.g., AAAA) and complementarily match the sample mixtures depicting mostly different items (e.g., ABBC) with the all different comparison arrays (e.g., ABCD), if the subjects based their responding on the proportion of common individual items within the arrays. Matching this way can be construed as perceptual process, based on the shared identity of the items in the arrays.

In this case, the baboons and humans exhibited highly similar response profiles, suggesting that both species adopted a common cognitive strategy in performing this task. The subjects from both species matched all of the various sample mixtures to the different comparison arrays, with the proportion of “different” response scores all exceeding .60. This strategy demonstrates that the relational structure of the sample arrays was the primary variable controlling subjects’ choice performance. Still, the proportion of “different” responses increased as the sample mixtures increasingly contained more different items, suggesting that both baboons and humans were primarily controlled by the relational structure of the sample displays, but that they were secondarily controlled by the perceptual variability of the sample displays.

A third project (Fagot & Parron, 2010) further confirmed the interplay between perceptual and relational processing in baboons. It used pairs of adjacent color patches as stimuli in the RMTS task. Because baboons have a bias for a local mode of visual processing over a global mode of visual processing (Fagot & Deruelle, 1997), the distance separating the two color patches was kept minimal (2 pixels) from the onset of the RMTS training in order to facilitate the processing of the stimulus duos as “pairs,” rather than as independent items. Six baboons learned this RMTS task after extensive training and later showed positive transfer when new stimulus colors and sizes were introduced. Interestingly, the baboons’ performance collapsed when the separation between the items was increased from 2 to 60 pixels, demonstrating that accurate performance could only be obtained under some perceptual constraints. Importantly, the effect of gap size was abolished when we later arranged an extended training procedure (entailing from 6,400 to 8,600 training trials) to progressively increase the size of the within-pair gap.

Maugard, Marzouki and Fagot (2013) further tested a subset of the baboons studied by Fagot and Thompson (2011) and Flemming et al. (2013). Its main innovation was to introduce *another* matching task between the presentation of the sample pair and the comparison pairs in the RMTS task. Specifically, the subject first saw the RMTS sample pair. The subject then saw the sample and comparison pairs of an IMTS task, which served as the interpolated task; the subject had to match these single sample and comparison stimuli by shape. An incorrect identity matching response aborted the trial at this stage, but a correct response triggered the display of the comparison pairs of the RMTS task; the baboon now had to select the comparison pair instantiating the same relation as the initial RMTS sample pair to receive reward.

Introducing the interpolated IMTS task had a detrimental effect on RMTS performance compared to a control condition involving the same RMTS task with delays between the sample and comparison pairs matched to the time taken to complete the interpolated IMTS task. This interference effect accords with dual-task performance with human subjects, which implicates the contribution of working memory to the formation of analogies (e.g., Morrison, Holyoak, & Truong, 2001). Perhaps more interestingly, the negative effect of the interpolated task was more robust for different sample trials than for same sample trials (same trials, dual task = 74% correct, control task = 79% correct; different trials, dual task = 46% correct, control task = 81% correct).

Earlier studies with these same baboons had demonstrated that they do in fact process the relational structure of the RMTS task. This study involving both IMTS and RMTS tasks further showed that processing of the different relation may be more demanding in terms of memory load than processing the same relation. A plausible account of this effect is that the different displays contain a richer set of perceptual information than the same displays. We interpret this selective effect of memory load on different trials as an additional argument supporting the idea that responses in the RMTS task result from the processing of both perceptual and relational cues.

Conclusions on second-order relational processing in animals

The studies reviewed here strongly suggest that apes (Thompson et al., 1997), baboons (e.g., Fagot & Thompson, 2011), capuchins (Truppa et al., 2011), crows (Smirnova et al., 2015), and pigeons (Cook & Wasserman, 2007) have sufficient cognitive resources to accurately perform the RMTS task. Of course, the RMTS task affords several perceptual cues (e.g., the identity of the individual stimuli in each display and the variability in the number and proportion of each type of item in the sample and comparison stimuli) that the animal might use in choosing the correct response. Nevertheless, evidence suggests that priority is not always given to these perceptual cues (e.g., Fagot & Thompson, 2011; Flemming et al., 2013; Smirnova et al., 2015).

The priority that can be given to relational cues demonstrates that nonhuman animals do indeed have the cognitive power to represent relations between relations and to adaptively act upon that information. These data argue against the claim of Penn, Holyoak, and Povinelli (2008) that animals only attend to the perceptual variability of the stimulus pairs in the RMTS task, without considering the pairs' constituent elements as entities or to the relations that these entities instantiate. Clearly, the story is not as simple as suggested by Penn, Holyoak, and Povinelli.

Another conclusion is that animals can be taught to apprehend the relations between relations by many means. The initial approach was to contrive a symbolic representation of the task by way of language- (Gillan et al., 1981) or token-training (e.g., Thompson et al., 1997). In the next section, we will further consider the role of symbolic or language training in the developmental literature on children. However, symbol training is surely not the only path to achieving a high level of understanding of second-order relations, contrary to Premack's (e.g., 1983) original claim. Dogged training is a slow, but effective option (e.g., Fagot & Thompson, 2011, Truppa et al., 2011). Finally, a rich prior history of first-order relational learning (including identity matching-to-sample) may promote successful transfer to RMTS without any explicit RMTS being given (Smirnova et al., 2015; Vonk, 2003).

Development of relational learning

Human relational and analogical reasoning capacities are often vaunted to be twin pinnacles of cognition (e.g., Hofstadter, 2001; Holyoak, Gentner, & Kokinov, 2001; Penn et al., 2008). But, these capacities appear to be limited and imperfect in infants and young children—much as they are in nonhuman species. And, as we shall see, several parallels can be drawn between the cognitive behavior of young children and nonhuman animals.

Tracing the development of relational and analogical reasoning is critical for fully understanding of the roots and mechanisms underlying these abilities. During development, children advance from perceptually-based to relationally-based processing, due to maturational processes as well as to innumerable life experiences. Nonetheless, for both children and adults, perceptual processes still seem to be intimately involved in advanced relational processing.

First-order relational processing in infants and children

Compared to the extensive literature in animals, rather little research has investigated first-order same-different relations in human infants and young children. Tyrrell, Stauffer, and Snowman (1991) reported that 7-month-olds are sensitive to first-order same-different relations. Two groups of infants were first familiarized to either a pair of identical toys (Identity group) or to a pair of nonidentical toys (Different group). Tyrrell et al. were interested in documenting an early ability to detect same-different relations rather than in teaching infants to detect these relations, so only one pair of items was presented, twice, to each of the two groups. Later, all of the infants were given a novelty preference test in which they were simultaneously presented with two pairs of completely novel toys: one pair portraying identical objects and the other pair portraying nonidentical objects. If the infants were retaining the relation instantiated by the habituation pair, then they should show a preference for the testing pair instantiating the novel relation. Indeed, in both groups, infants' fixation times were longer for the relation that had *not* been experienced during habituation. Thus, Tyrrell et al. interpreted their results as evidence for infants' spontaneous encoding of abstract same and different relations.

However, Ferry, Hespos, and Gentner (in press) failed to replicate Tyrrell et al.'s (1991) findings. Specifically, these researchers did not find that 7-month-olds could distinguish between same and different relations after the presentation of just one pair of items (Experiment 1). In their second experiment, Ferry et al. used a habituation-dishabituation paradigm in which testing was conducted with a single pair of objects, and again divided the infants into two groups: one familiarized with pairs of same objects and the second familiarized with pairs of different objects. Rather than presenting only one exemplar pair, the researchers provided the infants with four pairs of objects that were repeatedly presented until habituation occurred (on average, after seven trials). At testing, the infants looked significantly longer (that is, they dishabituated) at novel objects instantiating a novel relation than at novel objects instantiating the habituated relation. Ferry et al. concluded that the variety of exemplars experienced during the habituation phase allowed the infants to extract the common relational pattern and, thus, to form an abstract concept.

These findings closely accord with other results in both the adult human (Gick & Holyoak, 1983; Homa & Vosburgh, 1976; Loewenstein, Thompson, & Gentner, 1999) and animal categorization literatures (Castro et al., 2010; Castro et al., 2014; Katz & Wright, 2006; Maugard et al., 2014; Truppa et al., 2011), in which multiple instantiations of a relational concept increase the salience of abstract properties of stimuli. According to Gentner and her colleagues (Christie & Gentner, 2010; Gentner & Namy, 1999; Markman & Gentner, 1993), presenting several exemplars promotes a comparison process from which stimulus commonalities are revealed. As we shall see, this comparison process is critical for perceiving second-order relations as well.

An interesting additional observation in Ferry et al. (in press) was that infants' looking times were the longest of all to novel items and novel relations. This finding suggests that, as in the animal studies reviewed earlier—especially that of Wasserman et al. (2002)—item and relation processing co-occur. Children perceived the common relation between the objects and they were also sensitive to whether those particular objects were familiar or novel.

In another study—which attempted to find the youngest age at which infants could discriminate same and different relations—Addyman and Mareschal (2010) used a standard habituation/dishabituation paradigm with infants who were 4 and 8 months of age (Experiment 1). Half were habituated to the same relation, whereas the other half were habituated to the different relation. Up to a maximum of 19 pairs of unique photographic stimuli (a relatively large number) depicting either two same or two different items were presented during the habituation phase. In the testing phase, two novel same pairs and two novel different pairs were shown. Only the 8- month-olds who had been familiarized to pairs of either same or different objects showed a significant increase in looking when shown pairs of new objects portraying the novel relation.

In Experiment 2, Addyman and Mareschal (2010) adapted the anticipatory eye movement paradigm developed by McMurray and Aslin (2004) to explore the understanding of same-different relations by the same 4- and 8-month-old infants who had participated in Experiment 1. Their adaptation showed a pair of geometric shapes moving together behind an occluder and reappearing 3 s later on either the left or the right side of the occluder. If the shapes were the same as one another, then they moved in one direction; but, if the shapes were different from one another, then they moved in the opposite direction. If the infants could distinguish between same and different relations, then they should have learned to correctly anticipate the reappearance of the shapes. Both the 4- and 8-month-olds learned to anticipate the reappearance of the different pairs, but not the same pairs; likewise, they transferred their anticipatory behavior to novel different pairs, but not to novel same pairs.

For human adults, the concepts of same and different are assumed to be logical opposites of one another; if one knows what same means, then one necessarily knows what different means. Given Addyman and Mareschal's (2010) findings, an equivalent understanding of same and different does not appear to be true for infants nor, for that matter, for animals as well (Young & Wasserman, 1997). One possible reason, suggested by Smith et al. (2008), may be that, in order to establish that two items are the same, one must confirm that all properties of the objects are equivalent, whereas any single discrepancy establishes that two items are different. As we will discuss later, infants' ability to explore all possible alternatives is poor, perhaps due to their rather limited working memory (perhaps for pigeons too, Gibson, Wasserman, & Luck, 2011). Overall, Addyman and Mareschal's results disclose some sensitivity of infants to same-different relations, but they also reveal the absence of a fully-formed same-different concept equivalent to that of older children and adults.

Ferry et al. (in press) also found that attention to individual objects can interfere with same-different relational processing. When infants were allowed to play with some of the objects before the habituation/dishabituation task—possibly calling attention to the properties of those objects—if those same objects were later presented at testing in a new relation, then infants did not show dishabituation; that is, they did not respond based on the relation between the objects. These results are not unprecedented. Young children tend to make inferences about new objects from learned categories based on perceptual similarity rather than on categorical information (Sloutsky et al., 2007). Also, when two alternative matching choices are given—one based on the relations between objects and the other based on object similarity—young children strongly prefer object similarity over relational matches (Christie & Gentner, 2010; Richland, Morrison, & Holyoak, 2006).

Second-order relational processing in infants and children

Analogical reasoning is considered to be a central mechanism of human cognition (e.g., Hofstadter, 2001; Holyoak et al., 2001; Holyoak & Thagard, 1995). As we have just seen, despite of some limitations, both infants and young children do seem to be able to understand first-order same-different relations. However, analogical reasoning—requiring the appreciation of second-order relations—appears to take much longer to develop; although its rudiments may be seen at 2 years of age (Singer-Freeman, 2005), analogical reasoning does not approach adult-like performance until adolescence (Richland, et al., 2006).

A formal analogy is commonly represented: *A is to B as C is to D*. In typical research projects, an organism must infer item D after being given pair A-B and being prompted with item C. Completing an analogy requires several prior steps: (1) the general relation represented by items A and B must be known, (2) the relation instantiated by items A and B must be inferred, and (3) that relation must be applied to item C in order to generate the correct answer.

Goswami and Brown (1989) observed that studies reporting children’s failures to solve analogies before the age of 12 were using quite complex relations to form the analogies. For example, children were asked to provide the completing term for “bird is to air as fish is to X”

(Levinson & Carpenter, 1974) or “automobile is to gas as sailboat is to X” (Gallagher & Wright, 1977). Providing the solution to these analogies requires knowing the relation of animals to their ecological habitat or understanding the relation between mobile machines and the source of energy propelling them. The lack of knowledge of these relations rather than the capacity to solve analogies may be the real reason why young children failed in these tasks. Goswami and Brown suggested that using relations with which young children are actually familiar might yield decidedly different results.

Indeed, when Goswami and Brown (1989) presented children with partial analogies involving familiar objects such as snow or apples and familiar actions such as melting or cutting, children as young as 3 years of age could successfully complete a large number of them. There was also developmental improvement, with 4-year-olds successfully completing more problems than 3-year-olds. This improvement appeared to be due, not to an age-related increase in the ability to reason by analogy, but rather to an increasing ability to understand the relations underlying the analogy. As children become increasingly familiar with such causal relations as melting or cutting, they become better able to transfer these relations to other domains. Because 4-year-olds tend to know more about these relations than do 3-year-olds, they can solve more analogies based on them.

Yet, even if a first-order relation is within their realm of knowledge, children may still fail to infer the correct relation that connects elements A and B. Singer-Freeman (2005) tested 30-month-old children using familiar objects and familiar relations. However, only when the relations connecting the A and B terms were explicitly demonstrated (for example, how yarn can be stretched) did children under 3 years of age solve the analogies. It seems that, up to that age, children have difficulty inferring the relation between elements; that difficulty then hinders their ability to solve formal analogies. This inferential difficulty may be due to young children's tendency to attend to the particular items instantiating the relation rather than to the relation itself. As a consequence, the objects' appearance or other irrelevant attributes can exert a strong influence on children's analogical reasoning behavior. Indeed, errors in young children's analogical reasoning are characterized by difficulty ignoring irrelevant properties of the stimuli involved in the analogy task (e.g., Gentner & Rattermann, 1991; Richland et al., 2006).

Addressing the developmental and attentional trends in the evidence, Gentner and Rattermann (1991; Rattermann & Gentner, 1998) proposed that a *relational shift* occurs between the ages of 4 and 5: from attention to common object properties to attention to common relational structure. They further suggested that the mechanism underlying this relational shift is not tied to the chronological age of a child, but is instead determined by the amount and kind of relational knowledge that the child possesses; so, until children acquire adequate knowledge, they will fail to reason analogically (Goswami, 1992; 2001; Goswami & Brown, 1989).

In addition to the acquisition of knowledge, stronger executive functioning—in the form of increased working memory capacity (Halford, 1993) and increased inhibitory control (Richland et al., 2006) for coping with relational complexity—have been proposed as important mechanisms underlying developmental changes in analogical reasoning. Thibaut, French, & Vezneva (2010) studied analogy completion in 6-, 8-, and 14-year-olds. These researchers used abstract shapes, colors, and textures to avoid the influence of prior knowledge. The A-B pair could contain one specific shape and a similar, but transformed shape (for example, a half ring and an elongated half ring); item C would be a completely different shape, and the children had to choose item D representing the same relation as the relation between A and B. Choices could include, in addition to the correct response, items sharing no perceptual features with A, B, or C, or items sharing perceptual features with A, B, or C. When choices contained perceptual similarities, particularly with item C, the number of errors was greater than when no competing perceptual choices were presented, especially in young children, suggesting a poor capacity to inhibit attending to distracting information. Interestingly, 6-year-olds, who made many mistakes, were as fast to respond as 14-year-olds, who made very few mistakes. Thibaut et al. suggested that the reason for 6-year-olds' prompt responding is that they were not exploring all of the possible choices, but simply selecting the first salient item, probably because of a lack of inhibitory control but perhaps also because of limited working memory that could not hold all of the possible solutions. According to Thibaut et al., this kind of hasty decision process speaks to poor executive control in young children, and cannot be explained by a lack of knowledge (e.g., Goswami & Brown, 1990) or a shift in relational processing (Rattermann & Gentner, 1998). Richland et al. (2006) also found that relational complexity and irrelevant information can interfere with analogical reasoning, regardless of the child's knowledge of relations; therefore, limits in information processing during the early stages of development must be taken into account to fully understand the unfolding capacity for analogical reasoning.

Consensus holds that the prefrontal cortex is a critical brain area involved in executive control functions, such as working memory or inhibitory control. The human prefrontal cortex is much larger than in other primates, and birds do not even have a prefrontal cortex (although the avian nidopallium caudolaterale may serve analogous functions (e.g., Shimizu, 2009). So, it may be that poor working memory and inhibitory control, due to a lack of supporting brain structures, is also part of the reason for limited analogical capacities in nonhuman animals.

Facilitators of second-order relations

In an attempt to encourage analogical reasoning in 2-year olds, Singer-Freeman (2005) showed them two examples of the same relation with different items (A_1-B_1 and A_2-B_2), before presenting the second term in the analogy completion task. Such increased exposure to the target relation probably helped the children solve the analogies; however, Singer-Freeman did not systematically manipulate this variable, so its influence is unclear.

Subsequently, Christie and Gentner (2010) examined the effect of including several examples of the first term of an analogy task. Arguing that the process of comparing two exemplars of the same relation would highlight their common structure, these investigators presented one group of children with two objects in a specific spatial configuration, followed by two other objects in the same spatial configuration; both pairs were placed next to one another and could be seen simultaneously, thereby encouraging the comparison process. Another group of children was presented with only one pair of objects. Then, 3- and 4-year-olds were given the choices of: either a relational match (showing the same spatial relation as initially presented) or an object match (showing one or two of the same objects as initially presented). Regardless of age, children in the comparison group chose relational matches much more often than children in the no-comparison group. This result is consistent with the notion that the comparison process, prompted by the presentation of multiple exemplars, facilitates the extraction of common relations, as we have seen is true for first-order relations in both young children and animals.

Despite the noteworthy cognitive feats of animals reviewed earlier, we cannot deny that human adults’ analogical reasoning behavior surpasses that of animals. It could be that there truly is a qualitative distinction between the cognitive processes of humans and nonhuman animals (Penn et al., 2008). Or it could be that, beyond sharing the fundamentals of cognition, behavioral differences arise due to the participation of human language and culture.

Christie and Gentner (2014) explored these possibilities by testing young children with a relational matching-to-sample (RMTS) task, similar to the animal task described earlier. Two items (colored shapes) were presented that could be the same as or different from each other. Children had to choose between pairs of novel items: one pair containing two same items and another pair containing two different items. The 2- and 3-year-olds failed this task; they did not spontaneously choose the matching relation (Experiments 1 and 2). However, when children were given prior training with the words ‘same’ and ‘different’ (teaching a puppet the meaning of these words), 3-year-olds (but not 2-year-olds) could successfully solve the RMTS task (Experiment 3), thus showing that verbal labels facilitate the acquisition of relational concepts.

Christie and Gentner (2014) also tested the role of verbal labels in a different way. In Experiment 4, the sample pair was given a novel label (e.g., truffet) and the children were asked which of the two choice pairs was also a truffet. Now, both 2- and 3-year-olds succeeded in the RMTS task. Christie and Gentner suggested that the novel label invited comparison between the sample pair and the choice pairs: the task of finding the other truffet probably led children to compare the sample with each of the alternatives, and thereby to discover the common relational structure between the sample and the correct alternative, implying an interplay between linguistic symbols and comparison processes.

However, even if language and culture can facilitate and vault analogical reasoning to its highest levels, the research described earlier with baboons, apes, crows, pigeons, and prelinguistic infants suggests that language or symbol training is unnecessary for disclosing at least the basics of this cognitive capacity. Importantly, the baboons and pigeons in that earlier work had been trained to discriminate same from different collections of items before training on the RMTS task; this is normally the case for prelinguistic infants as well. Such prior learning of first-order relations may provide the scaffolding that facilitates the processing of second-order relations.

Concluding comments

Relational reasoning—particularly appreciating the relation between relations that is central to forming analogies—represents what contemporary theorists deem to be the pinnacle of human cognition. Such relational cognition promotes our adaptation to complex and ever-changing circumstances; it also allows us to go beyond immediate sense experience to engage in abstract thought. The evidence that we have reviewed in this chapter suggests that such abstract relational thought does not arise de novo; rather, it develops in humans and its evolutionary roots can be seen in nonhuman animals. To embrace these discoveries, we propose an emerging analytical perspective on the development and evolution of relational thinking, which suggests that perceptual and relational processes are inextricably interrelated in both humans and animals.

From perception to conception

Although individual stimuli may be processed in terms of their constituent features—thereby supporting their identification and memorization—two or more stimuli invite comparative judgments. Primary among those comparative judgments is *sameness* and its complement *differentness*. Evidence suggests that relational same-different control does not emerge distinct from perceptual control; the processing of individual stimuli is foundational to and continuous with the processing that occurs between or among stimuli. This finding not only holds true for processing first-order same-different relations, but for processing second-order same-different relations too, as in the case of analogies.

Furthermore, there appears to be a reciprocal relationship between processing the identity of individual stimuli and processing the relations between or among stimuli. For both infants and animals, comparing several different exemplars of a relation encourages abstracting the relations of sameness and differentness; on the other hand, focusing on the identity of individual stimuli impairs relational processing.

From animals to humans

Although animals may not achieve relational thinking of the same complexity as do humans, striking similarities nevertheless emerge between humans and other species. Mounting evidence in the realm of animal cognition questions the common belief that same-different conceptualization is uniquely human. Evidence from animals as diverse as pigeons, crows, monkeys, and apes shows that they too can master first-order same-different relations. In addition, a possibly narrower range of species have successfully mastered cognitive tasks which require them to understand the relation between relations (second-order relations).

From infancy to adulthood

During development, children too move from perceptually-based to relationally-based processing of stimuli, owing to innumerable relevant experiences. Nevertheless, for such higher-order abstract thinking, perceptual processes also seem to be intimately involved.

Although linguistic encoding of higher-order judgment tasks may ease and promote relational thinking in children, language seems not to be mandatory for relational thought, as shown by the success of nonverbal animals and preverbal humans learning advanced relational tasks. The contribution of language to relational thinking might better be seen to provide abstract symbols for humans to re-encode and thereby simplify complex stimulus relations, permitting us to solve higher-order relational problems that may be beyond the cognitive reach of animals.

Coda

Humans no doubt possess a powerful capacity for relational cognition, including analogical thought. This capacity appears to be continuous across development, with factors that affect relational thinking in adults and children also influencing infants as well.

More broadly, considerable evidence suggests that there is phylogenetic continuity in the nature of relational and analogical thought. Initially, human infants and nonhuman animals may exhibit qualitatively similar relational and analogical abilities. However, adult humans come to dramatically outperform other animals in the complexity and intricacy of their relational and analogical thinking. Humans' experience with language and culture are likely to promote this advantage, resulting in an ever expanding gap between humans and animals over the course of development. Nevertheless, we must appreciate that whatever heights of cognition may be attained by humans must have arisen via an evolutionary process about which we may gain key insights by studying the cognitive processes of our animal kin.

Lloyd Morgan would surely appreciate all that we have learned about relational thought since his fecund speculations over a century ago. We fully expect the next century to yield even more exciting revelations concerning relational thinking in animals and humans.

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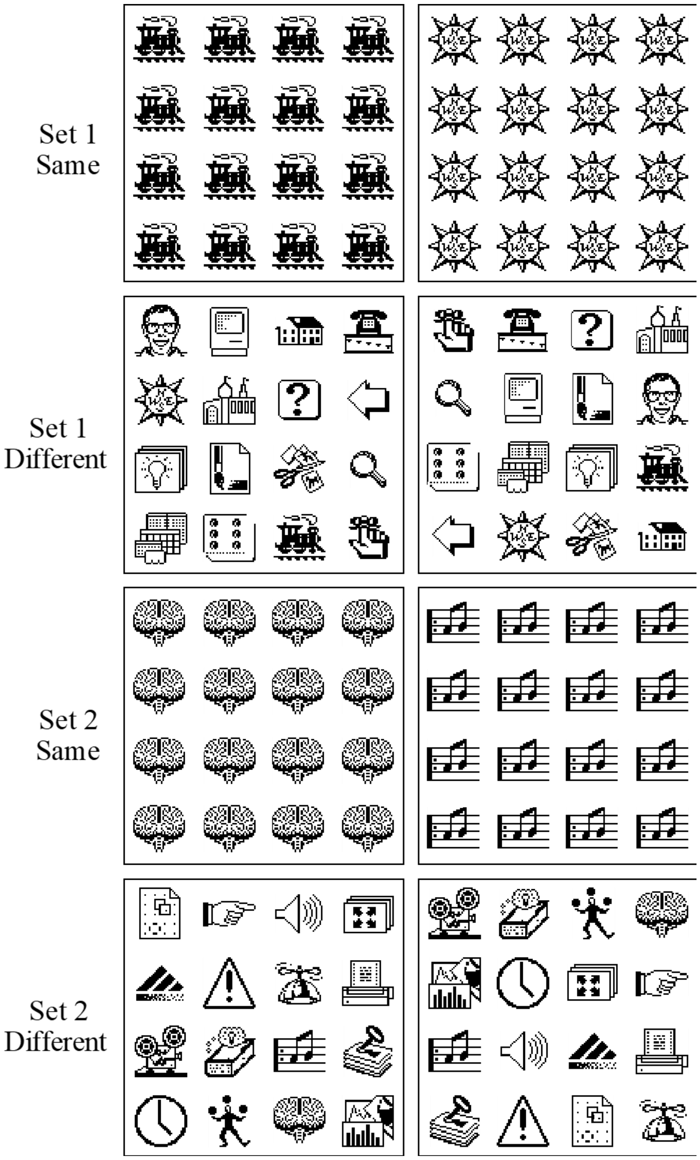
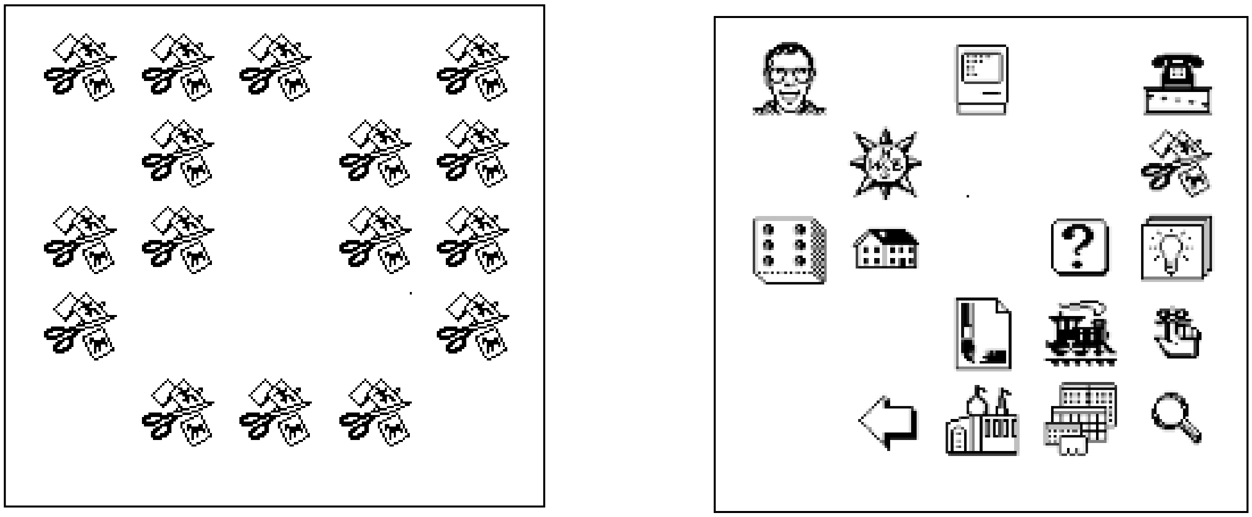


Figure 1. Wasserman, E. A., Hugart, J. A., & Kirkpatrick-Steger, K. (1995). Pigeons show same-different conceptualization after training with complex visual stimuli. *Journal of Experimental Psychology: Animal Behavior Processes, 21*, 248-252. Figure 1.



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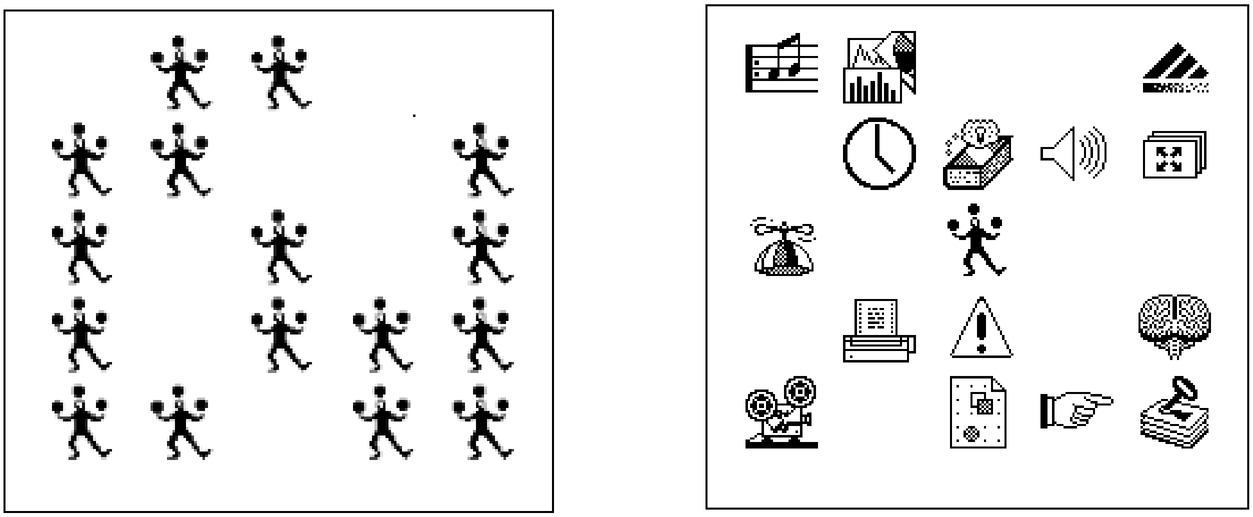


Set 2

Figure 2. Young, M. E., & Wasserman, E. A. (1997). Entropy detection by pigeons: Response to mixed visual displays after same-different discrimination training. *Journal of Experimental Psychology: Animal Behavior Processes, 23,* 157-170. Figure 1.

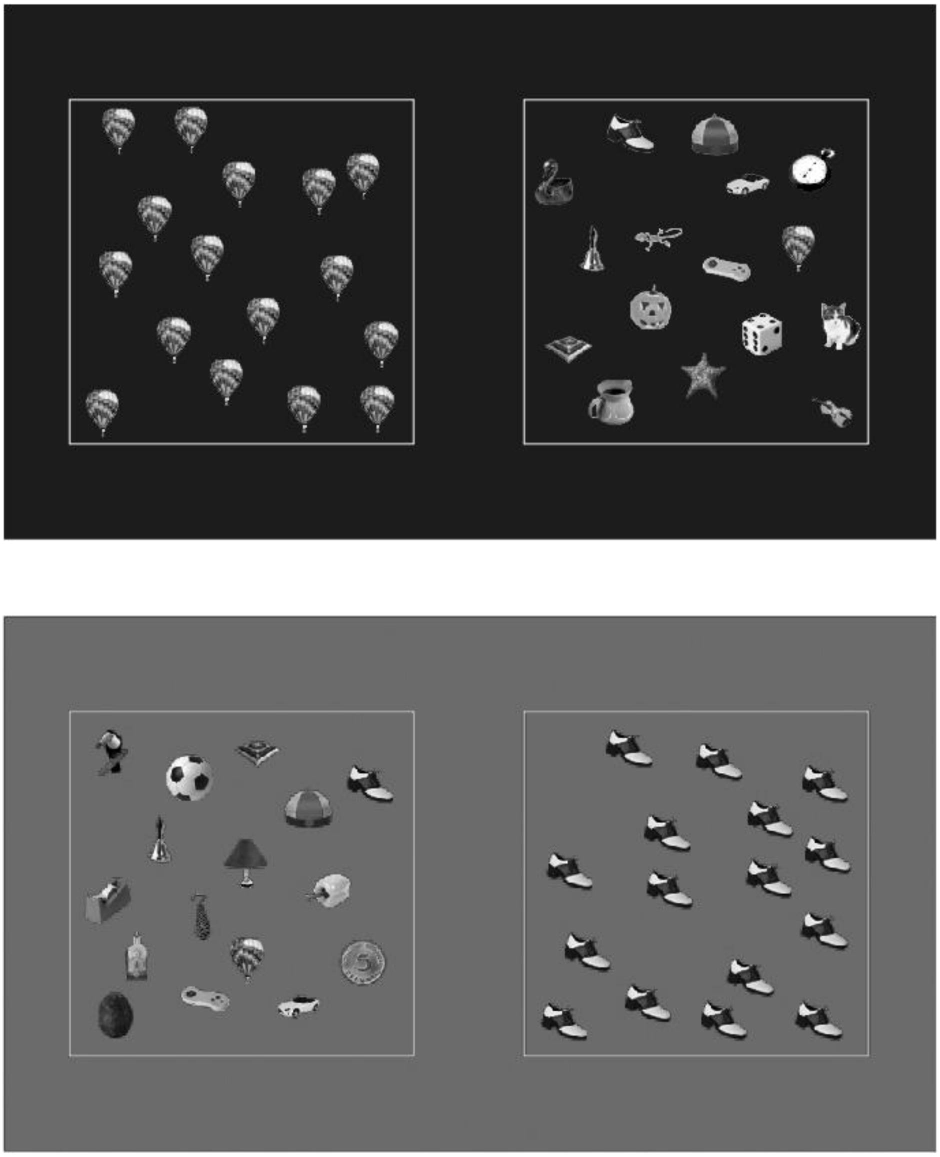


Figure 3. Castro, L., Kennedy, P. L., & Wasserman, E. A. (2010). Conditional same-different discrimination by pigeons: Acquisition and generalization to novel and few-item displays. *Journal of Experimental Psychology: Animal Behavior Processes, 36,* 23-28. Figure 1.

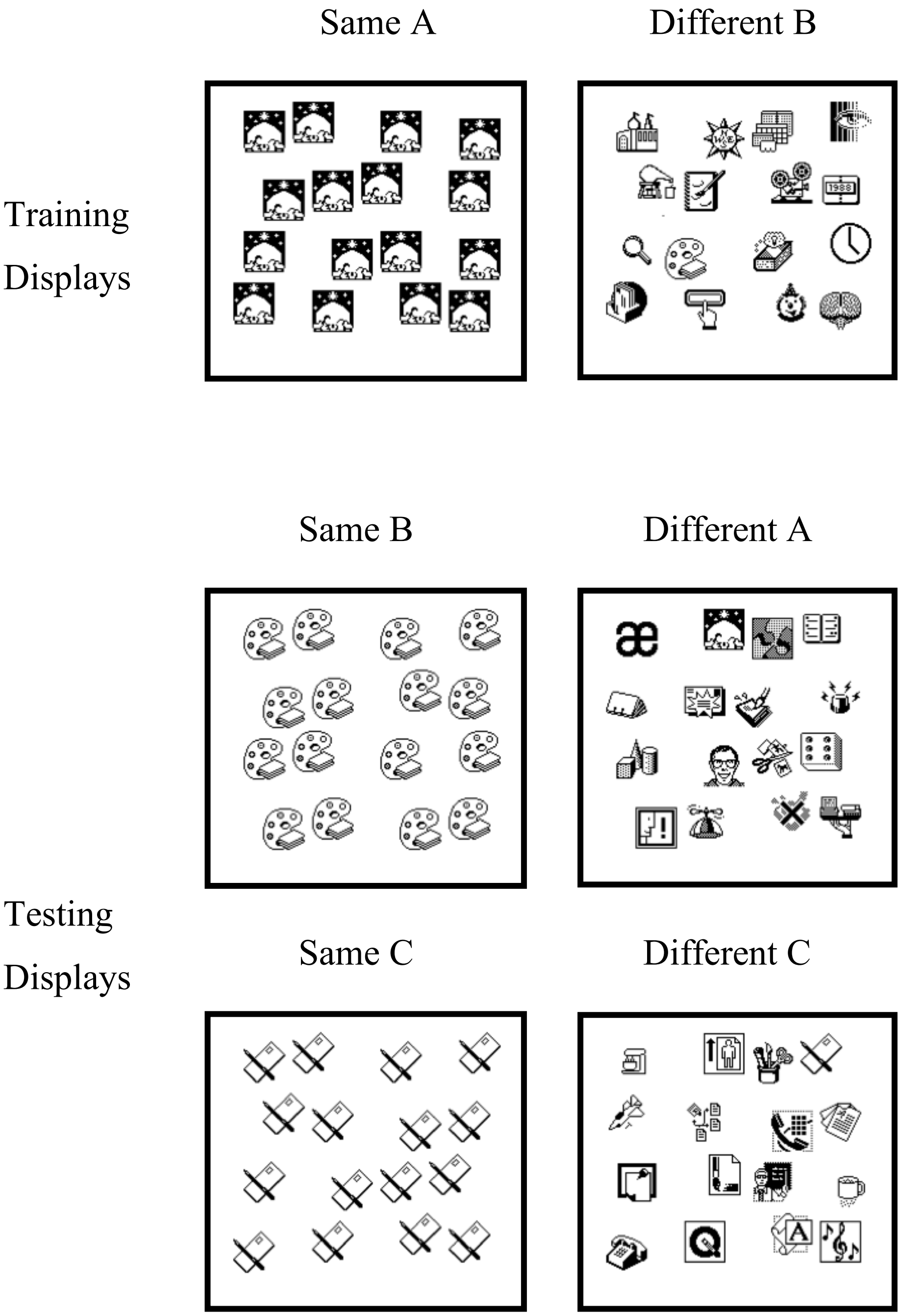
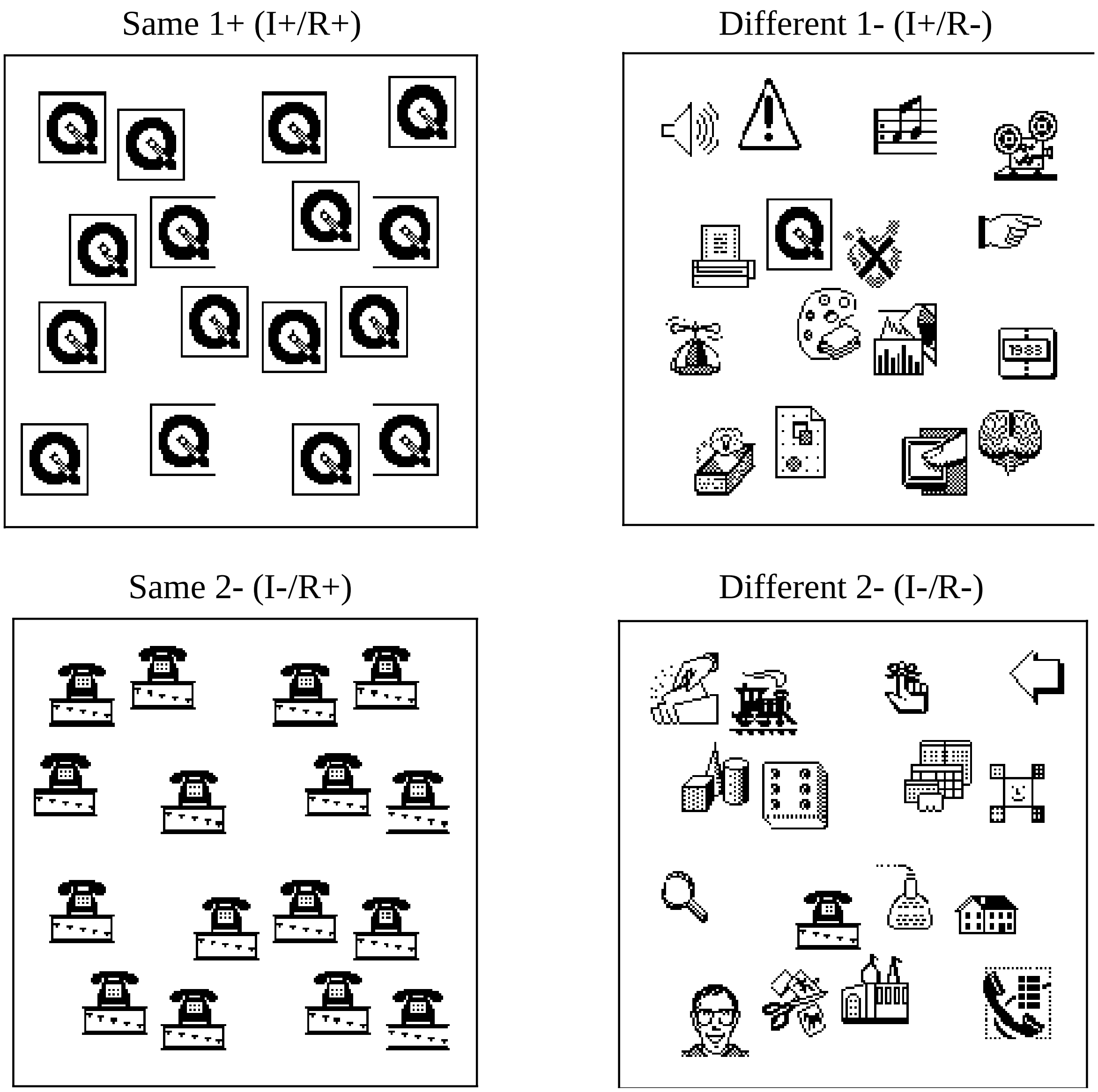


Figure 4. Gibson, B. M., & Wasserman, E. A. (2003). Pigeons learn stimulus identity and stimulus relations when both serve as redundant, relevant cues during *same-different* discrimination training. *Journal of Experimental Psychology: Animal Behavior Processes, 29,* 84-91. Figure 1.



Same 1+ (I+/R+)

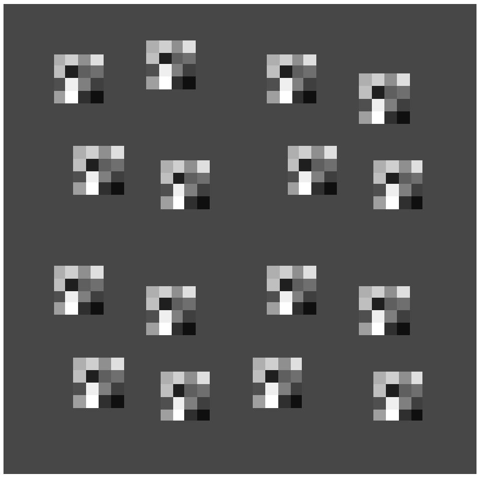
Different 1- (I+/R-)

Same 2- (I-/R+)

Different 2- (I-/R-)

Figure 5. Wasserman, E. A., Frank, A. J., & Young, M. E. (2002). Stimulus control by same versus different relations among multiple visual stimuli. *Journal of Experimental Psychology: Animal Behavior Processes, 28*, 347-357. Figure 1.

Same



Different

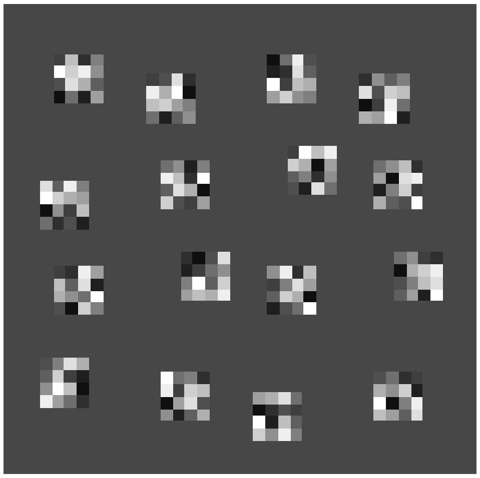


Figure 6. Brooks, D. I., & Wasserman, E. A. (2008). Same/different discrimination learning with

trial-unique stimuli. *Psychonomic Bulletin & Review, 15,* 644-650. Figure 1.

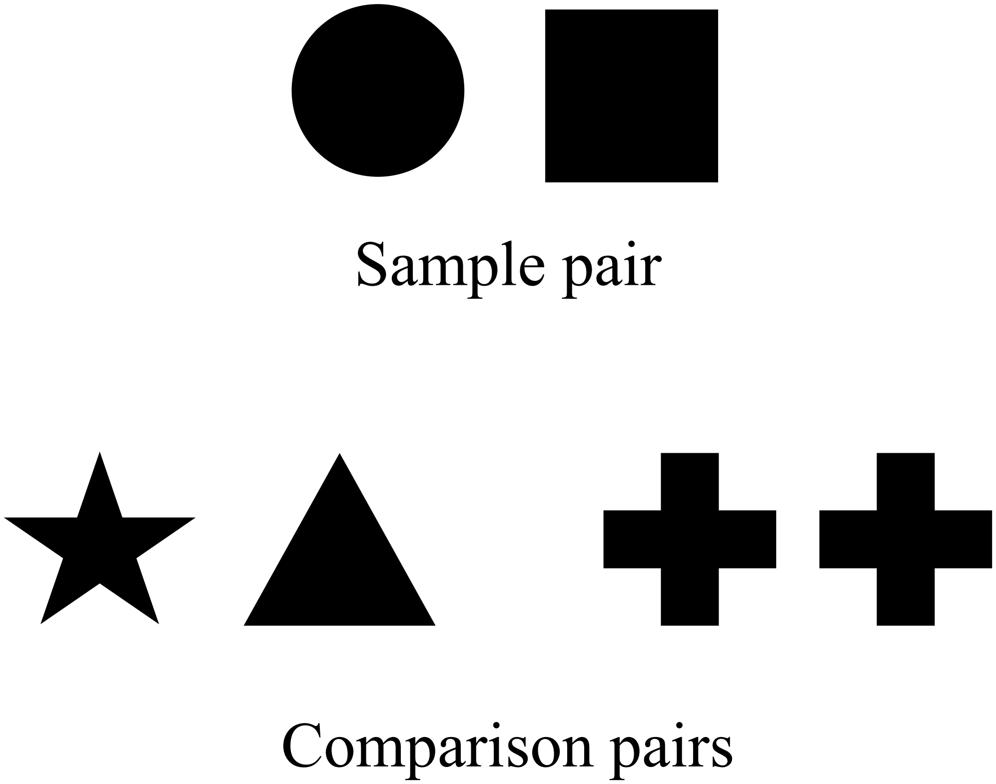


Figure 7. Illustration of the relational matching-to-sample task. On top, the sample pair, and on bottom, the comparison pairs. The animal has to choose the comparison pair that matches the relationship depicted on the sample pair. In this example, the relation between the items in the sample pair is “different,” so the correct choice is the comparison pair on the left, that also shows two different items.

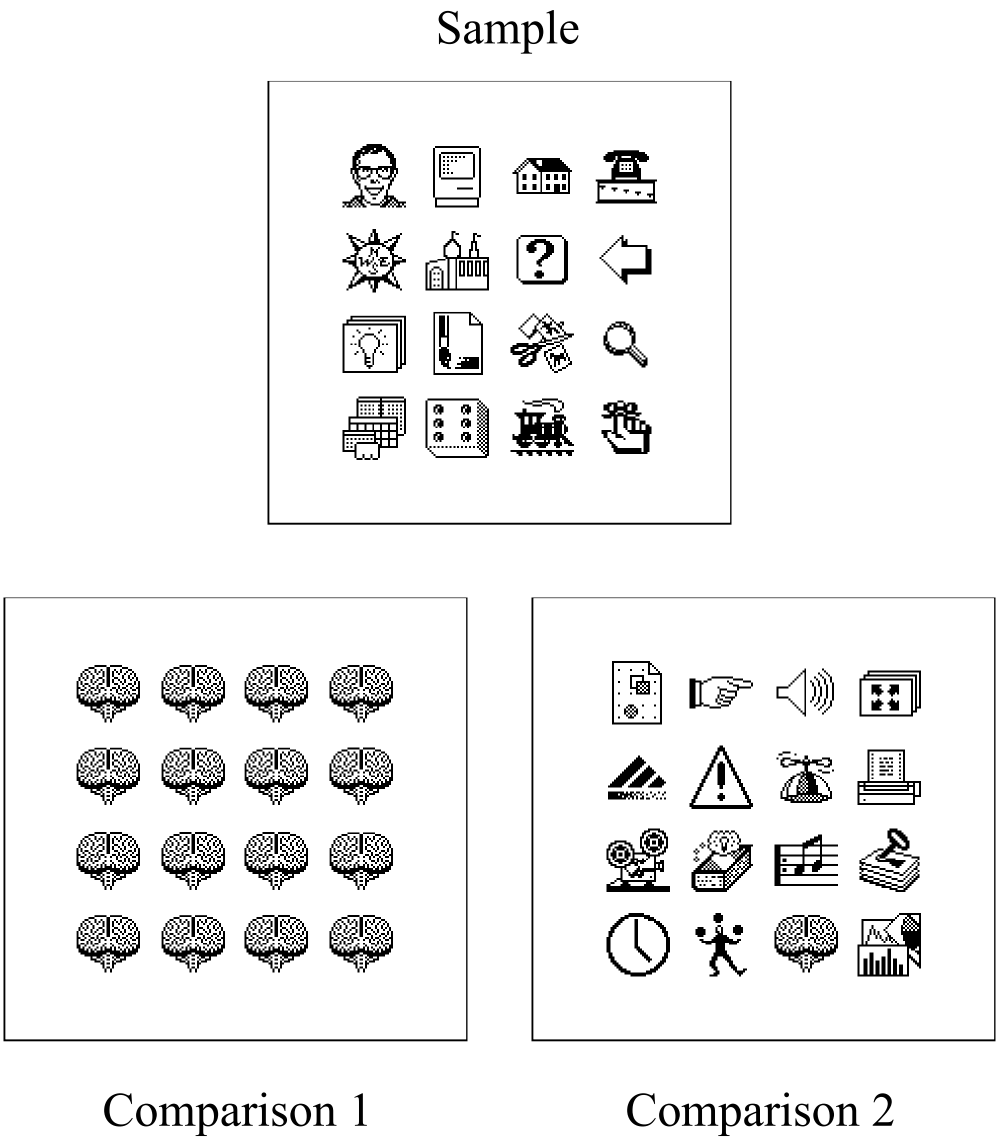


Figure 8. Relational matching task with arrays of icons. On top, the sample array, and on bottom, the comparison arrays. The animal has to choose the comparison array that matches the relationship depicted on the sample array. In this example, the relation among the items in the sample array is “different,” so the correct choice is the comparison array on the right, that also shows different items. Figure 1 from Fagot, J., Wasserman, E. A., & Young, M. E. (2001). Discriminating the relation between relations: The role of entropy in abstract conceptualization by baboons (*Papio papio*) and humans (*Homo sapiens*). *Journal of Experimental Psychology: Animal Behavior Processes, 27,* 316–32.