Chapter 5
Structure-Mapping Processes Enable Infants' Learning Across Domains Including Language

Susan J. Hespos, Erin Anderson, and Dedre Gentner

Abstract Humans have an astounding ability to acquire new information. Like many other animals, we can learn by association and by perceptual generalization. However, unlike most other species, we also acquire new information by means of relational generalization and transfer. In this chapter, we explore the origins of a uniquely developed human capacity—our ability to learn relational abstractions through analogical comparison. We focus on whether and how infants can use analogical comparison to derive relational abstractions from examples. We frame our work in terms of structure-mapping theory, which has been fruitfully applied to analogical processing in children and adults. We find that young infants show two key signatures of structure mapping: first, relational abstraction is fostered by comparing alignable examples, and second, relational abstraction is hampered by the presence of highly salient objects. The studies we review make it clear that structure-mapping processes are evident in the first months of life, prior to much influence of language and culture. This finding suggests that infants are born with analogical processing mechanisms that allow them to learn relations through comparing examples.

Turning to very early learning, we augmented our account by considering the nature of young infants' encoding processes, leading to two counterintuitive predictions. First, we predicted that young infants (2–3 months old) would be better able to form a relational abstraction when given two alternating exemplars than when given six different exemplars (Anderson et al. Cognition 176:74–86, 2018). This is based on the assumption that young infants may initially focus on the individual objects and shift to noticing the relation between them after repetition of the

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exemplar (Casasola. Child Development 76(1):279–290, 2005a; Casasola. Developmental Psychology 41:183–192, 2005b). Second, we predicted that younger, but not older, infants would be able to form a relational abstraction from one repeated exemplar; this follows from the assumption that young infants have unstable encoding processes, so identical exemplars may be variably encoded (Anderson et al. 2019).

Next, we revisited Premack's insight from 1983 that the tasks used to measure analogical abilities (RMTS, MTS, and *same/different* discrimination) are vastly different from each other. The takeaway from this section is that while many species can learn through association and perceptual generalizations, there are relatively few species that can succeed in the *same/different* discrimination task. Of these species that can succeed in the *same/different* task, humans are unique in that they need fewer than 10 trials to learn such relations. In the final sections, we reviewed how structure mapping extends to language acquisition, artificial grammar learning, and physical reasoning. The value of investigating the origins of our analogical abilities is that we will be in a better position to understand how language and culture capitalize on cognitive abilities. More broadly, we can address whether essential differences between humans and other species are evident from the earliest points in development.

Humans have an astounding ability to acquire new information. Like many other animals, we learn by association and by perceptual generalization. However, unlike most other species, we also acquire new information by means of relational generalization and transfer. In this chapter, we will explore the origins of a uniquely developed human capacity—our ability to learn relational abstractions through analogical comparison. We focus on whether and how infants can use analogical comparison processes to derive relational abstractions from examples.

By analogical comparison, we mean a comparison process in which the relational structure of the two items is aligned, as described in Gentner's structure-mapping theory (Gentner, 1983, 1989, 2010; Markman & Gentner, 1997). At first glance, the idea that infants might use analogical processes may seem absurd. After all, analogy is considered a sophisticated process even in adults. Further, there is a methodological challenge in studying whether prelinguistic infants can make analogical comparisons. Fortunately, decades of research have revealed general signatures of relational alignment and learning; thus, we can compare the performance of infants with established signatures of analogical processing.

The value of this pursuit is in allowing us to discover the roots of relational cognition. Adults' ability to use abstract categories and rules is supported by a vast store of conceptual knowledge, influenced by the culture that surrounds us and the languages we speak, as well as by real-world experience. To gain an understanding of the nature and origin of our extraordinary relational ability, we must investigate infants who have had less exposure to culture and language. If we can specify how infants learn relations from multiple examples, then we will be in a better position to understand how language and culture capitalize on these existing cognitive abilities and how our cognitive processes compare to those of other species.

Our field is only beginning to study the origins of human analogical ability. However, there has been considerable research on the development of analogical ability from preschool to adulthood. We briefly review this research to set the stage for examining what characteristics might be evident in infants. In general, children's comparison processing shows a relational shift whereby children focus on object matches early in learning and focus increasingly on relational commonalities as they gain in domain knowledge (Gentner, 1988; Gentner, Anggoro, & Klibanoff, 2011; Gentner & Rattermann, 1991; Gentner & Toupin, 1986; Paik & Mix, 2006, 2008; Richland, Morrison, & Holyoak, 2006). For example, Gentner and Rattermann (1991, Experiment 1) asked 3- to 5-year-old children to find a hidden sticker. The experimenter had three pots of increasing sizes in a row in front of them. The child had a similar series of three pots in front of them. On each trial, the experimenter secretly hid an object under one of the child's pots. Then, while the child watched, the experimenter placed a sticker under one of her pots. The stickers were always placed in the same relative position—left (smallest), middle (medium), or right (largest)—and the child was told that by watching where the experimenter put a sticker, they could find their sticker. Three-year-olds succeeded when identical objects occupied the same relational roles. The interesting manipulation was when the sizes of the pots were shifted, such that the experimenter had a small, medium, and large pot and the child had a medium, large, and extra-large pot. This arrangement sets up a cross-mapping—a case in which there is an object match that competes with the desired relational match (Gentner & Toupin, 1986; Ross, 1989). Cross-mapped analogies provide a stringent test of children's understanding of the relational match. In Gentner and Rattermann's study, younger (3-year-olds) children performed at chance, repeatedly choosing the object match, while older children (5-year-olds) chose the relational match.

Gentner and colleagues have argued that the relational shift is not age-linked, but rather results primarily from increases in relational knowledge (see also Gentner, 1989, 2003, 2010; Gentner & Medina, 1998; Gentner & Rattermann, 1991). As evidence for this claim, Gentner and Rattermann (1991, Table 7.5, p. 250) offered examples of the relational shift taking place between 4 and 6 months in an occlusion event (Baillargeon, 1994), between 3 and 4 years old (the Gentner and Rattermann task described above), and between 6 and 9 years old in a story-enacting task involving social causation (Gentner & Toupin, 1986). As further evidence that the shift is largely driven by knowledge, rather than maturational processes, Gentner and Rattermann showed that 3-year-olds could succeed on this task when provided with relational labels for the object sets (e.g., daddy, mommy, baby). This suggests that the 3-year-olds in the initial study were limited not by age-related processing constraints, but by the lack of a relational knowledge schema in this task (see also Loewenstein & Gentner, 2005). Other researchers have linked the relational shift to maturational increases in processing capacity (Halford, 1992) and to increases in executive ability, including inhibitory control (Doumas, Hummel, & Sandhofer, 2008; Richland et al., 2006; Thibaut, French, & Vezneva, 2010), and it is possible that all three factors play a role.

This work has also revealed characteristic patterns of analogical learning, including factors that facilitate and hinder the relational learning process. One signature component of relational learning is that the ability to perceive abstract relational matches can be enhanced by comparing instances of a relation. For example, Gick and Holyoak (1983) found that comparing two stories that had the same abstract causal structure enabled people to generalize that structure and to transfer it to a further situation. Similar effects of comparison have been found for preschool children in relational tasks (e.g., Christie & Gentner, 2010; Gentner et al., 2011; Gentner & Namy, 1999; Namy & Clepper, 2010). These findings are consistent with the structure-mapping theory (Gentner, 1983; Gentner & Forbus, 2011; Gentner & Markman, 1997) account that the act of comparison entails a structural alignment process. In structural alignment, the two analogs are aligned in such a way that the common relations are placed into correspondence. Once a structural alignment is achieved, the relational commonalities between the items are highlighted (Markman & Gentner, 1993; see also Gentner, 2010). In addition, further inferences may be projected, and certain differences may be highlighted; however, in this chapter, we focus on the role of structural alignment in revealing commonalities. The influence of structural alignment is a defining characteristic of analogical reasoning in adults (Doumas & Hummel, 2013; Forbus, Ferguson, Lovett, & Gentner, 2017; Gentner, Holyoak, & Kokinov, 2001) and the evidence of its influence in children as young as 3 years of age suggests a possible continuity in relational processing through human development. In this chapter, we explore whether this continuity extends to infants.

The Gentner and Rattermann study also exemplifies a second signature of analogical processing: namely, that attention to individual objects can interfere with relational processing. The 3-year-olds in these studies were able to carry out the mapping quite well when the objects matched but failed when there were competing object matches (unless given support from relational language). There are many studies showing that preschool children perform far worse on relational matching tasks when competing object matches are present (Gentner & Toupin, 1986; Richland et al., 2006), especially if the objects involved are rich and distinctive (DeLoache, 1995; Gentner & Rattermann, 1991; Paik & Mix, 2006). For example, children can pass the relational match-to-sample (RMTS) task (exemplified on the left in Fig. 5.1) at 4.5 (Christie & Gentner, 2014) or 5 years of age (Hochmann, Mody, & Carey, 2016). However, when Christie and Gentner (2007) gave children and adults a version of the RMTS task in which there was a competing object match (see the right side of Fig. 5.1), the results showed a steep gradient across age: 4.5-year-olds chose the relational match only 17% of the time, 8.5-year-olds performed at chance (50%), and adults chose the relational match 90% of the time.

The finding that attention to objects can overshadow attention to relations has also been found in word-learning tasks (Casasola, 2005a; Maguire, Hirsh-Pasek, Golinkoff, & Brandone, 2008). In the work we will describe below, we focus on infant relational learning and ask whether it is similarly facilitated by comparison and hindered by object focus. Finding substantive evidence for the signatures of analogical reasoning in infants would suggest that the relational process is continuous through development.

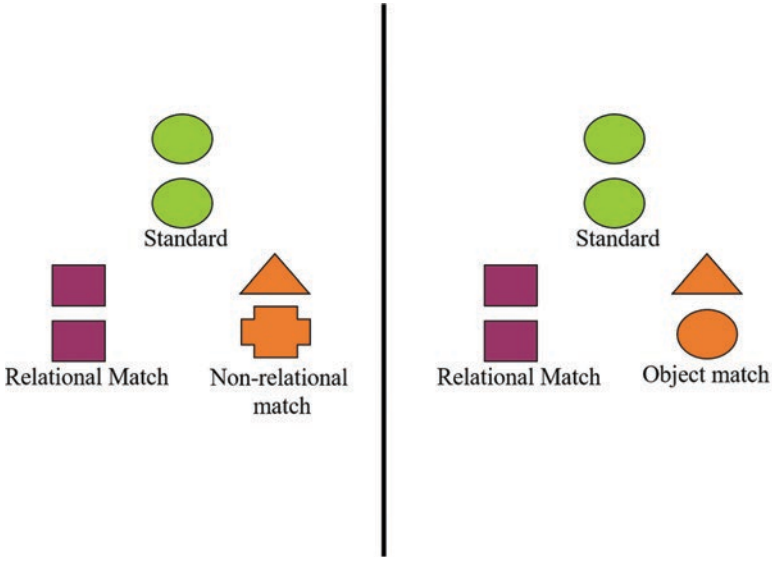

Fig. 5.1 On the left is a sample triad from Christie and Gentner (2014). They found 4.5-year-olds chose the relational match significantly more often than chance. On the right is a sample trial that contains a competing object match from Christie and Gentner (2007), and the pattern of results was very different. In trials with a competing object match (the green and orange circles), 4.5-year-olds preferred the object match, adults chose the relational match, and 8.5-year-olds were in the middle; their performance was not different from chance

The existing literature on the development of analogical abilities highlights the role of linguistic symbols in facilitating relational learning (Gentner, 2003, 2010; Gentner & Rattermann, 1991). There is evidence that children's relational insight is improved by having symbolic labels for relations and relational systems (Carey, 2010; Christie & Gentner, 2014; Gentner, 2005; Hermer & Spelke, 1994; Loewenstein & Gentner, 2005; Pyers, Shusterman, Senghas, Spelke, & Emmorey, 2010; Son, Doumas, & Goldstone, 2010). There is also considerable evidence that common labels can prompt children (and adults; see Lupyan, 2012) to compare referents and abstract the commonalities they share, for concrete nouns (Ferry, Hespos, & Waxman, 2010; Gentner & Namy, 1999; Liu, Golinkoff, & Sak, 2001; Namy & Gentner, 2002), relational nouns (Gentner, 2005; Gentner et al., 2011), adjectives (Waxman & Klibanoff, 2000), and verbs (Haryu, Imai, & Okada, 2011; Waxman et al., 2013; see Gentner & Namy, 2006, for a review). More specifically, there is evidence that relational language, such as verbs, prepositions, and comparative adjectives, can foster retaining and transferring relational patterns (Casasola, 2005b; Childers, 2011; Christie & Gentner, 2014; Gentner et al., 2011; Hermer & Spelke, 1994; Jamrozik & Gentner, under review; Loewenstein & Gentner, 2005; Pyers & Senghas, 2007; Son et al., 2010). While it is clear that language plays a critical role in relational learning and reasoning in children and adults, the focus of this chapter will be on infants' prelinguistic abilities, prior to much influence from language and culture. If we see evidence of relational learning in early infancy, then we can infer that these processes exist prior to the acquisition of language. Moreover, such findings would put us in a better position to understand how language learning may capitalize on this preexisting relational ability.

The central question in this chapter is how human analogical ability arises. More specifically, when and how does our ability to derive relational abstractions from examples arise? One possibility is that we are born with a core set of abstract relations, which we can perceive in specific examples. Such a set would almost certainly include the relations *same* or *different* (Christie & Gentner, 2014; Hochmann et al., 2017; Wasserman, Castro, & Fagot, 2017). A second possibility is that infants are born with an analogical processing mechanism that allows them to learn relations through comparing examples. A third possibility is that analogical ability develops by combining other abilities through cultural and linguistic experience. To decide among these proposals, we focus on the *same-different* relation. The relations of *same* and *different* are among the simplest and most basic relations in the human repertoire and are therefore a logical starting point.

Possibility (1)—that we are born with a core set of abstract relations—has been widely assumed, based on a highly cited study by Tyrrell, Stauffer, and Snowman (1991). Tyrrell et al. (1991), using a preferential looking paradigm, reported that 7-month-old infants encode abstract *same* and *different* relations without training, simply from exposure to a single exemplar. However, examination of the reported results revealed ambiguity as to whether infants genuinely abstracted the relation. We therefore replicated Tyrrell et al.'s methods with the same age group (Ferry, Hespos, & Gentner, 2015). The results showed no evidence for relational abstraction. Infants showed a novelty response when comparing the identical pairs they had seen (e.g., AA) with a new pair (BC), but when the familiarized relation and the competing relation were tested with new objects (e.g., XX vs. YZ), the infants showed no preference. Thus, there is no evidence that these infants formed a relational abstraction from one exposure.

Next, we tested the second proposal: whether infants are capable of learning an abstract relation by structural alignment across exemplars. We showed infants a sequence of four exemplars of *same* or *different* toys. Half the infants saw *same* pairs (e.g., AA, BB, CC, DD), and half saw *different* pairs (AB, CD, BC, DA), repeated until infant looking declined sufficiently to demonstrate habituation (about 6–9 pairs). We then showed infants a sequence of six test trials. On alternating trials, infants saw pairs of objects that were either the *same* or *different*, and the dependent measure was the duration of infants' looking times. The key question was whether infants would look longer at the novel relation (AA vs. AB), even when instantiated with new objects (XX vs. YZ). Indeed, that is what happened, both for infants habituated to *same* and for those habituated to *different*—evidence that they had abstracted the common relation across the habituation pairs (see Fig. 5.2).

This ability to learn an abstract relation from a series of examples is one signature of analogical learning in older children and adults. We also tested the second signature of relational learning—whether object salience would interfere with structural alignment. Prior to the experiment, we gave infants a brief exposure to a

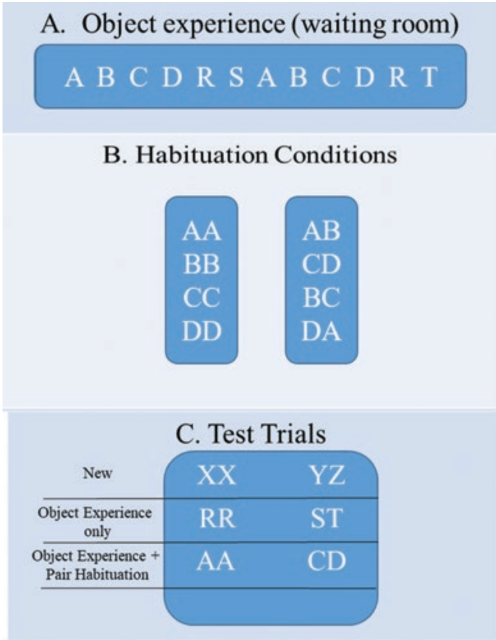

Fig. 5.2 Schematic of events in Ferry et al. (2015). (**a**) In the waiting room, infants saw a subset of the individual toys before the experiment. (**b**) Infants were habituated to four pairs of objects, either *same* or *different*. (**c**) In six sequential test trials, looking time was recorded to the novel and familiar relational pairs in three different types of test trials

subset of the objects used in test trials, thus increasing the salience of these individual objects. We found that infants failed to discriminate between the *same* and *different* relations when the test pairs contained objects that had been rendered individually salient prior to habituation—consistent with the findings among older children, for whom object salience interferes with analogical comparison (Gentner & Toupin, 1986; Paik & Mix, 2006). These findings suggest that by 7 months, infants show the basic characteristics of analogical learning—their learning was facilitated by comparison across examples and hindered by object focus. We interpret these findings as showing that the analogical processing ability is present in the first year of life and may be continuous through development.

Given our non-replication of the Tyrrell et al. study, we cannot assume that infants have a preexisting relational vocabulary that they can apply to examples in the world. Rather, our studies provide evidence that infants have a relational processing mechanism that can compare across examples to form abstract relations. These findings also argue against the third possibility that analogical ability arises through combining other capacities and experiences. Although language and conceptual learning refine and extend our analogical abilities, these abilities are present before extensive cultural and linguistic experience.

Our next study tested for relational abstraction at the earliest age possible to serve as a base for capturing developmental changes and variability in the learning process across age groups. Anderson, Chang, Hespos, and Gentner (2018) tested 3-month-old infants—the earliest age at which infants have the neck control to participate in a looking-time paradigm. As in the prior study, the key dependent measure is whether infants are able to differentiate the familiar relation (e.g., *same*, if habituated to *same*) from the unfamiliar one (e.g., *different*) when they see test pairs composed of new objects. The specific predictions were that if infants are learning by comparison, then (1) relational learning should benefit from comparing a series of analogous exemplars and (2) performance on test pairs should be hampered for pairs that contain objects that were rendered individually salient through object experience in the waiting room prior to the experiment.

Learning theories broadly agree that increasing the variability in a set of exemplars should lead to a greater range of transfer (Markman & Wisniewski, 1997; Rogers & McClelland, 2005; Wasserman, Young, & Fagot, 2001; Xu & Tenenbaum, 2007). Following this logic, young infants may require a larger training set than the four exemplars given to older infants in Ferry et al.'s (2015) study. Therefore, in one study, we increased the number of exemplars seen in habituation to six.

But there is an alternate possibility. Because alignment of relational structure is the sine qua non for discovering new relational commonalities, the ability to successfully compare and align is a prerequisite for relational learning. As discussed below, some studies have found that increasing the number and variability of examples can be detrimental to young children's relational learning (Casasola, 2005a; Maguire et al., 2008). To allow for this possibility, in our second experiment, we gave infants two exemplars that alternated across habituation (see Fig. 5.3).

The results revealed no evidence of learning the relation when 3-month-old infants were presented with six exemplars. However, the infants did learn the relation when they were presented with two alternating exemplars during habituation trials. In the two-exemplar condition, the 3-month-olds showed the key signature of analogical abstraction: they looked significantly longer at the novel relation during test even when that relation was instantiated with new objects, thus suggesting that they were able to transfer the relation to objects that they had not seen previously. In addition, there was evidence that object focus hindered learning. As in our prior studies, there was no difference in looking time between the novel and familiar relations when instantiated by objects that had been made individually salient through pre-exposure. Further, there was a significant difference in performance across test trial types that contrasted pairs seen in the waiting room before the experiment and new objects. These findings show that the signatures of analogical learning are present not only at 7 months (Ferry et al., 2015) but also by 3 months of age (Anderson et al., 2018). Clearly, language is not a necessary prerequisite for relational processing—the ability to carry out structural alignment and abstraction is in place prior to and independent of language. In contrast to the possibility that relational knowledge depends on language, we speculate that language may capitalize on the relational processes and may be used in learning grammatical structures (Gentner, 2010; Gentner & Namy, 2006).

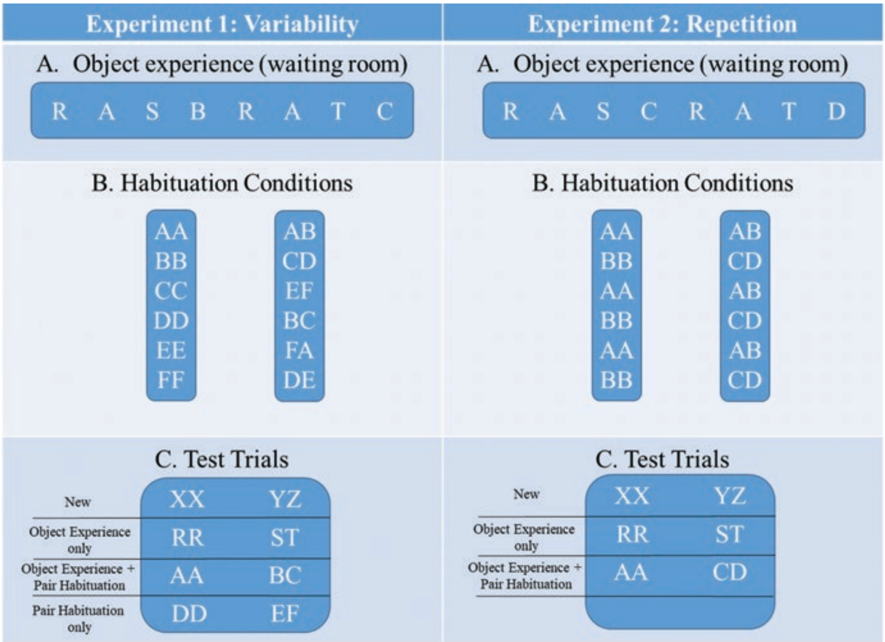

Fig. 5.3 Schematic of events in Anderson et al. (2018). In Experiment 1 on the left, infants saw six exemplars during habituation trials. In Experiment 2 on the right, infants saw an alternation between two exemplars. (**a**) In the waiting room, infants saw a subset of the individual toys before the experiment. (**b**) Infants were habituated to pairs of objects, either same or different. (**c**) In sequential test trials, looking time was recorded to the novel and familiar relational pairs across different types of test trials

When Is High Variability Helpful and When Not?

Across these studies, we have found evidence that infants can abstract a common relation from a sequence of examples. At 7–9 months, infants formed a relational abstraction from four exemplars. At 3 months, infants formed a relational abstraction with two alternating exemplars but not with six exemplars. This second finding—that 3-month-olds were better at forming an abstraction with two exemplars than with six—seems at odds with the many findings in both animal and human learning that have found that increasing the number and variability of exemplars promotes generalization (Cooper, Heron, & Heward, 2007; Thompson, Oden, & Boysen, 1997; Wasserman & Young, 2010).

The existing developmental literature reveals many studies that have found better learning with more exemplars (Bomba & Siqueland, 1983; Casasola & Park, 2013; Castro, Kennedy, & Wasserman, 2010; Gerken, 2006; Gerken & Bollt, 2008; Gomez, 2002; Needham, Dueker, & Lockhead, 2005; Quinn & Bhatt, 2005). Yet, there are a few studies that align with the "less is more" pattern (Bulf, Johnson,

& Valenza, 2011; Casasola, 2005a; Gerken & Quam, 2017; Maguire et al., 2008). These findings suggest a divide between studies in which the desired generalization depends on common object properties and those in which the desired generalization depends on relational commonalities. In the former case, more variability generally helps to broaden the generalization. But in order to form a relational abstraction, the learner must be able to carry out structural alignment over the exemplars. If the exemplars look very different from one another, the learner may fail to align them. For example, in our studies with 3-month-olds, infants could form a relational abstraction when given two alternating exemplars, but not when given six examples. We suggest that repeated exposure to two exemplars allowed the infants to go beyond noticing only the individual objects to also encode the relations, which could then be aligned across exemplars (see Casasola, 2005a, for a similar account).

The standard learning principle—"breadth of training predicts breadth of transfer"—is a useful rule, widely applicable for relatively concrete categories. But because alignment of relational structure is essential for discovering new relational commonalities, the ability to successfully compare and align is a prerequisite for relational learning (Anderson et al., 2018; Gentner & Hoyos, 2017). Thus, as Gentner and Hoyos (2017) noted, the standard principle must be amended for relational learning to be "breadth of *alignable* training predicts breadth of transfer."

Promoting Relational Learning

As noted above, structural alignment is essential to relational abstraction. But it remains true that breadth of training (in this case, alignable training) will increase generalization. Is there a way to have it both ways? Can we ensure alignment while increasing the number and variability of exemplars in infant relational learning tasks? Research on older children suggests that progressive alignment (Kotovsky & Gentner, 1996) provides a way to do this. In progressive alignment, relational learning is facilitated by initially giving children highly similar (and readily alignable) exemplars of a relation before presenting them with more surface-dissimilar pairs (Childers, Parrish, Olson, Fung, & McIntyre, 2016; Gentner et al., 2011; Gentner, Loewenstein, & Hung, 2007; Haryu et al., 2011; Hoyos, Horton, & Gentner, under review; Kotovsky & Gentner, 1996; Loewenstein & Gentner, 2001). These initial pairs with their highly similar corresponding objects are likely to be spontaneously aligned, and this alignment boosts the salience of the common relation (Gentner & Namy, 1999; Namy & Gentner, 2002). Note that progressive alignment operates quite differently from the alternation technique used by Anderson et al. (2018), in which repetition reduced the salience of the objects. In progressive alignment, close surface matches are used to seed comparison and promote initial alignment and thereby increase relational focus. Thus, in the progressive alignment condition, the infants would be presented with a series of six pairs in which the first pairs are highly similar to each other; then the variability will increase (a schematic depiction for habituation to *same* would be OO, QQ, CC, SS, WW, FF).

A second prediction is based on the idea that if comparison is critical for relational learning, then infants would never be able to learn a relation from a single example. This is consistent with our non-replication of Tyrrell et al. (1991). However, it is possible that the higher-order process of analogical comparison could interact with low-level encoding processes. In a recent set of experiments, we made the following counterintuitive prediction: for very early learners, even one example might be perceived as many due to immature/inconsistent encoding (Anderson, Hespos, & Gentner, 2019). This prediction is based on the assumption that infants' early encoding processes are unstable, resulting in variable encodings of the same external situation. This means that for the young infant, multiple exposures of a single example could be perceived as a series of highly similar pairs that share an alignable relational structure. In contrast, older infants who have a more stable ability to encode would recognize the repeated single example and would fail to learn the relation. We found that 3-month-old infants were indeed able to generalize a same or different relation from a single pair that was repeated over the course of habituation. In contrast, 7- and 9-month-olds did not generalize, though they did successfully distinguish the habituation pair from a novel pair. These findings are consistent with the idea that comparison is important to relational abstraction but highlight that comparison processes operate over representations that vary according to the learner's level.

What Paradigms Are Usually Used to Test Our Theory?

Relational learning paradigms have a diverse and extensive history stretching far back into the comparative literature. As Premack (1983) pointed out, three tasks that might seem to recruit similar processes are in fact vastly different in the ease with which animals can master them. The easiest is the object match-to-sample (MTS) task (given A, choose A over B), which can be passed by many species, including pigeons, macaques, and honeybees, as well as by 14-month-old human infants (Fagot & Thompson, 2011; Flemming, Beran, & Washburn, 2007; Giurfa, Zhang, Jenett, Menzel, & Srinivasan, 2001; Hochmann et al., 2016; Thompson et al., 1997; Wasserman & Young, 2010). In contrast, the relational match-to-sample (RMTS) task (given AA, choose XX over YZ; given BC, choose YZ over XX)[1] is far more challenging. The set of species that succeeds in the RMTS task is far smaller than the set that succeeds in object matching. So far, this set includes humans above the age of about four (without special training), chimpanzees with symbol training (Premack, 1983; Thompson et al., 1997), and hooded crows, also with considerable training (Smirnova, Zorina, Obozova, & Wasserman, 2015). The fact that success with MTS is evident across many species and success with RMTS is sparse calls for

[1] We follow Premack (1983) in restricting the term "relational match-to-sample (RMTS)" to the two-item version and refer to matches of four or more identical (or nonidentical) items (e.g., Wasserman et al., 2001) as "array match-to-sample."

an analysis of what each task requires. The MTS task requires recognizing an object match. In contrast, the RMTS task requires encoding the relation between each pair of objects and choosing the alternative that shares a relation with the standard. The third similarity task Premack discussed is the *same-different* task. Although making a same-different judgment might seem rather like making a match-to-sample, far fewer species are able to master the same-different task than can master the match-to-sample task (Premack, 1983).

Our chief reason for focusing on the same-different relation is the centrality of sameness and difference in conceptual thought. Wasserman and Young (2010) quote William James as follows: "the recognition and integration of the 'sense of sameness is the very keel and backbone of our thinking' (p. 459) as well as 'the most important of all the features of our mental structure' (p. 460)." A second reason for choosing the *same-different* task is that it has been used extensively with nonhuman primates, offering the possibility of cross-species comparison. A third, more pragmatic reason is that it can be tested without language and is therefore feasible for use with infant populations. Of course, many researchers in the comparative arena have found this option attractive for the same reason; the *same-different* task has been used with a wide variety of species (Fagot & Thompson, 2011; Fagot, Wasserman, & Young, 2001; Flemming et al., 2007; Shields, Smith, & Washburn, 1997; Thompson et al., 1997; Thompson & Oden, 2000; Truppa, Mortari, Garofoli, Privitera, & Visalberghi, 2011; Wright & Katz, 2006; Young & Wasserman, 1997, 2002; Zentall, Singer, & Miller, 2008). There appears to be broad cross-species continuity in the ability to carry out *same-different* judgments on arrays of multiple objects (Zentall et al., 2008). For example, pigeons can be trained to successfully differentiate between an array of 16 all-identical objects and an array of 16 all-different objects (Young & Wasserman, 2002). However, other research by this group indicates that pigeons could be responding to differences in degree of entropy. Studies by Young and Wasserman (1997) varied the degree of sameness within arrays of 16 objects and showed that pigeons are highly sensitive to the degree of entropy within an array (where entropy is high if all the objects are different and low if all are identical). Therefore, if we define relational ability as requiring the ability to distinguish *same pairs* (AA, BB, etc.) from *different pairs* (AB, CD), then this ability is extremely rare in nonhuman species. Nevertheless, human infants can succeed in the *same-different* task.

If we focus on the rare nonhuman species capable of making the *same-different* distinction for pairs, we find that extensive training is required for successful performance. For example, Wright and Katz (2006) were able to train rhesus monkeys, capuchin monkeys, and pigeons to distinguish *same* pairs from *different* pairs; however, to show full transfer to novel pairs, the two species of monkey required over 4700 training trials, and the pigeons required nearly 14,000 training trials. Flemming et al. (2007) showed that rhesus monkeys could learn the *same-different* task with larger arrays and that they could subsequently succeed on the *same-different* task with pairs. In general, apes—notably chimpanzees—have shown greater success in learning abstract *same-different* relations than have monkeys. The RMTS task has proved highly challenging for monkeys (but see Fagot et al., 2001) and is difficult even for young children (Christie & Gentner, 2014; Hochmann et al., 2017). However, adult humans readily pass the RMTS task.

Researchers have differed in how to interpret this difference across species. Gentner (2003, 2010) and colleagues have proposed that there is a continuum of relational ability between humans and primates. They cite work showing that chimpanzees who have learned symbols (either distinctive tokens or some other differential response) for *same* and *different* can pass the RMTS task—generally considered strong test of relational ability (Premack, 1983; Thompson et al., 1997). In contrast, Penn, Holyoak, and Povinelli (2008) propose that humans are the only species that possesses any relational ability. They discount evidence that chimpanzees can pass the RMTS task, arguing that the task can be passed via entropy detection and therefore does not indicate the ability to carry out relational matching. In making this argument, they are extrapolating from Young and Wasserman's (1997) demonstration that pigeons are responding to entropy when matching large arrays of same vs. different. However, this argument appears to be incorrect—recent research demonstrates that while the multi-item array match-to-sample can be passed via entropy detection, the classic two-item RMTS task cannot (Hochmann et al., 2017). More direct evidence comes from other recent studies that have found that chimpanzees (and bonobos) can pass relational tasks (Christie, Gentner, Call, & Haun, 2016; Haun & Call, 2009).

A more general point is that tasks that aim to measure sameness—such as MTS, same-different discrimination, and RMTS—may call on very different processes and knowledge. This is important for understanding what we can infer from these tasks. For example, passing the object MTS task does not require forming the relation of *same*. We know this because many animals can pass the MTS task but will fail to learn a same-different discrimination. All we can infer when an animal (or infant) passes the MTS task is that seeing two identical objects feels different from seeing two distinct objects[2]. Likewise, being able to pass the RMTS task does not require forming a higher-order relation of sameness between the two SAME relations. To spell out this analogy:

Matching X with X instead of Y does not imply that the animal has formed a relation of SAME (X,X).
Likewise, Matching (X,X) with (A,A) instead of (B,C) does not imply that the animal has formed a higher-order relation of SAME {SAME (X,X), SAME (A,A)}.

In any case, it is clear that humans excel in relational ability, even compared to our nearest cousins among the great apes. This examination of the comparative literature reveals two important points for understanding infant relational ability. First, focusing on the same-different task, human infants readily learn *same-different* discrimination. This contrasts with the difficulty many other species experience with

[2] Further, Hochmann et al. (2016) have found evidence suggesting that 14-month-olds in a nonmatch to same task pass the "different" task by first finding the match and then choosing the other one.

these relations. Second, infants learn the relation in very few trials (six to nine habituation trials), whereas nonhuman species often require extensive training.

How Could Structure-Mapping Theory Extend Beyond Contexts?

The work that we described in this chapter differs from most work on infant cognition in that it focuses on the nature of the learning process not the nature of the representation. Research on infants' expectations about how objects behave and interact has made enormous progress in the last 30 years and has revealed impressive early capacities in several different arenas, including spatial relations (Casasola, 2005b; Casasola & Cohen, 2002; Hespos, Grossman, & Saylor, 2010; Hespos & Piccin, 2009; Hespos, Saylor, & Grossman, 2009; Hespos & Spelke, 2004; Kibbe & Feigenson, 2015; McDonough, Choi, & Mandler, 2003; Moher, Tuerk, & Feigenson, 2012; Quinn, Cummins, Kase, Martin, & Weissman, 1996) and physical reasoning (Baillargeon, 1994; Hespos & Baillargeon, 2001, 2006, 2008; Needham & Baillargeon, 1993; Wang & Baillargeon, 2008 for reviews, see Baillargeon, Li, Gertner, & Wu, 2011; Baillargeon, Li, Ng, & Yuan, 2009; Spelke, Breinlinger, Macomber, & Jacobson, 1992). This work has focused on tracing the early development of understanding of spatial and physical events. Thus, the focus of this prior research is on revealing the knowledge infants have acquired in the world and how that knowledge supports infants' expectations. In contrast, the focus for this chapter is on the *learning processes during the experiment itself*. We suggest that the structure-mapping approach to learning has implications for many other arenas of human learning. Here we discuss two such areas: language learning and learning about the physical world.

Structure-mapping theory leads to a set of predictions concerning how comparison can benefit language learning (Gentner, 2010; Gentner et al., 2007; Gentner & Christie, 2010):

- Comparing two things engages a structural alignment process that renders their commonalties more salient—and this effect is greatest for common relational structure (Gentner & Namy, 1999).
- Structural alignment also renders *alignable differences*—differences that play the same role in the common relational structure—more salient (Gentner & Markman, 2006; Markman & Gentner, 1993; Sagi, Gentner, & Lovett, 2012).
- Progressive alignment is beneficial in early learning. Early in learning, when domain knowledge is weak, alignment purely on the basis of relations is often impossible. In progressive alignment, learners are first given a close overall similarity match that instantiates the desired relational structure, as exemplified below.

As Gentner and Namy (2006) reviewed, there is considerable evidence that language learning benefits from these processes. Studies of word learning have demonstrated the power of comparison to reveal common relational structure. For example, Gentner and Namy (1999) taught 4-year-olds a new noun (e.g., "blicket" for a bicycle) and asked them to choose another blicket. Children mostly chose a perceptually similar alternative (eyeglasses) instead of a perceptually dissimilar object from the same conceptual category (a skateboard). The same result occurred for children who were told that "blicket" was a name for a tricycle. But when a third group of 4-year-olds was shown both the bicycle and the tricycle, told that they were both blickets, and asked "can you see why these are both blickets?," the results were strikingly different. Despite the fact that they had twice as much evidence for the matching perceptual features, they chose the conceptual match (the skateboard). Gentner and Namy (1999) (see also Namy & Gentner, 2002) concluded that structurally aligning the two standards had highlighted their common causal and functional relations. Gentner et al. (2011) found that comparison aided children aged 3–6 years in learning the meanings of relational nouns—nouns such as *container*, whose meanings are determined not by common features but by common relations.

As Childers (2011) and colleagues have noted, this feature of structural alignment—that it preferentially highlights common relational structure—suggests that it would be particularly applicable to verb learning (see Imai & Childers, this volume). Learning verb meanings is challenging to young children. Not only are verbs slower to enter the vocabulary than nouns ((Bates et al., 1994; Bornstein, 2004; Gentner, 1982; Gentner & Boroditsky, 2001; Gleitman, Cassidy, Nappa, Papafragou, & Trueswell, 2005; Imai, Haryu, & Okada, 2005; MacNamara, 1972), but also even when children do learn a new verb, they often initially use it in a highly restrictive way (Forbes & Poulin-Dubois, 1997; Huttenlocher, Smiley, & Charney, 1983; Tomasello, 1992, 2000). Thus, an important question is how—by what processes—children acquire and extend new verbs. There is a growing body of research and theory that supports the idea that structure-mapping processes are integral to this learning (Childers, 2011; Childers, Hirshkowitz, & Benavides, 2014; Childers & Paik, 2009; Haryu et al., 2011; Tomasello, 2000). For example, Childers and colleagues have shown that children benefit from seeing multiple enactments of a given verb, rather than repeated enactments with the same objects (Childers & Paik, 2009). In another study, Childers, Heard, Ring, Pai, and Sallquist (2012) found that 2.5-year-olds taught a new verb performed as well after seeing a set of comparable enactments as they did after receiving direct instruction about the verb from an experimenter.

Other research on language learning has found evidence for a more specific prediction of structural alignment theory: namely, that progressive alignment benefits early learning. Progressive alignment is a way of addressing a bottleneck that arises in children's relational learning. Comparing two examples (such as two sentences involving the same novel verb) is a route to relational learning, but early in learning, children may lack sufficient relational knowledge to be able to align two disparate examples. In progressive alignment, learners are first given a close, overall similarity match that instantiates the desired relational structure. The high overall similarity makes it likely that children will spontaneously compare the two examples, and because the object matches are consistent with the relational alignment, young learners are likely to arrive at the correct alignment. Thus, progressive alignment can serve as "training wheels" for purely relational matches (Gentner, 2010; Gentner & Medina, 1998).

Childers et al. (2016) asked whether progressive alignment could aid children's verb learning. Indeed, the study found evidence that 3.5-year-old children benefit from progressive alignment. They presented children with two novel verbs under three conditions. In one condition, each verb was enacted four times with the same objects. In the progressive alignment condition, each verb was enacted first with highly similar objects playing similar roles in the events, followed by two events in which the objects were highly dissimilar across the enactments of the verb. In the all-far condition, each verb was enacted four times, with all enactments having highly dissimilar objects. After children witnessed these enactments, they were asked to enact the verb themselves, first using new objects similar to the ones used in the learning trials and one (the "far extension") using dissimilar objects. There were two results of note. First, children seeing multiple enactments of the same verb produced more correct extensions on the test than would children seeing a single enactment, consistent with prior findings (e.g., Childers, 2011; Childers & Paik, 2009). Second, on the critical far test, children who received progressive alignment from highly similar to less similar enactments performed best—significantly better than the single-enactment group.

Another study of progressive alignment in verb learning was done by Haryu et al. (2011). They taught 4-year-old children a verb for a novel event and asked whether the children could extend the verb to other events. They found that children were initially limited to close overall matches (i.e., literally similar events). That is, they extended the verb only when the new event shared similar objects as well as depicting the same action as the initial event; they failed when the objects were dissimilar, even when the new event shared its action with the initial event. In a second study, Haryu et al. found that progressive alignment from close to far matches enabled a new group of 4-year-olds to extend the verb based on sameness of action, without support from object similarity. Similarly Gentner et al. (2007) used high object similarity to help children to make the correct correspondences, thus supporting the correct alignment of relational structure. As in other work with progressive alignment, structural alignment resulted in heightening the common structure, which the children could then extend to an event that shared only that structure.

These findings are consistent with the general position that initial representations of verbs may be quite concrete and tied to the context in which they are learned (Lieven, Pine, & Baldwin, 1997; Tomasello, 1992, 2000) and that comparisons between current and stored utterances lead to more general, abstract representations of verb meaning. Initially, those comparisons will be between overall similar utterances, in which verbs appear in very similar frames. But via progressive alignment, these early concrete matches will potentiate future more abstract matches (Childers & Paik, 2009; Childers & Tomasello, 2001; Pruden, Shallcross, Hirsh-Pasek, & Golinkoff, 2008; see Gentner & Namy, 2006, for a more extensive discussion).

Structure mapping also has application to studies of artificial grammar learning—another arena in which infant researchers have investigated learning during the course of the experiment. Many artificial grammar tasks can be viewed as relational learning tasks (Aslin & Newport, 2012; Gerken, 2006; Gomez & Gerken, 2000; Johnson et al., 2009; Kuehne, Gentner, & Forbus, 2000; Marcus, Vijayan, Rao, & Vishton, 1999; Saffran, Pollak, Seibel, & Shkolnik, 2007). For example, in Marcus et al.'s (1999) study, after 7.5-month-olds heard 48 examples (16 patterns, three times each) of a syllable pattern such as AAB, they could then discriminate new instances of the AAB pattern from instances of an ABA pattern, even when all the specific syllables were new (see also Gomez & Gerken, 1999). Further, there is evidence that the ability to generalize across such patterns may operate across a broad range of stimuli, including tones and visual stimuli (Gomez & Gerken, 2000; Johnson et al., 2009; Saffran et al., 2007).

We suggest that structure mapping provides a natural mechanism for this process. Two key points supporting this claim are (1) by 7 months (and even earlier) infants are capable of structural alignment and abstraction and (2) our simulations reveal that the structural alignment process can capture key phenomena in artificial grammar learning. To take the first point, our studies of *same-different* learning show that infants can form a relational abstraction over a series of examples. More specifically, this process shows signatures of structural alignment and mapping, as discussed earlier.

Support for the second point—that the same process of structural alignment and abstraction can account for infants' artificial grammar learning—comes from simulation studies. Kuehne et al. (2000) showed that a computational model of analogical generalization called the sequential learning engine (SEQL) can capture the Marcus et al. (1999) findings. SEQL and its successor, SAGE,[3] use the structure-mapping engine (SME; Falkenhainer, Forbus, & Gentner, 1989; Forbus et al., 2017) to iteratively compare input examples, creating an ongoing generalization. If SAGE (or SEQL) is given an input example, it will store that example. If the example is followed by another, SAGE compares it to the first one, using SME. If there is sufficient overlap (i.e., if SME's score is above a preset threshold), the common structure is stored as a generalization. If the overlap is below threshold, the example will be stored separately. This process continues as new examples arrive; if new examples are sufficiently similar to the ongoing generalization, they are assimilated into it and the generalization is updated. New examples that cannot be assimilated into the main abstraction are compared to the set of examples; if a new example is very similar to a stored example, a new generalization is formed from their common structure. Thus, it naturally results in a generalization (or sometimes more than one generalization) plus exceptions.

SEQL was given the same input as the infants in Marcus et al.: three repetitions of each of the 16 three-syllable strings, for a total of 48 strings. Each syllable was encoded as having 12 phonemic features (following Elman, 1998). The relational pattern within each string (e.g., AAB) was encoded by Magi, which uses SME to encode symmetry and repetition within an item (Ferguson, 1994). As the strings were

[3] SAGE (McLure, Friedman, & Forbus, 2015) operates using the same basic iterative comparison process as SEQL but keeps track of frequency information about alignable structures, enabling it to produce probabilistic generalizations.

presented, SEQL computed a generalization by comparing the first two exemplars (via SME) and storing their common structure and then incrementally comparing subsequent exemplars to the ongoing abstraction. After all 48 exemplars were presented, SEQL was given two test strings with new syllables. Like the infants in Marcus et al., SEQL found the test string with the same relational structure (e.g., CCD) more similar to its generalization than the one with different structure (e.g., CDC).

Structure mapping has application to studies on physical reasoning too. For example, in a series of six experiments, Wang and Baillargeon (2008) describe teaching trials that helped and hindered infants' learn the variable of height in covering events 1 month earlier than usual. The authors describe their findings in the context of their explanation-based learning theory. However, understanding these studies in the context of relational learning illustrates the broad context in which this ability operates. Successful learning was demonstrated in Experiments 1 and 2 that allowed infants to compare the height of the object to the height of multiple tall and short covers. In a third experiment, they replicated the effect of learning after three comparison trials even when the test was delayed by 24 hours. Learning was hindered in low-alignment conditions. In Experiment 4, infants failed to learn when they could not compare between an object being fully and partially hidden. In Experiment 5, infants failed to learn when there was no direct comparison between the relative heights of the covers and the object. Given the key roles of visual alignment and comparison across these experiments, structure-mapping theory predicts the same pattern of results.

Conclusions

We began this chapter highlighting the amazing ability humans have for deriving relational abstractions. Like many other animals, we can learn by association and by perceptual generalization. However, unlike most other species, we also acquire new information by means of relational generalization and transfer. In this chapter, we explore the origins of a uniquely developed human capacity—our ability to learn relational abstractions through analogical comparison. We focus on whether and how infants can use analogical comparison to derive relational abstractions from examples. We frame our work in terms of structure-mapping theory, which has been fruitfully applied to analogical processing in children and adults. We find that young infants show two key signatures of structure mapping: first, relational abstraction is fostered by comparing alignable examples, and second, relational abstraction is hampered by the presence of highly salient objects. The studies we review make it clear that structure-mapping processes are evident in the first months of life, prior to much influence of language and culture. This finding suggests that infants are born with analogical processing mechanisms that allow them to learn relations through comparing examples.

Turning to very early learning, we augmented our account by considering the nature of young infants' encoding processes, leading to two counterintuitive predictions. First, we predicted that young infants (2–3 months old) would be better able to form a relational abstraction when given two alternating exemplars than when given six different exemplars. This is based on the assumption that young infants may initially focus on the individual objects and shift to noticing the relation between them after repetition of the exemplar (Casasola, 2005a). As predicted, this pattern was found for young but not older infants. Second, we predicted that younger, but not older, infants would be able to form a relational abstraction from one repeated exemplar; the prediction follows from the assumption that young infants have unstable encoding processes.

Next, we revisited Premack's insight from 1983 that the tasks used to measure analogical abilities (RMTS, MTS, and *same/different* discrimination) are vastly different from each other. The takeaway from this section is that while many species can learn through association and perceptual generalizations, there are relatively few species that can succeed in the *same/different* discrimination task. Of the species that can succeed in the *same/different* task, humans are unique in that they need fewer than 10 trials to learn such relations. In the final sections, we reviewed how structure mapping extends to language acquisition, artificial grammar learning, and physical reasoning. The value of investigating the origins of our analogical abilities is that we will be in a better position to understand how language and culture capitalize on cognitive abilities. More broadly, we can address whether essential differences between humans and other species are evident from the earliest points in development.

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