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Comparison within pairs promotes analogical abstraction in three-month-olds

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ABSTRACT

This research tests whether analogical learning is present before language comprehension. Three-month-old infants were habituated to a series of analogous pairs, instantiating either the *same* relation (e.g., AA, BB, etc.) or the *different* relation (e.g., AB, CD, etc.), and then tested with further exemplars of the relations. If they can distinguish the familiar relation from the novel relation, even with new objects, this is evidence for analogical abstraction across the study pairs. In Experiment 1, we did not find evidence of analogical abstraction when 3-month-olds were habituated to six pairs instantiating the relation. However, in Experiment 2, infants showed evidence of analogical abstraction after habituation to *two* alternating pairs (e.g., AA, BB, AA, BB…). Further, as with older groups, rendering individual objects salient disrupted learning the relation. These results demonstrate that 3-month-old infants are capable of comparison and abstraction of the *same/different* relation. Our findings also place limits on the conditions under which these processes are likely to occur. We discuss implications for theories of relational learning.

1. Introduction

Analogical processing is a powerful learning mechanism for organizing the world around us. For example, the ability to compare relations across events may be one important route by which categorization and category-based induction occur (Gentner & Markman, 1997; Higgins & Ross, 2011; Markman & Wisniewski, 1997). Mapping from a familiar analog to an unfamiliar situation can facilitate learning and creative problem solving (Gentner & Holyoak, 1997; Gick & Holyoak, 1980, 1983). In line with its demonstrated benefits, performance on a test of analogical ability (the Raven's matrix task) predicts performance on a wide range of intelligence tests (Snow, 1978). Relational ability is arguably the key capacity supporting higher-order cognition (Gentner & Medina, 1998), and recent theories have suggested that our exceptional analogical ability is the central cognitive difference between humans and other primates (Gentner, 2003; Gentner, 2010; Penn, Holyoak, & Povinelli, 2008).

Adults can process analogies with comparative ease. But there are many contributors to the sophistication of adult cognition. Adults have had the benefit of cultural transmission of knowledge, and have acquired symbol systems such as language and mathematics, skills such as perspective-taking, and cultural technologies like written representations. We therefore cannot disentangle whether our relational ability is the root or the result of other cognitive abilities by studying adults. To gain understanding of the nature and origin of our extraordinary relational abilities, we must investigate infants who have not yet acquired these resources.

This brings us to our central question: How does human relational ability arise? We can distinguish two broad positions. One possibility is that analogical ability develops through combining other abilities and experience, and is in no way inherent in human biology. In this position, developing cognitive capacities such as language comprehension, or a vocabulary that can be mapped to categories and concepts might play a critical role in beginning to encode relations. A second possibility is that human infants are born with analogical processing ability, with which they can learn relations from experience before they acquire other capabilities like language.

To track the development of analogical ability in infancy, we need to first characterize the process that underlies this ability in adults and older children. According to structure-mapping theory (Gentner, 1983; Gentner, 2003), comparison entails a process of *structural alignment* that places the representations into correspondence based on aligning like relations (Falkenhainer, Forbus, & Gentner, 1989; Gentner & Markman, 1997; Wolff & Gentner, 2000). One important outcome of this process is that the common relational structure becomes more salient; thus, comparison may result in the extraction of a relational structure that was not apparent in either analog before alignment (Gentner & Hoyos, 2017; Gentner & Medina, 1998; Gentner & Namy, 1999). Promoting

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comparison may be especially helpful for infants and young children whose limited conceptual knowledge of objects leads to a focus on perceptual properties.

1.1. Generalization in infancy

There is abundant evidence that young infants can generalize across a series of objects to arrive at basic-level categories in the first year of life (Bornstein & Arterberry, 2010; Fulkerson & Waxman, 2007; Mareschal & Quinn, 2001; Plunkett, Hu, & Cohen, 2008; Xu, 2002). For example, 3-month-olds exposed to a series of examples can learn basic-level categories like cats and dogs (Quinn, Eimas, & Tarr, 2001). Further, common object labels enhance this process (Fulkerson & Waxman, 2007; Plunkett et al., 2008; Xu, 2002), even among 3-month-olds (Ferry, Hespos, & Waxman, 2010). However, there is comparatively little evidence concerning domain-general relational ability in infancy, despite abundant research on the development of analogical ability from preschool to adulthood. The most compelling evidence for learning abstract relations occurs for linguistic stimuli. These studies show that infants can abstract patterns of syllables such as AAB, ABA and ABB structures in speech from the first days of life and into later infancy (Gervain, Berent, & Werker, 2012; Gervain, Macagno, Cogoi, Pena, & Mehler, 2008; Gómez, 2002; Marcus, Vijayan, Rao, & Vishton, 1999). It is unclear, though, whether language is a privileged domain or whether these findings point to a domain-general relational learning mechanism present in early infancy.

Work that examines domain-general analogical ability in children and adults has revealed key signatures of analogical learning. One such signature is that the perception of abstract relational matches can be enhanced by comparing across instances of a relation. For example, Gick and Holyoak (1983) found that comparing two stories that had the same causal structure enabled people to generalize that structure and to transfer it to a further situation, and adults can abstract relational categories from a series of examples (Kurtz, Boukrina, & Gentner, 2013). Similar effects of comparison have been found for preschool children (e.g., Christie & Gentner, 2010; Gentner, Anggoro, & Klibanoff, 2011; Kotovsky & Gentner, 1996). These findings are consistent with other research suggesting that the act of comparison entails a structural alignment process that highlights the relational commonalities between the items compared (Markman & Gentner, 1993).

A second signature of relational learning is that attention to individual objects can interfere with relational processing. Preschool children perform far worse on relational matching tasks when competing object matches are present (Gentner & Toupin, 1986; Richland, Morrison, & Holyoak, 2006), especially if the objects involved are rich and distinctive (DeLoache, 1995; Gentner & Rattermann, 1991; Paik & Mix, 2006). Although adult analogical processing can also be disrupted by competing object matches (Goldstone & Medin, 1994), the tendency to focus on objects is generally stronger in early learning; as relational knowledge increases, children are better able to focus on relational matches (Gentner, 1988; Gentner & Rattermann, 1991). There appears to be continuity in the signature components of relational learning through human development. This raises the question of whether the signature components of analogical processing would be evident in infants.

Recent studies with 7- and 9-month-old infants suggest that the answer is yes. Ferry, Hespos, and Gentner (2015) habituated infants to a series of exemplars of either *same* pairs or *different* pairs, and then tested them with new pairs. Infants looked longer at pairs instantiating the novel relation; for example, infants habituated to *same* looked longer at YZ than at XX. Importantly, this pattern held even when none of the objects had been seen before—evidence of relational abstraction. This is evidence for the first signature—the ability to abstract a relation by aligning across a series of examples. The studies also showed evidence for the second signature—the adverse effects of object salience on relational abstraction. To test this, the experimenter manipulated the salience of some of the objects (e.g., R) by showing them individually to the infants in the waiting room prior to the experiment. When the infants subsequently saw these objects presented as part of *same* or *different* pairs in test trials (e.g., RR), they showed no evidence of abstracting the relations for those pairs—suggesting that the salient objects had disrupted their relational processing. Together, this evidence demonstrates the operation of structural alignment process in infant learning: alignment across multiple exemplars during habituation facilitated analogical generalization and transfer to new items, while individual object salience hindered analogical learning.

This display of analogical learning at 7–9 months is consistent with the position that this ability is available to humans from birth, but it is not conclusive. By 7 to 9 months of age, infants have already demonstrated abilities across a number of domains, such as: encoding others' beliefs (Kovács, Téglás, & Endress, 2010); tolerating punishment for wrongdoing (Hamlin, Wynn, Bloom, & Mahajan, 2011); and comprehending familiar labels for objects and body parts (Bergelson & Swingley, 2012). To understand the ontogeny of analogical processing, we need to test younger infants. Testing younger infants will also allow us to capture any developmental changes and variability in the learning process.

1.2. The current experiment

In the following experiments, our goal was to track the emergence of analogical learning in 3-month-olds—the youngest age we could test with the habituation/dishabituation paradigm. As in Ferry et al.'s (2015) studies, we focused on the ability to abstract *same* and *different* relations. We tested for two signatures discussed above: (a) whether the ability to abstract relations benefits from the comparison of multiple exemplars and (b) whether infants would be less likely to generalize the abstracted relation to pairs containing an object that had been made individually salient, via prior exposure. If infants are learning via structural alignment, they should differentiate the familiar relation (e.g., *same*, if habituated to *same*) from the unfamiliar one (e.g., *different*) for pairs comprised of new objects, but should not discriminate between novel and familiar relations when they are comprised of objects that have been made salient.

We investigated the *same-different* relation because it is arguably the simplest and most basic relation, and therefore likely to be available early in development, and because the perception of sameness is critical to a broad range of cognitive functions, from memory retrieval to categorization. A further advantage of studying the development of *same* and *different* is that it allows us to compare our findings with the rich set of findings from comparative psychology (Fagot & Thompson, 2011; Flemming, Beran, & Washburn, 2007; Premack, 1983; Thompson, Oden, & Boysen, 1997; Wasserman & Young, 2010).

The between-subjects factor of training condition also allowed us to ask whether 3-month-old infants are equally proficient at learning *same* and *different* relations. For example, it could be that *same* is an elemental relation, while *different* is represented as "not same" (Clark & Chase, 1972; Hochmann, Mody, & Carey, 2016). If this is the case for infants, then they should be better at abstracting the *same* relation than the *different* relation. There is some evidence for this with other age groups (Hochmann et al., 2016; Smith, Redford, Haas, Coutinho, & Couchman, 2008; but see Addyman & Mareschal, 2010 who reported cases where *different* is easier). On the other hand, Ferry et al. (2015) found no measurable difference in the likelihood of learning *same* versus *different* in their studies of 7- and 9-month-olds. Still, it is possible that younger infants will show an advantage for *same* over *different*.

In Experiment 1, 3-month-old infants received training on either *same* or *different* relations (see Fig. 1). During test trials, infants saw pairs of objects instantiating both *same* and *different* relations. The design was similar to that used by Ferry et al. (2015) with 7- and 9-month olds. However, based on evidence that generalization improves when

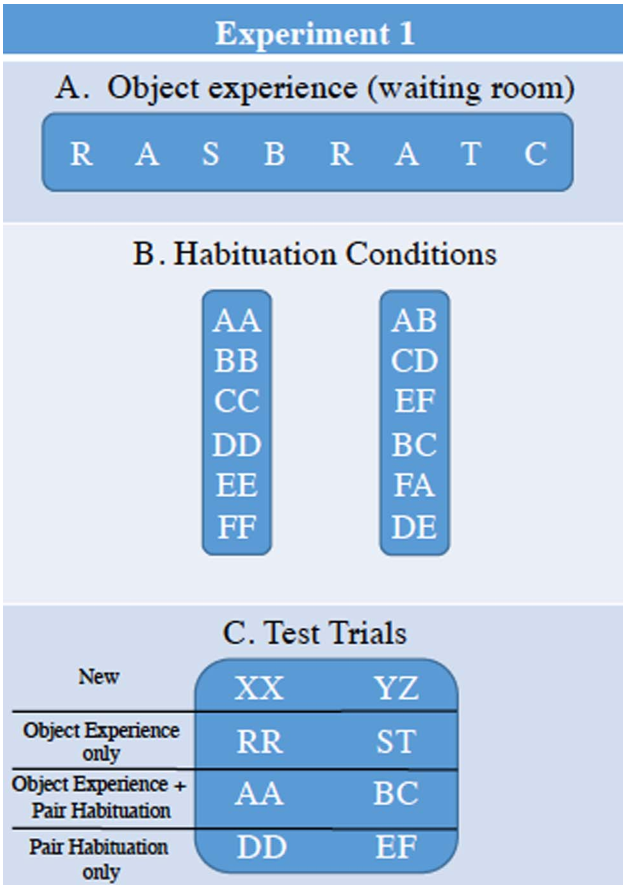

Fig. 1. Schematic of events in Experiment 1. (A) In the waiting room, infants saw a subset of the individual toys before the experiment. (B) Infants were habituated to pairs of objects; the pairs were either *same* or *different.* (C) In eight sequential test trials, the dependent measure was looking time to the novel and familiar relational pairs in four different types of test trials: *new, object experience only, object experience + pair habituation,* and *pair habituation only*.

the number of examples increases (e.g. Gerken, 2006, 2010; Gerken & Bollt, 2008; Gweon, Tenenbaum, & Schulz, 2010; Needham, Dueker, & Lockhead, 2005; Quinn & Bhatt, 2005; Xu & Tenenbaum, 2007), we increased the number of example pairs shown to infants from four to six.

Critically, each infant saw four types of test trials. The first type of test trial consisted of entirely new objects. This pair of trials tested the main prediction: whether infants had abstracted the relation across the habituation pairs and transferred this relation to new objects. A second type of test trial measured whether object salience would disrupt analogical processing. This pair consisted of objects that had been rendered individually salient in the waiting room but were not seen in habituation trials. The third type of test trial was made up of objects that had been rendered individually salient in the waiting room, but that had subsequently appeared as part of pairs during the habituation phase. This pair tested whether repeated alignment across habituation trials would allow infants to overcome initial object salience. The final type of test trial was pairs made of objects that were not seen in the waiting room but were viewed in pairs during habituation trials. This pair provided an experimental check for whether infants recognized the pairs that they had seen before. If infants treat these pairs as familiar, but not the other kinds of test pairs, then this would constitute evidence for recognition, but not for abstraction.

2. Materials and methods

2.1. Participants

The participants were 31 healthy, full-term 3-month-old infants (17 male and 14 female) with an average age of 3 months, 2 days ranging from 2 months, 9 days to 4 months, 1 days. Fifteen of the infants were assigned to the *same* condition; sixteen, to the *different* condition.

Eighteen additional infants were tested but eliminated from the final analysis: 11 because of fussiness (defined as two independent coders judging the infant's state as fussy or crying for more than half the test trials), one because of sleepiness (defined as two independent coders judging the infant's state as drowsy for more than half the test trials), one because they were inattentive (defined as looking less than 4 s on half the trials), three because they took long breaks (three infants took breaks less than one minute and they were included in the data, but these three infants took breaks of 8, 10, and 14 min that we felt would influence memory demands, so they were eliminated), and two because they looked the maximum amount of time on 7 out of 8 test trials. These exclusion criteria were determined in advance, and have been in use in the Hespos lab for more than 10 years. Excluding infants who looked the full time on all or all but one test trial has been used as an exclusion criterion in many other looking time studies (e.g., Aguiar & Baillargeon, 2002; Hespos & Baillargeon, 2001; Hespos, Ferry, & Rips, 2009; Hespos & Spelke, 2004).

2.2. Apparatus

Parents sat in a chair facing a wooden puppet stage that displayed all stimuli, with their infant on their lap. Parents were asked to refrain from interacting with the infant during the experiment and to close their eyes during the test trials. The stage measured 243.5 cm high, 128 cm wide, and 61 cm deep. The opening in the front of the stage that displayed the objects was 93 cm above the floor, 61 cm high, and 106 cm wide. The back wall had two rectangular openings with cloth fringe over the openings that allowed the experimenter to manipulate the objects between trials. A screen that covered the infants' view of the stage was raised and lowered between trials. The Baby Looking Time MATLAB program (BLT, Chang & Wang, 2014) was used to record looking times for habituation and test trials during the experiment.

The stimuli consisted of 20 three-dimensional objects: two Elmos, two blue fuzzy aardvarks, two pink dotted blocks, two red striped blocks, two yellow and green pyramids, two wooden wedges with green puff balls, two porcelain cups, two red and green foam blocks, a checkered cylinder, an elephant, a blue triangle, and a pig (see Fig. 2). Each pair was placed on a 26.5 × 15.5 cm cardboard tray covered with contact paper. Eight of the objects were presented in the waiting room before the experiment began (two pink blocks, two blue aardvarks, the elephant, the cylinder, one red block and one pyramid). Twelve objects were seen in the habituation phase within the six *same* or *different* pairs. Four of these objects had been seen in the waiting room (the two pink blocks, a red block and a pyramid). Finally, 16 objects were used in pairs during the test phase (8 pairs). Of these, four objects had been seen (individually) in the waiting room only, four had been seen in habituation only, four had been seen in the waiting room and habituation and four objects had not been seen before this point (see Figs. 1 and 2). Up to six pairs of objects were seen in habituation, depending on the number of trials infants needed to meet the habituation criteria. Several of the objects had faces and several were geometric objects. Previous literature has shown that infants prefer stimuli with faces (Lauer, Udelson, Jeon, & Lourenco, 2015), but the mean looking time to stimuli with faces (23.54 s) was almost equal to the mean looking time to stimuli without faces (23.69 s).

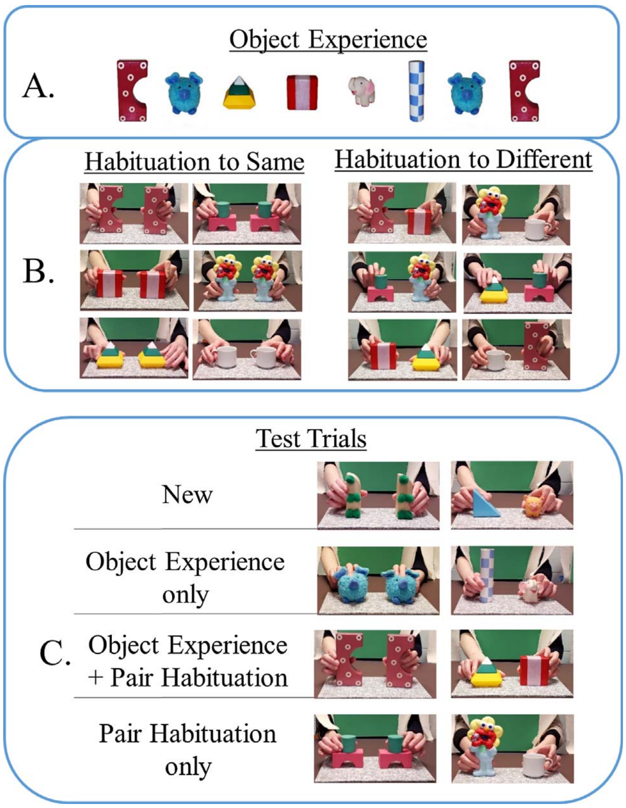

Fig. 2. Photos of the objects represented by the letters in Fig. 1.

2.3. Coding

There was a small hole in the front face of the stage containing a camera that captured a video image of the infant's face. While the experimenter conducted habituation and test trials in the room with the infants, two research assistants in a separate room viewed the video and coded infants' visual fixations online as either on target or off. Each researcher depressed a computer button when the infant attended to the events on stage and released the button when the infant looked away. Each trial ended when the infant either looked away for 2 consecutive seconds after having looked at the event for at least 2 s or looked at the event for 60 cumulative seconds without looking away for 2 consecutive seconds. The Baby Looking Time program determined the end of the trial and beeped, signaling to the experimenter to lower the screen and move to the next trial. After each test trial, research assistants also checked one or more boxes to indicate the behavioral state of the infant on the preceding trial: sleepy, quiet and alert, active, fussy or crying. Coders also noted any breaks and their length. As noted above, if two coders independently judged the infant's state as fussy, crying, or falling asleep for more than half the test trials, the infant's data was excluded from the analysis. The coders were blind to the condition and the trial order. Interobserver agreement was measured for all infants and averaged 91%. The average measure ICC was .836 with a 95% confidence interval from .664 to .921, $F(3,31) = 6.097$, $p < .001$.

2.4. Design and procedure

Experiment 1 had one between-subjects factor of habituation condition (*same* or *different)* and four different types of test trials. For each of these test trial types, we showed infants a novel and a familiar relation in consecutive test trials, for eight total test trials.

2.4.1. Object experience phase

In the object experience phase, we manipulated object focus by showing eight of the test objects to the infants in the waiting room prior to the experiments, during naturalistic play interactions. The experimenter held up each object between themselves and the infant and made comments such as "Look!" and "See this one?" The objects were presented individually for approximately 5 s for each object and without showing two identical objects in a row. Four of these waiting room objects were then seen in habituation and subsequently in test trials (i.e., *object experience + pair habituation* trials; A, A, B & C in Fig. 1). The other four waiting room objects reappeared in test trials only (i.e., *object experience only* trials; R, R, S & T in Fig. 1).

2.4.2. Pair habituation trials

In the *same* condition, infants saw habituation trials in which the pairs of objects were the *same* as each other (see Fig. 1). In the *different* condition, infants saw habituation trials in which the pairs of objects were *different* from each other. To engage infants' attention the pairs of objects were moved during both habituation and test trials. When the screen was raised at the start of every trial, a pair of objects rested on the cardboard tray on the stage. The experimenter grasped one object in each hand and raised the objects straight up (1 s), tilted them to the left (1 s), returned them to the center (1 s), tilted them to the right (1 s), returned them to the center (1 s), returned them to the tray (1 s), and paused on the tray (2 s). This 8-s cycle repeated continuously until the trial ended. The number of habituation trials was infant-controlled and ranged from 6 to 9 trials until infants' looking times declined by 50% from the first three trials to the last three, or until infants had completed nine trials. Ending habituation at nine trials has been standard practice in the Hespos lab for more than 10 years (see Hespos, Saylor, & Grossman, 2009; Hespos, Ferry, et al., 2009), to avoid putting undue demands on the infant's attention before the test events. In this study, we also wished to maintain the same procedures as had been used in Ferry et al. (2015), to preserve comparability between the results.

The order of pairs across the nine possible habituation trials was Pair 1, Pair 2, Pair 3, Pair 1, Pair 4, Pair 2, Pair 5, Pair 3, and Pair 6 (i.e., AA, BB, CC, AA, DD, BB, EE, CC, FF or AB, CD, EF, AB, BC, CD, FA, EF, DE). The order of the pairs within each experiment (i.e., whether Pair 1 was AA or EE) was counterbalanced across participants. Twelve of 31 infants saw all six exemplars across nine habituation trials. Eleven infants habituated after seven or eight trials, seeing five exemplars, and eight infants habituated after only six trials, seeing four exemplars.

2.4.3. Test trials

Infants viewed eight test trials. In each test trial, infants viewed one pair of objects, presented in the same motion pattern as in the habituation trials, while their looking time was recorded. Each infant received test trials with both *same* and *different* pairs of objects, presented in alternation, with order counterbalanced across infants. As discussed earlier, there were four kinds of test trials, each consisting of two pairs. The objects in the pairs could be either (a) objects that were completely new (*new*); (b) objects that the infant had only experienced individually in the waiting room (*object experience only*); (c) objects that the infants had experienced individually in the waiting room and then in pairs during habituation trials (*object experience + pair habituation*); or (d) objects that the infant had only experienced in pairs during habituation trials (*pair habituation only*). There were four trial orders: adcb, bcad, cbda and dabc. This allowed each type of test pair to be first for a quarter of the infants.

3. Results

Our data in Experiment 1 significantly deviates from a normal distribution per the Shapiro-Wilks test. Therefore, we performed the following parametric tests on log-transformed data, following recommendations outlined by Csibra, Hernik, Mascaro, Tatone and Lengyel (2016). An analysis of variance (ANOVA) with the between-subject factors of habituation condition (*same* or *different*), sex, and test order, and the within-subject factors of test relation (novel or familiar) was performed on log-transformed looking times.

The first analysis addressed our central question: whether 3-month-old infants would discriminate between *same* and *different* relations after seeing multiple exemplars. The answer is yes; infants did look longer at the novel relation compared to the familiar relation when we collapsed across test trial types, $F(1,23) = 4.95$, $p = .036$, $\eta_p^2 = .177$, despite average looking times of 25.31 s ($SD = 14.50$) for the novel relations and of 23.34 s ($SD = 15.00$) for the familiar relations. There was also an effect of habituation condition, $F(1,23) = 12.21$, $p = .002$, $\eta_p^2 = .347$, such that infants who were habituated to *same* had shorter looking times overall ($M = 17.26$) than infants who were habituated to *different* ($M = 31.27$) regardless of whether the test relation was novel or familiar. Additionally, there was a marginal interaction between relation and condition, $F(1, 23) = 4.20$, $p = .052$, such that, across test trial types, infants in the *same* condition showed longer looking at the *different* pairs than the *same* pairs ($M_{Novel} = 18.91$, $M_{Familiar} = 15.62$), whereas in the *different* condition infants showed more similar looking times between pairs ($M_{Novel} = 31.81$, $M_{Familiar} = 30.73$). There was also a significant three-way interaction between relation, condition, and order, $F(1,23) = 4.74$, $p = .04$, $\eta_p^2 = .171$, where infants habituated to *same* looked longer at *different* during test when the trials were presented in the *same*-first order. Finally, there was a three-way interaction between sex, condition, and order, $F(1, 23) = 7.86$, $p = .01$, $\eta_p^2 = .255$. Where, regardless of whether infants were habituated to *same* or *different*, female infants had looked longer on average across all test trials when they were assigned to the order where *different* pairs preceded *same* pairs, though this difference was more pronounced for the habituation to *same* condition. Male infants looked longer on average across all test trials when they were assigned to the order where *same* pairs preceded *different* pairs, though this difference was more pronounced for the habituation to *different* condition.

3.1. Effects of object experience and pair habituation

Ferry et al. (2015) found that 7- and 9-month-olds showed a particular pattern of relational learning. Despite abstracting the relation in *new* test trials, (a) individual objects reduced relational discrimination in object experience test pairs, but (b) this adverse effect was ameliorated by showing infants habituation pairs containing these same objects. To determine whether 3-month-olds show a similar pattern of results, we conducted planned comparisons between looking times at the novel and familiar relation for each test trial type (see Fig. 3). Given the marginal interaction between looking between relations and habituation condition in the omnibus, we included condition as a between-subjects factor in these comparisons. The critical test of relational learning is whether infants can generalize the relation from habituation to pairs containing new objects. Infants showed no difference in looking time between novel and familiar relations when the relations were composed of new objects (*new*), $F(1,28) = .669$, $p = .420$. Infants also did not discriminate when salient objects appeared in test pairs (*object experience only*), $F(1,25) = .270$, $p = .608$. While this null effect is consistent with Ferry et al. (2015)'s findings and our predictions, we cannot know here whether this is due to the object salience interfering with relational alignment, because infants did not generalize the familiar relation in any of the test trials. Additionally, there was no discrimination for pairs that contained these salient objects during habituation (*object experience + pair habituation*), $F(1,27) = .418$, $p = .523$, or for pairs shown only shown in habituation pairs (*pair habituation only*), $F(1,23) = 2.092$, $p = .162$.

These comparisons did not reveal any significant interaction between condition and test looking for *new* trials, $F(1,28) = 1.183$, $p = .286$, for *object experience only* trials, $F(1,25) = .313$, $p = .581$, or for *object experience + pair habituation* trials, $F(1,27) = 1.006$, $p = .325$. The *pair habituation only* trials did show a marginal interaction between looking time at novel vs familiar relations and habituation condition, $F(1,23) = 3.865$, $p = .061$, such that infants in the *same* condition recognized a habituation pair at test, looking longer at the novel pair, $M = 28.82$ vs 14.22, but infants in the *different* condition failed to discriminate the pair they had previously seen, $M = 28.86$ vs 27.97.

3.2. Effects of habituation condition

We next examined whether learning *same* was easier than learning *different*. As reported above, the omnibus ANOVA revealed an effect of condition on overall looking time, but this resulted in only a marginal interaction between condition relation (novel vs. familiar). In addition, there were similar learning patterns across habituation conditions (see Fig. 4). Infants habituated to *same* or to *different* pairs were not distinct in their total looking time across the habituation phase, $F(1,29) = 2.425$, $p = .13$, nor was there a significant interaction between habituation condition and the magnitude of their decline across habituation trials, $F(5,25) = 2.197$, $p = .087$. In Experiment 1, there were 11 infants who did not who did not meet the habituation criterion before the ninth habituation trial, eight in the *different* condition and three in the *same* condition. An analysis comparing 11 randomly selected infants who did habituate to the 11 who did not habituate revealed no difference in looking-time between novel and familiar relations for the critical *new* test trials, $F(1,19) = .646$, $p = .432$. Overall, our findings do not reveal different learning patterns for *same* versus *different*.

4. Discussion

Experiment 1 did not reveal any analogical learning. We found no evidence of generalization to new pairs, despite both conditions showing a decline in looking consistent with habituation. This failure to generalize the relation to the novel objects could indicate that three months is simply too young for infants to grasp abstract relations like *same* and *different*. This would be consistent with the first position we outlined previously, that analogical ability is a product of the cumulative advantages of human culture. It would also fit with the developmental evidence that early in learning, children are more likely to focus on object properties rather than on relations (Chen, Sanchez, & Campbell, 1997; Gentner, 1988; Gentner & Rattermann, 1991). But before concluding this, we must consider another possibility: that these young infants are capable of analogical learning, but that training on six exemplars in Experiment 1 was ineffective. It could be that these young infants need a greater range of examples to abstract the relation. This would be consistent with evidence that greater variability in training is associated with greater generalization and transfer (e.g. Gerken, 2006; Gerken, 2010; Gerken & Bollt, 2008; Gweon et al., 2010; Needham et al., 2005; Quinn & Bhatt, 2005; Xu & Tenenbaum, 2007).

However, some recent studies have found the opposite: that young infants show more analogical learning if given *fewer* objects during habituation. Although this may seem counterintuitive, it follows from two key ideas discussed above: first, that structural alignment is essential for relational abstraction; and, second, that structural alignment can be impeded by attention to objects (Gentner & Medina, 1998; Gentner & Toupin, 1986). Infants may therefore be more hindered than helped by a long parade of pairs. Seeing six novel exemplars during habituation could lead to a focus on the properties of the novel objects rather than on the relational pattern. Supporting this possibility, Casasola (2005) found that 10-month-old infants were better able to learn and generalize the spatial category of support when they were given two alternating exemplars of the relation than when they were given six exemplars of the relation (see also Bulf, Johnson, & Valenza, 2011; Gerken & Quam, 2016; Maguire, Hirsh-Pasek, Golinkoff, & Brandone, 2008). As Casasola and Park (2013) suggest, for infants and young children, "…objects are not simply encoded along with the spatial relation but, in some cases, may overshadow attention to spatial information. It appears that young children find objects sufficiently

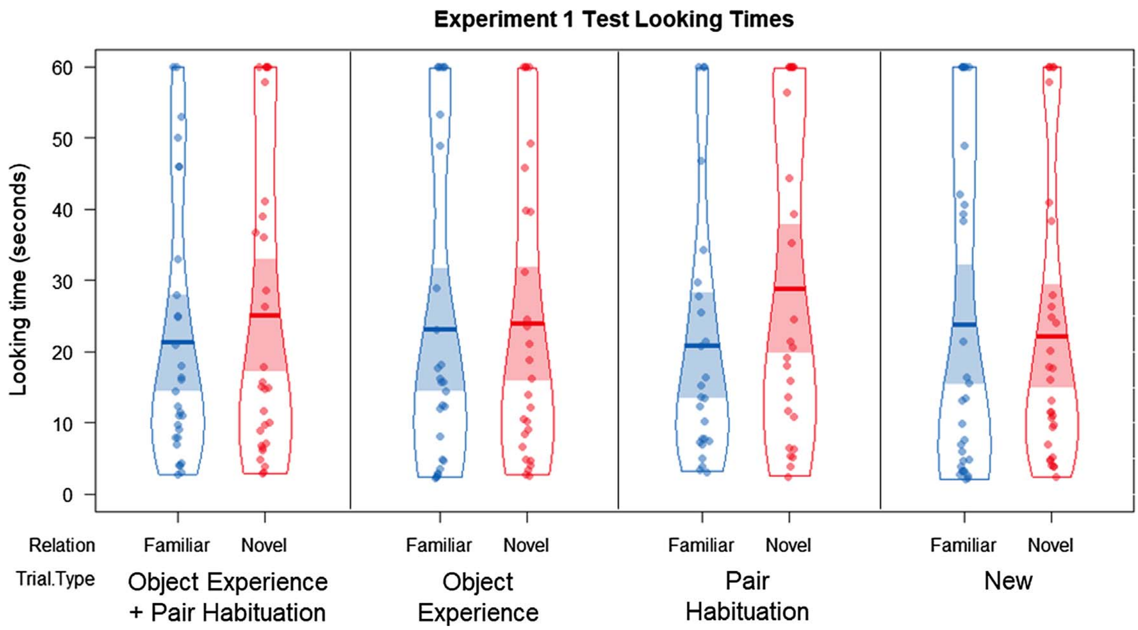

Fig. 3. Experiment 1 looking times at novel and familiar pairs for each test type collapsed across *same* and *different* conditions. The thick central line in each box is the mean, and the upper and lower shaded portions represent the 95% Confidence Intervals (CIs) for this mean (i.e., there is a 95% probability that the true population mean falls within this interval). Dots indicate the raw data points. The width of the bean indicates the density of the data distribution at a looking time value.

compelling that they fail to use—or perhaps even notice—relational correspondences."

If this is the case, then alternation and repetition could foster analogical abstraction. This is because alternating between just two example pairs may allow infants to become sufficiently familiar with the individual objects that they can then take in the whole pattern, rather than just the objects themselves. This would facilitate aligning the common relation across the habituation pairs. Following this logic, in Experiment 2, we increased alternation and repetition by reducing the number of habituation exemplars to two.

5. Experiment 2

In Experiment 2, we habituated 3-month-old infants to two *same* or *different* exemplars in alternation. As in Experiment 1, we aimed to test for the two key signatures of analogical learning: (1) that comparing relationally-similar exemplars promotes analogical abstraction and (2) that focusing on individual objects interferes with it. We test the first of these by asking whether infants can generalize the relation to test exemplars consisting of entirely new objects. We test the second by asking whether infants will be less likely to generalize the abstracted relation to pairs containing an object that had previously been made salient (see Fig. 5).

The between-subjects factor of training condition also allowed us to ask whether 3-month-old infants are equally proficient at learning *same* and *different* relations. As in Experiment 1, infants received training on either *same* or *different* relations. During testing, infants saw pairs instantiating both the *same* and *different* relation. The question was whether they would differentiate the familiar relation from the new relation at test.

With a limited number of habituation pairs available, we were forced to drop one of the test trial types from Experiment 1, leaving only three test trial types (6 test trials total). We chose to drop the *pair habituation only* trials. This cell tests only whether infants have retained a memory of the examples that they saw during habituation; therefore, it is the least informative with respect to our hypotheses. The remaining test trial types (*new, object experience only* and *object experience + pair habituation*) were identical to Experiment 1.

If reducing the number of exemplars aids infants in aligning and abstracting across the exemplars, then infants should succeed in abstracting the target relation. In this case, they should look longer at the novel relation in the novel-object test trials. This is because, even when instantiated with new objects, the trained relation will seem familiar. If, as predicted, object focus hinders relational focus, then infants will fail to show a novelty preference for pairs containing an object they had seen on its own. Finally, we can also ask whether the infants will show a novelty preference for test pairs made of objects first seen individually, but subsequently experienced in pairs during habituation. Ferry et al. (2015) found this pattern in their studies of 7- and 9-month-olds, and concluded that structural alignment had allowed the infants to overcome this object focus. Whether we will see this pattern with younger infants remains to be seen.

6. Materials and methods

6.1. Participants

The participants were 32 healthy, full-term, 3-month-old infants (19 male and 13 female) average age 3 months and 16 days, ranging from 2 months 10 days to 4 months 15 days. Half of the infants were assigned to the *same* condition; the other half, to the *different* condition. Ten additional infants were tested but eliminated from the final analyses because of fussiness (using the same criteria as Experiment 1).

6.2. Procedure

The procedure was identical to Experiment 1, except that there were 6 test trials. The stimuli consisted of a subset of the objects used in Experiment 1. There were fewer objects shown in habituation, so we could present only three types of test trials (rather than four, as in Experiment 1). Fewer objects in habituation also meant that, for the *object experience + pair habituation* trial, infants in the *same* condition saw only two of the waiting room items in both habituation and test (pink blocks), while infants in the *different* condition saw three (pink block, red square, pyramid). This was done to avoid asymmetry between conditions in the number of object kinds that only appeared during habituation. The full set of objects was: pink blocks, Elmo, red striped square, blue head, elephant, blue checked cylinder, blue triangle

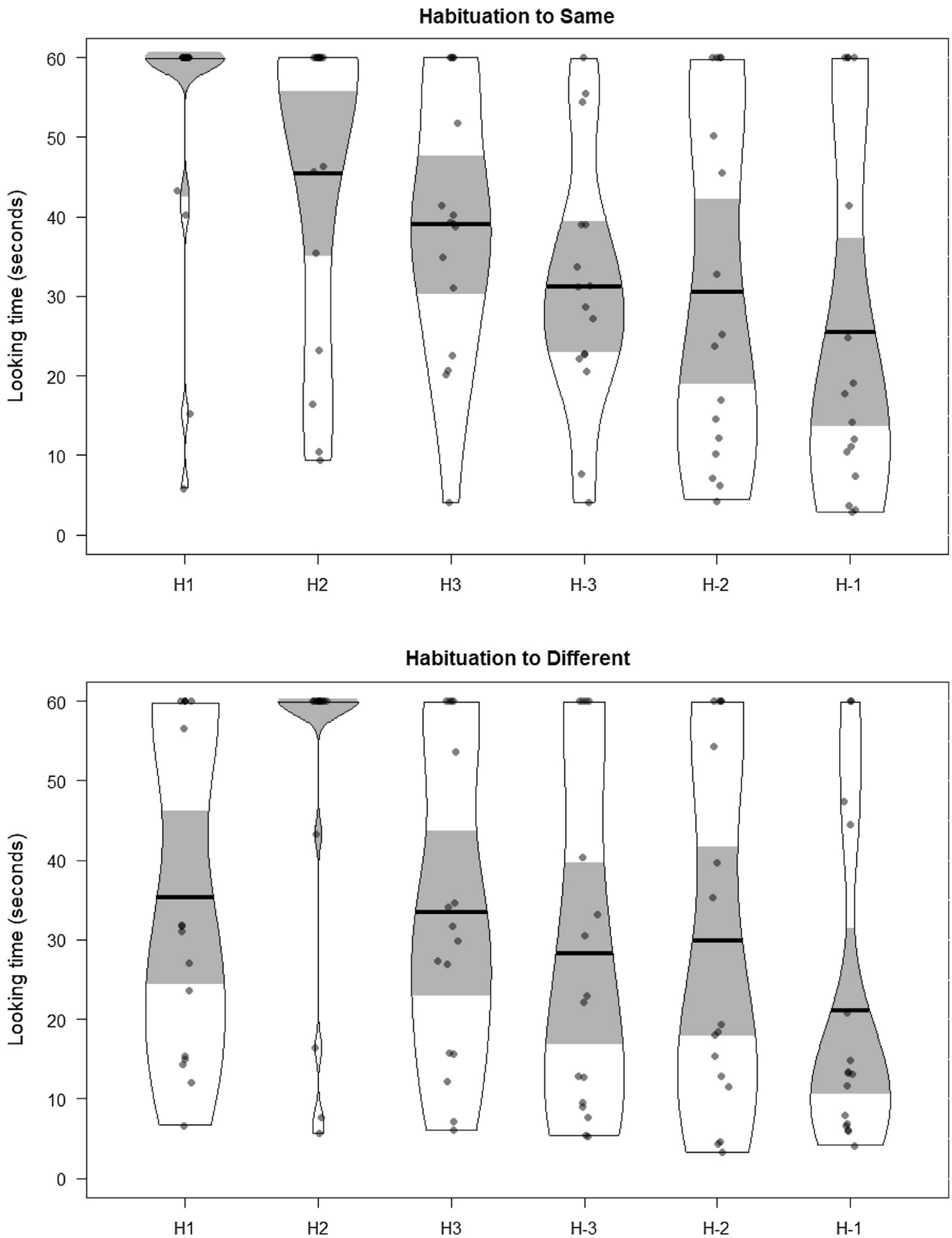

Fig. 4. Bean plots showing mean looking times during the habituation in the *same* and *different* conditions in Experiment 1. The plots include results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H-3, H-2, H-1). The thick central line in each box is the mean, and the upper and lower shaded portions represent the 95% Confidence Intervals (CIs) for this mean (i.e., there is a 95% probability that the true population mean falls within this interval). Dots indicate the raw data points. The width of the bean indicates the density of the data distribution at a looking time value.

and the pig. The object movements in the habituation and test trials were identical to Experiment 1. All aspects of coding and trial duration were identical to Experiment 1. Interobserver agreement was measured for all infants and averaged 93%. The average measure ICC was .999 with a 95% confidence interval from .999 to 1.0, $F(3,32) = 1973.26$, $p < .001$.

6.2.1. *Object experience phase*

The object experience phase was the same as Experiment 1.

6.2.2. *Pair habituation*

In Experiment 2, only two unique pairs alternated and repeated across the 6 to 9 trials it took infants to reach criterion (a 50% decline in looking from the first three to the last three trials). Infants habituated to *same* saw Elmo & Elmo and Pink-Block & Pink-Block in alternating

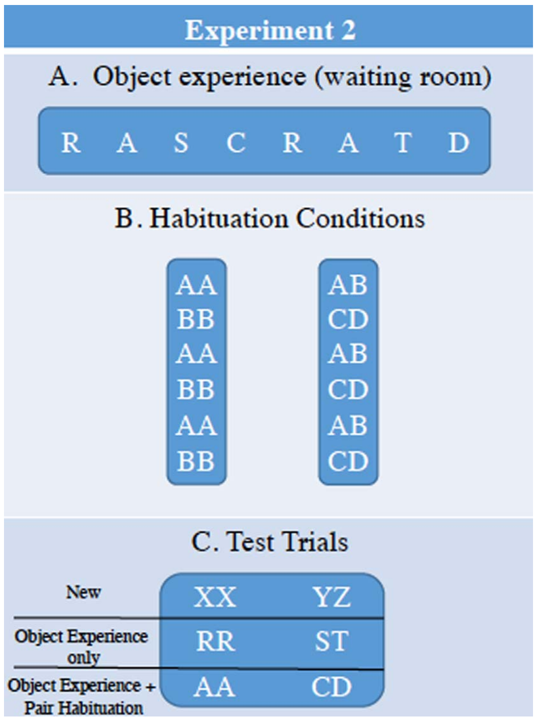

Fig. 5. Schematic of events in Experiment 2. (A) In the waiting room before the experiment, infants were shown a subset of individual objects used in the experiment. (B) During habituation trials, infants were shown either pairs of *same* or *different* objects. (C) During test trials, infants saw pairs of objects presented sequentially. There were three types of test trials that systematically varied the infants' experience with the objects to measure the influence on performance.

trials, while infants habituated to *different* saw Elmo & Pink-Block and Red-Square & Pyramid in alternating trials.

6.2.3. Test trials

The three trial orders were abc, bca, and cab. This allowed each type of test pair to be first for a third of the infants.

7. Results

Consistent with the analogical abstraction account, infants looked significantly longer at novel relations after habituating to two alternating pairs. Critically, this novelty preference was found not only for pairs seen before (as in Experiment 1), but also for pairs composed of new objects—evidence that the infants had abstracted the relation during habituation.

Our data in Experiment 2 significantly deviates from a normal distribution per the Shapiro-Wilks test. Therefore, we performed the following parametric tests on log-transformed data, following recommendations outlined by Csibra et al. (2016). A 2 × 2 × 2 × 2 ANOVA on the log-transformed looking times examined the between-subject factors of habituation condition (*same* or *different*), sex, test trial order, and the within-subject factor of relation (novel or familiar). The ANOVA revealed a significant main effect of relation, $F(1, 24) = 9.30$, $p = .006$, $\eta_p 2 = .279$. Here, there was no effect of condition, $F(1, 24) = 1.13$, $p = .299$, nor interaction between condition and relation, $F(1, 24) < 1$, $p = .61$. There was an interaction between condition and sex, with girls looking longer overall in the habituation to different condition, and the reverse being true for boys, $F(1, 24) = 10.27$, $p = .004$, $\eta_p 2 = .299$.

Our central question was whether infants are capable of abstracting *same* and *different* relations from two exemplars. The answer is yes; infants looked significantly longer at the novel relation than at the familiar relation during the test trials for both *same* and *different* habituation conditions (see Fig. 6). As noted above, the ANOVA revealed a significant main effect of relation, $F(1, 24) = 9.30$, $p = .006$, $\eta_p 2 = .279$. Collapsing across all test trial types, 22 of the 32 infants (69%) had longer looking times for the novel test relation ($p = .05$, binomial comparison). The average looking time for the novel relation was 26.88 s ($SD = 14.47$), and for the familiar relation was 20.37 s ($SD = 11.31$).

7.1. Effects of object experience and pair habituation

As in Experiment 1, we conducted a series of planned comparisons for each of the test trial types. For the key question—whether infants abstract the relation when it is presented with new objects—the answer is yes (see Fig. 6). Analysis of the *new* trials reveals a clear novelty

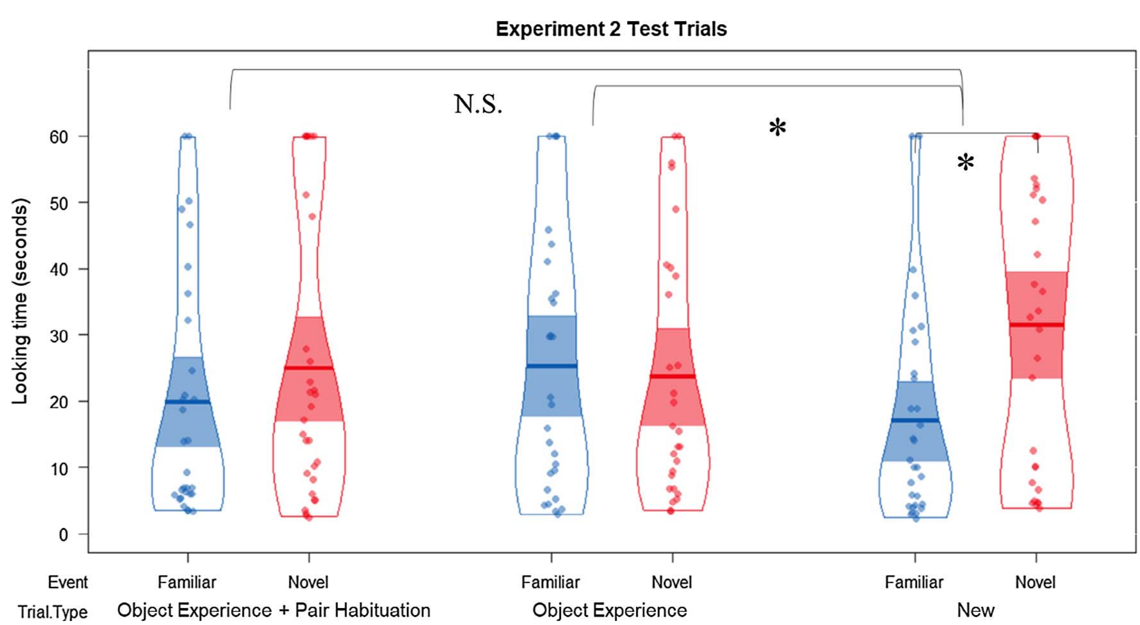

Fig. 6. Experiment 2 looking times at novel and familiar pairs for each test type, collapsed across *same* and *different* conditions. The thick central line in each box is the mean, and the upper and lower shaded portions represent the 95% Confidence Intervals (CIs) for this mean (i.e., there is a 95% probability that the true population mean falls within this interval). Dots indicate the raw data points. The width of the bean indicates the density of the data distribution at a looking time value. The * indicates $p < .01$.

preference, indicating that infants generalized the relation to new objects, $t(29) = 3.07$, $p = .005$, $d = .494$. The next set of analyses tested (a) whether calling attention to individual objects would impede relational focus for *object experience* test pairs containing these objects, and, if so, (b) whether this adverse effect would be mitigated by exposure to pairs containing these same objects during habituation (*object experience + pair habituation)*. Consistent with (a), the looking times for novel and familiar relations in the *object experience* trials were not significantly different, $t(27) = -.14$, $p = .89$. However, contrary to (b), we also found no difference in the looking times for the novel and familiar relations in the *object experience + pair habituation* trials, $t(29) = 1.16$, $p = .26$. Finally, there was a significant difference in the paired t-tests contrasting the difference scores from *new* to *object experience* test types, $t(24) = -2.987$, $p = .006$, $d = .472$. The other two contrasts were not significant (*new* versus *object experience + pair habituation:* $t(26) = -1.443$, $p = .161$ and *object experience + pair habituation* versus *object experience:* $t(25) = 1.191$, $p = .245$.[1]

7.2. Are infants learning during the test trials?

In Ferry et al. (2015), infants showed evidence of learning over the course of test trials, with distinct patterns for 7-month-olds versus 9-month-olds. Collapsing across test trial types, the 7-month-old infants showed only a small difference in looking times between the novel and familiar on the first test pair, but this difference increased over the course of test pairs—suggesting that analogical abstraction was continuing over the test trials. In contrast, the 9-month-old infants showed the opposite time course—suggesting that they had abstracted the relation during habituation. To investigate the course of learning in the 3-month-old infants, we did planned comparisons of looking at the novel versus familiar relations in the 1st, 2nd, and 3rd test pairs respectively $t(30) = .16$, $p = .876$, $t(30) = .970$, $p = .34$, $t(28) = 2.95$, $p = .006$, $d = .54$. These tests show that, like 7-month-olds in Ferry et al., infants in this study showed increasing differences in looking time between the novel and familiar relations over the course of the test pairs. This suggests that 3-month-olds in Experiment 2 may have still been actively learning during the test phase. Additionally, this pattern seems to be driven largely by the *new* test trial type. For *new* trials, 4 of 10 infants looked longer at the novel relation when this trial type was the first test pair, 7 of 11 infants looked longer at the novel relation when it was the second test pair, and 9 of 11 infants looked longer at the novel relation when this when the new trial type was the third test pair. The other trial types show a more static pattern. For *object experience only* trials, the number of infants that discriminated increased only slightly, from 4 of 11 in the first pair and 4 of 11 in the second pair to 6 of 10 in the third pair. The poor performance on the *object experience only* trials was as predicted, and is parallel to the prior pattern found with 7–9 months-olds (Ferry et al., 2015). Unlike with older infants, though, we failed to find a 'remediation' effect on the *object experience + pair habituation* trials. For these *object experience + pair habituation* trials, the number of infants that discriminated remained steady from 6 of 11 in the first pair to 6 of 10 in the second pair to 6 of 11 in the third pair.

7.3. Effects of habituation condition

Our next question was whether infants would find it easier to abstract the *same* relation than the *different* relation. A 2 × 2 ANOVA with the between-subject variable of habituation condition (*same* or *different*) and within-subject variable of test relation (novel or familiar) revealed a significant main effect of relation $F(1,30) = 10.7$, $p = .003$, in that infants looked longer at the novel relation. However, there was no main effect of habituation condition $F(1,30) = 1.21$, $p = .28$., nor an interaction between habituation condition and relation, $F(1,30) = 2.19$, $p = .15$.

There were also no differences in performance comparing across habituation conditions (see Fig. 7). Infants habituated to *same* or to *different* pairs were not distinguishable in the number of habituation trials required to meet criterion, $F(1,30) < 1$, $p > 0.99$, in their total looking time across the habituation phase, $F(1,30) < 1$, $p > 0.978$, nor was there an interaction between habituation condition and the magnitude of their decline between the first and final three habituation trials, $F(5,26) = 1.492$, $p = 0.227$. In Experiment 2, there were 10 infants who did not meet the habituation criterion before the ninth habituation trial, five in the habituation to *different* condition and five in the *same* condition. An analysis comparing 10 randomly selected infants who did habituate to the 10 who did not habituate revealed no difference in looking-time between novel and familiar relations for the critical *new* test trials, $F(1,15) = .756$, $p = .398$. Overall, our findings do not reveal different learning patterns for *same* versus *different*.

7.4. Learning differences between experiments

Given that the methods across Experiment 1 and 2 were similar, we can contrast performance across the two experiments. An ANOVA comparing the between-subject variable of Experiment (1 or 2) and test relation (novel or familiar) reveals a significant main effect of test relation, $F(1,61) = 11.60$, $p = .001$, $\eta_p^2 = .16$. Overall, the infants looked longer at the novel than at the familiar relations. However, comparison of the *new* test condition—the critical test of whether infants abstracted the relation—yields a main effect of relation, $F(1,58) = 8.46$, $p = .005$, $\eta_p 2 = .127$. The analysis also found a marginal Relation by Experiment interaction $F(1,58) = 3.57$, $p = .064$. In Experiment 1, looking times to the novel and familiar relations did not differ ($M = 22.17$ and 23.75, respectively); but in Experiment 2, infants looked significantly longer at the novel than at the familiar relation ($M = 31.45$ and 16.92, respectively) for the *new* pair.

8. Discussion

The findings in Experiment 2 provide evidence for very early analogical learning. Infants' looking time at test reflected a significant preference for the novel relation over the familiar one. Critically, this occurred for relations composed of new objects—allowing us to conclude that infants had abstracted the *same* and *different* relations. The second signature of analogical processing—the disruptive potential of object focus—was also apparent. There was a significant difference in performance for pairs of objects seen before the experiment, compared to pairs containing new objects. Unlike the 7- and 9-month-old infants in Ferry et al. (2015), the younger infants in the Experiment 2 did not show a remediation effect—once objects were made salient, seeing them in pairs that could potentially align with other pairs during habituation did not suffice to shift the infants' focus to the relation. This is consistent with the idea that relational representation is fragile for these very young infants, relative to a focus on salient objects.

Interestingly, the difference between looking times to the novel versus familiar pairs increased over the course of the experiment, even during the test trials. This mirrors the pattern found by Ferry et al. (2015) with 7-month-old infants. This suggests that the infants continued to engage in alignment and abstraction across the test trials.

Perhaps surprisingly, there were no detected differences in relational learning across *same* and *different* habituation conditions, either in the looking decline during habituation or in interaction with looking times at novel versus familiar relations at test. Although infants in the *same* condition showed marginally better discrimination between a pair seen in habituation and one not seen in Experiment 1, we found no evidence that infants had abstracted either the *same* relation or the

[1] Additionally, the differences we find between test trial types do not seem to relate to whether objects in a pair contained faces, which infants might prefer (Lauer et al., 2015). In this experiment, three test trials included objects with faces, and three did not. We found no difference in looking at pairs containing faces, compared to pairs without any faces, $M_{Faces} = 23.54$ s; $M_{Without} = 23.69$ s.

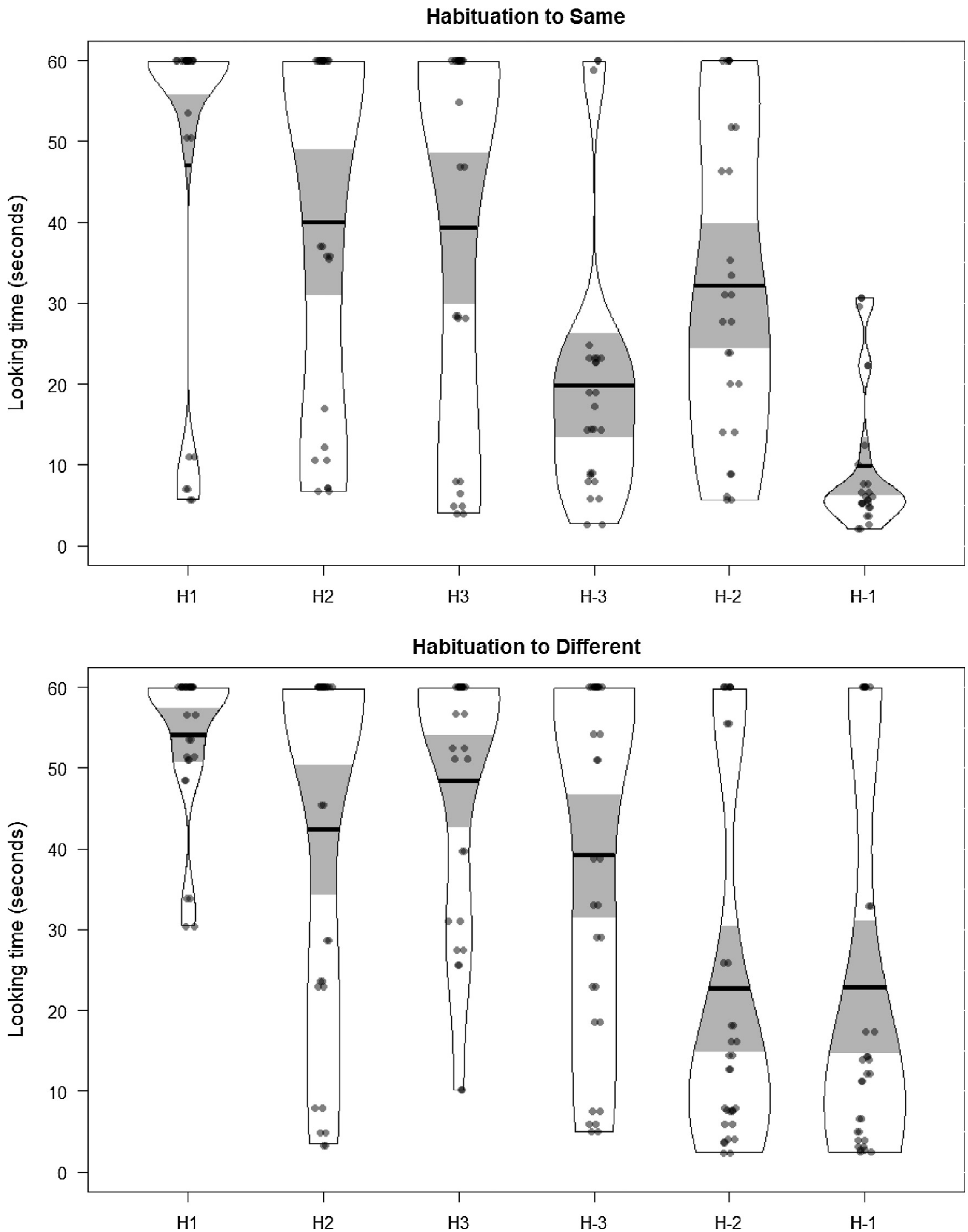

Fig. 7. Bean plots showing mean looking times during the habituation in the *same* and *different* conditions in Experiment 2. The plots include results for the first three trials (H1, H2, H3) and the last three trials before the habituation criterion was met (H-3, H-2, H-1). The thick central line in each box is the mean, and the upper and lower shaded portions represent the 95% Confidence Intervals (CIs) for this mean (i.e., there is a 95% probability that the true population mean falls within this interval). Dots indicate the raw data points. The width of the bean indicates the density of the data distribution at a looking time value.

different relation when they were tested on the critical *new* pairs.

Comparing Experiment 1 and Experiment 2, we see that 3-month-olds were better able to abstract the relation when given two alternating examples than when given six examples. This result runs contrary to the predictions of standard learning theories—yet there is precedent for it in other research on infant relational learning (Casasola, 2005; Maguire et al., 2008). We believe this result is best explained by noting that the process of comparison and alignment is critical for relational learning. Following Casasola and Park (2013), we suggest that when infants received up to six exemplars in Experiment 1, their attention was repeatedly drawn to the novel objects within these pairs. We suspect that they encoded each pair in terms of the concrete properties of one or both objects, rather than noticing any relations between the objects. The alternation of just two examples during Experiment 2 had the effect of decreasing object salience over the course of repetition, permitting the infants to notice relations within the pairs. Even though these initial relational representations may have been highly concrete, they provided the grist for structural alignment between the pairs[2]—and this led to relational abstraction.

9. General discussion

To our knowledge, these findings are the earliest evidence of analogical processes in very early infancy (apart from those involving language, which might be a privileged domain). When 3-month-old infants were given two alternating exemplars instantiating either *same* or *different*, they were able to form abstract relations that generalized to new exemplars of the relation. Further, heightening the salience of individual objects hindered this learning. When test pairs contained an individual object that infants had seen previously, they failed to discriminate between familiar or novel relations. Thus, signatures of analogical processing are evident at 3 months of age.

These findings bear on the central question of how human relational ability arises. In the introduction, we raised two broad positions. The first position—that analogical ability in humans emerges through combining other capacities such as linguistic knowledge and/or causal schemas—is difficult to reconcile with our evidence of analogical ability in 3-month-olds. The evidence is more consistent with the second possibility—that human analogical ability is present from the earliest ages we can test.

A related question concerns the nature of the infants' initial representations. We can differentiate two possibilities. First, it could be that human infants are born with a set of primitive relations, including *same* and *different*. In this case, the learning process that infants in our studies would undertake would be to apply these relations to the current stimuli and abstract the common relational pattern across the series. This seems unlikely to capture the findings in these experiments —particularly the finding that although it was *possible* for 3-month-olds to form abstract *same* and *different* relations, it was not easy (for example, they failed when given a large set of pairs in Experiment 1). This assumption is also difficult to reconcile with the results of Ferry et al.'s (2015) Experiment 1, in which 7–9-month-olds failed to show relational transfer from a single instance of either *same* or *different* (presented twice) to a new instance of the relation.

The second possibility is that the relations of *same* and *different* are not inborn, but are abstracted from perceptual representations of the pairs over the course of the study, via structure-mapping across these representations. For example, early in the series, the infants' encodings of sameness in AA might have involved only a few fragmentary matches. But on subsequent experience with AA, further matches might have been noticed. Further, finding a sense of sameness between one pair could have facilitated noticing sameness in other pairs. This would be consistent with evidence that children and adults can gain insight from iterated comparisons across a series of analogous examples (e.g., Kotovsky & Gentner, 1996). An analogous account could be offered for *different* (although admittedly, this account seems more intuitive for sameness than for difference). The idea that the same and different representations are – at least in part – abstracted from experience is also consistent with Ferry et al. (2015)'s finding that 7- and 9-month-olds formed abstract *same* and *different* relations when given a series of examples, but (as noted above) failed to do so when given only one example.

Another contribution of these studies is to characterize the state of analogical ability at 3 months. Though we see evidence for structure-mapping processes even at 3 months of age, there is a clear change in how these processes are deployed over the course of development. Comparing our findings with 3-month-olds with the patterns found for 7- and 9-month-olds in Ferry et al. (2015), we note three signs of this change. First, the older infants were able to align and abstract across four different pairs, whereas the younger infants succeeded only when given just two pairs in alternation. Second, although all three age groups showed the predicted adverse effects of object salience, the 7- and 9-month-olds showed a remediation effect—they could overcome the effects of object salience if they subsequently (during habituation) had the opportunity to align pairs containing the salient object with other examples of the relation. In contrast, 3-month-olds failed to benefit from the same scenario. Third, both 3-month-olds in Experiment 2 and 7-month-olds in Ferry et al. (2015) showed signs of continued learning during test trials, while 9-month-olds' attention to the novel relation peaked after the first test pair.

Together, the evidence from these experiments points not to core knowledge of *same* and *different,* nor to a process that arises entirely from experience, but to a structural alignment learning mechanism that is continuous from at least 3 months to adulthood. To strengthen the claim that this a lifelong learning process that is not limited to specific relations, future work should try to connect the rule-learning shown by newborns for linguistic structures to the domain-general learning mechanism we have documented here.

9.1. Implications for learning theories

Our most important finding is that 3-month-olds are able to use analogical comparison process to form abstract relations. But an equally surprising finding is that comparison across two repeating pairs (as in Experiment 2) was more effective for forming an abstract relation than was comparison across a greater variety of pairs (as in Experiment 1). The six exemplars presented during habituation in Experiment 1 offered a greater range of variation, but failed to promote abstraction and generalization in the infants. We suggest that the larger series was ineffective because, for the 3-month-olds, the objects were sufficiently interesting that when they encountered a new pair, they attended only to the object properties and not to potential relations between the two objects. Only after becoming familiar with the individual objects did they encode anything about the relation between the two objects. The alternation and repetition of two pairs in Experiment 2 addressed this problem by decreasing object salience over the course of repetition, permitting the infants to notice the relations within the exemplars and align them.

Consistent with this account, the more sophisticated 7- and 9-month-old infants tested by Ferry et al. (2015) were able to generalize the relation over four pairs. (The sequence was repeated until habituation occurred, so infants typically saw a few of these pairs twice.) We suggest that they had sufficient experience with objects in general that they could encode not only objects, but also relations between them. This "less is more" finding is consistent with other studies of early relational learning in which infants learn better from fewer exemplars (Casasola, 2005; Maguire et al., 2008). This pattern speaks to structural alignment as a mechanism. Comparison through the process of structural alignment is critical to relational learning, and this requires that the learner's encoding go beyond a focus on individual objects.

Our findings have important implications for accounts of learning. Most theories of learning assume that breadth of training predicts breadth of transfer. Of course, this is sometimes the case: for example, exposure to a large range of exemplars can suggest a broader abstraction (e.g., *dogs*) rather than a more specific one (e.g., *dachshunds*). The evidence that for 3-month-olds, two exemplars allowed a greater degree of abstraction than did six exemplars runs counter to this general view.

This pattern points to an important insight about relational learning: 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. Variability is desirable—but only if the learner can align the examples (Christie & Gentner, 2010; see also Spencer, Perone, Smith, & Samuelson, 2011). As Gentner and Hoyos (2017) assert, for relational learning, the learning principle must be amended to be "breadth of *alignable* training predicts

[2] Although we do not know how the infants initially encoded the relations within the pairs, there is evidence from older children that comparison across examples fosters common relational representations (Kotovsky & Gentner, 1996).

breadth of transfer."

This is not to dismiss the cases where variability can be beneficial to relational learning. Many recent studies have manipulated the number of exemplars and measured subsequent learning in older infants and children. While some of these studies support the 'less is more' finding (Bulf et al., 2011; Casasola, 2005; Gerken & Quam, 2016; Maguire et al., 2008), many others that instead find 'more is more'—that variability across examples promotes generalization (Bomba & Siqueland, 1983; Casasola & Park, 2013; Castro, Kennedy, & Wasserman, 2010; Gerken, 2006; Gerken & Bollt, 2008; Gómez, 2002; Needham et al., 2005; Quinn & Bhatt, 2005). Variation across these studies is diverse in terms of what was presented (e.g., visual presentations of object categories and relations versus auditory presentations of linguistic stimuli), how it was presented, the ages tested, and the intended generalization (e.g., *same/different*, support/containment, grammatical pattern, object category, shape). It is likely that multiple factors influence the relative effectiveness of high vs. low variability, including the learner's familiarity with the domain and whether the learning is active or passive (Carvalho & Goldstone, 2014). We argue that the important factor is whether the intended generalization is a relational abstraction or a feature-level abstraction. When the learning target is a basic-level object concept, as in many infant studies, the items will already be highly alignable, so that increasing irrelevant variability can contribute to learning the relevant abstraction. But for relational categories, the ability to align the exemplars is critical for arriving at the abstraction. Thus, early in learning, higher alignability (and lower variability) may best promote abstraction and transfer—as with our 3-month-olds, who successfully abstracted *same* or *different* relations from two, but not six, exemplars.

9.2. Further issues

Are humans alone in possessing analogical ability, as suggested by Penn, Holyoak and Povinelli (2008)? We would argue against this claim. Recent research has shown evidence of analogical processing in chimpanzees and bonobos (Christie, Gentner, Call, & Haun, 2016; Haun & Call, 2009), and there is evidence suggesting that infant chimpanzees can abstract the *same* relation over a series of examples (Oden, Thompson, & Premack, 1990). Beyond primates, recent evidence also suggests that hooded crows can learn *same* and *different* relations by analogical comparison (Smirnova, Zorina, Obozova, & Wasserman, 2015). Still, humans—even human children—appear to have considerably greater analogical ability than our nearest relatives among the apes (Christie et al., 2016). Further research is necessary to better understand the nature of the cognitive difference between our species and others.

There is considerable evidence that relational language plays an important role in facilitating relational learning (Christie & Gentner, 2014; Gentner & Rattermann, 1991; Son, Smith, Goldstone, & Leslie, 2012; see Gentner, 2016, for a review). There is considerable evidence that relational symbol learning may augment our analogical ability—for example, by inviting nonobvious comparisons that reveal new relational abstractions (Gentner, 2003; Gentner, 2010). Indeed, Gentner and Simms (2011) suggest that relational language is a major contributor to the species-level differences in analogical ability just discussed. However, our findings with 3-month-olds clearly demonstrate that language is not a necessary prerequisite for analogical processing. Infants have extremely limited comprehension of relational terms (even terms like "allgone" and "more") until 10 months of age (Bergelson & Swingley, 2013). Thus, we conclude that analogical processing is a core process that does not depend on language, even though it is clearly influenced by language learning at later points in development. Indeed, we suggest (consistent with Gentner's (2010) relational bootstrapping proposal) that analogical processes are used in learning language. We speculate that the structure-mapping mechanism, which supports relational learning from experience, is an important contributor to the rapidity with which human learn patterns—including grammatical structures—during their first years of life.

10. Conclusions

Our findings are the first to show that analogical ability is present in 3-month-old infants. Given a series of two exemplars, 3-month-olds can form abstract *same* and *different* relations. Further, the factors that facilitate and hinder relational learning in older children and adults are evident in these young infants. These findings suggest that humans are born with a core relational learning mechanism that is continuous over development. That this ability is present at 3 months of age shows that analogical processes exist prior to language learning. Indeed, language learning may capitalize on this pre-existing relational ability.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.03.008.

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