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Induction, Overhypothesis, and the Origin of Abstract Knowledge: Evidence From 9-Month-Old Infants

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Abstract

Human cognition relies on the ability to extract generalizable knowledge from limited evidence. One type of inductive learning, overhypothesis formation, allows learners to make inferences that take them beyond the limits of direct experience, leading to the creation of abstract knowledge. The developmental roots of this ability have yet to be investigated. We report three experiments examining whether 9-month-old infants are capable of forming overhypotheses. Our results show that when given evidence about a few objects in some category, infants formed a second-order generalization about categories in general. These findings provide evidence that infants possess a powerful mechanism for inductive learning—a mechanism that may be applied to many domains and that can account for the development of many inductive biases later on.

Keywords

overhypothesis formation, inductive learning, cognitive development

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One of the greatest puzzles of human learning is how experience leads to the formation of abstract knowledge. The “problem of induction” (Hume, 1748/1993) concerns people’s ability to infer a general law or principle on the basis of observation of particular instances. Inductive inferences go beyond the available data in order to arrive at conclusions that are likely, but not certain, given the available evidence (Goodman, 1955/1983; Hume, 1748/1993; Quine, 1960). Given that the majority of people’s everyday beliefs about how the world works are based on induction, it is important to understand how inductive generalizations are able to lead to the formation of abstract knowledge.

Human cognition centers on a unique capacity for extracting generalizable knowledge from sparse data. Consider that a single labeled exemplar is enough for children to learn the meaning of some words (e.g., Carey & Bartlett, 1978), and children develop grammatical constructions that are rarely found in the sentences they hear (e.g., Chomsky, 1980). These inductive leaps appear even more impressive when one considers the countless interpretations of the data that are logically possible but never entertained (Quine, 1960). The ability to generalize from a few specific examples is essential, not only in language acquisition, but also in causal learning (e.g., Gopnik & Sobel, 2000; Kelley, 1972), property induction (e.g., Madole & Cohen, 1995), social cognition (e.g., Jones, 2003), and many other domains.

In order to circumvent the problem of induction, Goodman (1955/1983) proposed that multiple levels of generalization are required in order to form a hypothesis or principle, which can subsequently be applied to novel instances. Goodman introduced the term *overhypothesis* to embody this inferential ability and used the following example to illustrate the idea. Suppose you are shown a selection of identical bags. A few white marbles are drawn from the first bag. A handful of red marbles are pulled out of the second bag. Some green marbles are pulled from the third bag. If you saw a single blue marble being sampled from a new bag, what would you expect the color of the next marble drawn from that bag to be? Your answer would probably be “blue.” Arriving at this answer involves making both a first-order and a second-order generalization. The first-order generalization concerns the contents of each individual bag: The next marble drawn from the first bag is most likely to be white, and the next marble drawn from the second bag is most likely to be red. The second-order

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generalization, or overhypothesis, is that “bagfuls of marbles are uniform in color,” and it allows you to make predictions about a brand new bag containing novel-colored marbles.

The inferential mechanism of overhypothesis formation enables learners to make inferences that take them beyond the limits of their direct experience. The ability to form overhypotheses allows learners to go beyond the specific categories and properties they have learned (e.g., dogs bark) in order to make a principled generalization about all categories and properties of a given type (e.g., all animals of the same kind make the same sound; Shipley, 1993). The main advantage of such a mechanism is that once abstract knowledge has been formed, this knowledge can be applied to new exemplars and new categories of objects.

Researchers have applied the general idea of overhypothesis formation to account for the acquisition of several cognitive learning biases (Kemp, Perfors, & Tenenbaum, 2007; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). Work in computational cognitive science, using a hierarchical Bayesian model of overhypothesis formation (Kemp, 2008; Kemp et al., 2007), suggests that certain cognitive biases (i.e., the shape bias in word learning, the ability to group categories into ontological kinds, learning of causal schemata) can be acquired via this inductive mechanism. The computational work provides a plausible analysis and instantiation of overhypothesis formation as a mechanism for acquiring inductive biases, but empirical evidence is lacking in infants.

If this inductive mechanism is responsible for the formation of early-developing learning biases, then even young infants should be able to demonstrate overhypothesis formation. Research to date has examined the mechanism of overhypothesis formation in preschoolers and adults (Macario, Shipley, & Billman, 1990; Nisbett, Krantz, Jepson, & Kunda, 1983). Our experiments tested whether 9-month-old infants are able to form overhypotheses about feature variability. In three experiments using the violation-of-expectancy looking-time methodology (Onishi & Baillargeon, 2005; Spelke, Breinlinger, Macomber, & Jacobson, 1992), we investigated whether, when provided with partial evidence about a few objects in a few categories, infants would be able to form a second-order generalization about a new category.

Experiment I

Method

Participants. Participants were 48 full-term infants, 24 male and 24 female (mean age = 9 months 19 days; range = 8 months 18 days to 10 months 13 days). Equal numbers of infants were randomly assigned to the experimental condition (mean age = 9 months 22 days) and the control condition (mean age = 9 months 17 days). Infants were recruited from the Vancouver, Canada, area by mail and subsequent phone calls. Most of the infants came from a middle-class, non-Hispanic White background (19% were Asian). An additional 11 infants were

tested but were excluded because of experimenter error (4) or fussiness (7).

Materials. Objects were sampled from four identical foam-core boxes measuring $22 \times 16 \times 16$ cm. The tops of the boxes were not covered. A transparent Plexiglas container that measured $14 \times 4 \times 4$ cm was attached to the front of each box. Five types of objects were sampled from the boxes: spheres (2.5 cm in diameter), cubes (2.5×2.5 cm in size), stars (3×2.5 cm in size), triangular pyramids (3×3.5 cm in size), and thimbles (3×2 cm in size). Each of the sampled objects was made of wood and was painted in one of five colors (blue, green, red, yellow, or purple).

Apparatus. The events were presented on a stage with a display area that measured 94 cm (width) \times 55 cm (height). The infant sat in a high chair 70 cm from the stage, with eye level 8 cm above the floor of the stage. The parent sat next to the infant with his or her back toward the stage. A video camera, set up under the stage, focused on the infant's face and recorded the entire session. The video camera was connected to a 19-in. television placed in one corner of the room. An observer watched the infant on the television monitor and pressed a key on a laptop computer when the infant was looking on target. The observer was not able to see what was presented on the stage and was not aware of the order of the trials. A computer program written specifically for looking-time studies (Hypercard, Version 2.4.1; Pinto, 2002) was used to record the looking times.

Design and procedure. Infants were randomly assigned to either the experimental or the control condition. Each infant received four test trials, with *expected-outcome* and *unexpected-outcome* trials presented in alternation. The experimenter began by waving keys at all corners of the stage in order to define the infant's gaze parameters for the observer. During the study, the experimenter sat behind the stage in view of the infant at all times.

Figure 1 presents a schematic representation of the test events in both the experimental and the control conditions. In the experimental condition, four identical boxes, each with a transparent container attached to its front, were placed across the stage. Beginning with the right-most box (Box 1), the experimenter closed her eyes, reached into the top of the box, pulled out a shape (e.g., a sphere), and placed it into the container on the front of the box. This sampling procedure was repeated until the container for Box 1 was filled with four different-colored objects of uniform shape (e.g., spheres). The experimenter repeated this procedure with Boxes 2 and 3. Each of the first three boxes consistently produced a different-shaped sample (e.g., spheres from Box 1, cubes from Box 2, and triangular pyramids from Box 3). With the three boxes and their samples in view of the infant, the experimenter sampled a novel-shaped object (e.g., a red star) from the test box (Box 4) and placed it in the test box's container.

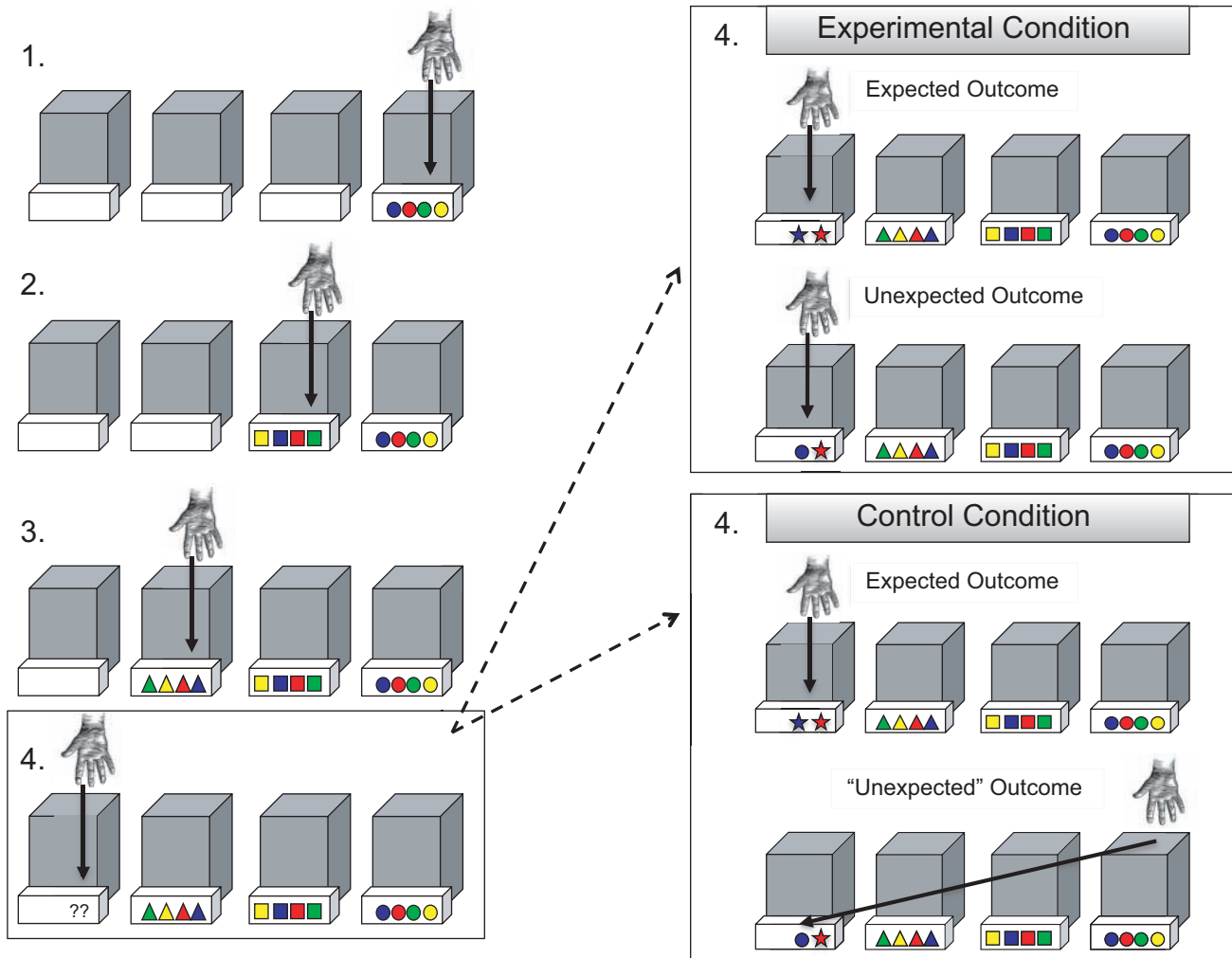


Fig. 1. Schematic representation of the test events in the experimental and control conditions of Experiment 1. On each trial, the experimenter pulled four different-colored objects of uniform shape from each of the first three boxes and then pulled a novel-shaped test object from the fourth box (the test box). In an unexpected outcome in the experimental condition, a second test object, with a shape different from that of the first test object, was drawn from the test box, and in an unexpected outcome in the control condition, the second test object was drawn from the first box. In an expected outcome in both conditions, the second test object, which had the same shape as the first test object, was drawn from the test box.

During an expected-outcome trial, the second object sampled from the test box matched the first object in shape (e.g., a blue star); thus, the test sample consisted of two same-shaped objects (two stars). During an unexpected-outcome trial, the second object sampled from the test box did not match the first object in shape (e.g., a blue sphere); thus, the test sample consisted of two different-shaped objects (a star and a sphere).

On each trial, after the second object was placed in the test box's container, the experimenter said, "Look, [baby's name], look!" and then lowered her head to ensure that she was not making eye contact with the infant. The infant's looking time was recorded. When the infant turned away for 2 consecutive seconds, the trial ended. The boxes, and their samples, were removed from the stage.

The trials in the control condition were identical to the trials in the experimental condition, except that in the unexpected-outcome trials, the second test object was not sampled from the test box, but was instead sampled from the first box (whose previously sampled contents matched the second test object in shape).

Looking time was measured after the experimenter retrieved the second test object from the fourth box (experimental condition) or from the first box (control condition).

Results

An alpha level of .05 was used in all statistical analyses. Preliminary analyses found no effect of gender or test-trial order (whether the expected-outcome or unexpected-outcome trial

was presented first). Subsequent analyses were collapsed over these variables. All infants were observed off-line by a second observer who was completely blind to condition and test-trial order. Interscorer reliability averaged 87%.

Infants' looking times to the test outcomes were compared by means of a 2×2 repeated measures analysis of variance (ANOVA) with outcome (expected vs. unexpected) as a within-subjects factor and condition (experimental vs. control) as a between-subjects factor. The analysis revealed a significant Outcome \times Condition interaction, $F(1, 46) = 4.58, p = .04, \eta_p^2 = .09$. A planned comparison was performed for each condition in order to determine whether infants looked longer at one test outcome than at the other (expected vs. unexpected). Infants in the experimental condition looked significantly longer at the unexpected outcome ($M = 14.28$ s, $SD = 8.83$) than at the expected outcome ($M = 11.32$ s, $SD = 6.24$), $t(23) = -2.40, p = .03$. In contrast, infants in the control condition looked for equivalent durations to the unexpected outcome ($M = 10.29$ s, $SD = 6.54$) and the expected outcome ($M = 11.06$ s, $SD = 5.70$), $t(23) = 0.62, p = .54$.

Discussion

Sampling from Boxes 1 through 3 supported the formation of the overhypothesis that each box contained uniformly shaped objects. If the infants had formed this overhypothesis, the sampling of a second same-shaped object from the test box would have been expected, as it would be consistent with this overhypothesis. However, it would be unexpected for the second object sampled from the test box to not match the first object in shape, as this would violate the overhypothesis. Infants in the experimental condition looked longer at the unexpected outcome than at the expected outcome. Thus, 9-month-olds in this condition expected sampling to be consistent with the overhypothesis and were surprised when the overhypothesis was violated.

A control condition, which presented test displays identical to those of the experimental condition, was included to ensure that infants' looking pattern was not driven by an inherent preference for different- over same-shaped objects. In the control condition, sampling same-shaped objects from the test box was consistent with the overhypothesis, as was sampling a second, different-shaped object that matched the objects from the box it was sampled from. In the control condition, infants' looking times were equivalent for the two test outcomes.

If infants have a general ability to form overhypotheses, they should be equally adept at forming overhypotheses across various perceptual dimensions. In Experiment 1, infants formed an overhypothesis over the dimension of shape, ignoring color. In Experiment 2, we investigated whether 9-month-olds are able to form the relevant overhypothesis when these features are switched (i.e., color varies across boxes and shape varies within boxes).

There is reason to believe that infants may be more acutely attuned to the dimension of shape than to other perceptual dimensions. Shape is an especially salient property for many

cognitive tasks of early development (e.g., generalizing new properties: Diesendruck & Bloom, 2003; acquiring new words for object categories: Dewar & Xu, 2007; Landau, Smith, & Jones, 1988; reaching for objects in the dark: Robin, Berthier, & Clifton, 1996). If overhypothesis formation is a bottom-up learning mechanism, infants should be able to form overhypotheses across all perceptual dimensions, even those less salient and predictive than shape.

Experiment 2

Method

Participants. Participants were 40 full-term infants, 20 male and 20 female (mean age = 9 months 25 days; range = 8 months 15 days to 10 months 16 days). Equal numbers of infants were randomly assigned to the experimental condition (mean age = 9 months 23 days) and the control condition (mean age = 9 months 26 days). All infants were recruited from the same population as in Experiment 1, but none participated in the first experiment. Most of the infants came from a middle-class, non-Hispanic White background (28% were Asian). An additional 7 infants were tested but were excluded because of experimenter error (1) or fussiness (6).

Materials and apparatus. All materials and apparatus were the same as were used in Experiment 1.

Design and procedure. Experiment 2 was identical to Experiment 1, except that each box contained different-shaped objects (cubes, spheres, stars, thimbles, triangles) of a single color (e.g., Box 1 contained blue shapes, Box 2 contained yellow shapes, and Box 3 contained green shapes). (See Fig. S1 in the Supplemental Material available online for a schematic representation of the test events in the experimental and control conditions of Experiment 2.)

In the experimental condition, sampling from the test box yielded two same-colored objects in expected-outcome trials and two different-colored objects in unexpected-outcome trials. In the control condition, sampling from the test box also yielded two same-colored objects in expected-outcome trials; in unexpected-outcome trials, the second different-colored test object was sampled from the first box (and matched the color of the previously sampled objects from that box) and was placed in the test box's container.

Results

Preliminary analyses found no effect of gender or test-trial order. Subsequent analyses were collapsed over these variables. All infants were observed off-line by a second observer who was completely blind to condition and test-trial order. Interscorer reliability averaged 88%.

Infants' looking times to the test outcomes were compared by means of a 2×2 repeated measures ANOVA with outcome

(expected vs. unexpected) as a within-subjects factor and condition (experimental vs. control) as a between-subjects factor. The analysis revealed a significant Outcome \times Condition interaction, $F(1, 38) = 5.08, p = .03, \eta_p^2 = .12$. A planned comparison was performed for condition in order to determine whether infants looked longer at one outcome than the other (expected vs. unexpected). Infants in the experimental condition looked significantly longer at the unexpected outcome ($M = 11.35$ s, $SD = 5.79$) than the expected outcome ($M = 8.74$ s, $SD = 5.18$), $t(19) = -2.91, p = .01$. In contrast, infants in the control condition looked for equivalent durations to the unexpected outcome ($M = 9.57$ s, $SD = 5.90$) and the expected outcome ($M = 10.06$ s, $SD = 4.48$), $t(19) = 0.47, p = .65$.

Discussion

The results of Experiment 2 mirror those of Experiment 1. Infants in the experimental condition looked longer at the unexpected outcome than at the expected outcome. Thus, 9-month-olds in this condition expected sampling to be consistent with the overhypothesis that boxes contain same-colored objects, and they looked longer when this overhypothesis was violated. In contrast, infants in the control condition, in which neither test outcome violated the overhypothesis, looked at the two outcomes for equivalent durations. It appears that infants have a general ability to form overhypotheses: They are equally adept at forming overhypotheses across various perceptual dimensions.

An alternative interpretation of the results of Experiments 1 and 2 is that the infants' looking pattern was driven not by a second-order generalization formed over the sampled contents of Boxes 1 through 3, but by a first-order generalization formed over the first object sampled from the test box. Under this interpretation, even if the infants had not been given evidence about the contents of Boxes 1 through 3, they might have expected the second test object to match the first test object along at least one property dimension, and they might have been surprised if it did not match. In order to ensure that the results of Experiments 1 and 2 were not driven by a first-order generalization performed over the objects drawn from the test box alone, we conducted a control study (Experiment 3) in which infants saw objects being sampled from the test box only (i.e., they saw no sampling from Boxes 1–3).

Experiment 3

Method

Participants. Participants were 24 full-term infants, 10 male and 14 female (mean age = 9 months 7 days; range = 8 months 16 days to 10 months 8 days). Equal numbers of infants were randomly assigned to the shape condition (mean age = 9 months 7 days) and the color condition (mean age = 9 months 6 days). All infants were recruited from the same population as before, but none participated in the first two experiments.

Most of the infants came from a middle-class, non-Hispanic White background (19% were Asian). An additional 3 infants were tested but were excluded because of experimenter error (2) or fussiness (1).

Materials and apparatus. All materials and apparatus were the same as were used in Experiments 1 and 2.

Design and procedure. Infants were randomly assigned to either the shape condition or the color condition. Infants received eight test trials: Trials 5 through 8 were repetitions of Trials 1 through 4. Infants in the shape condition were shown test events identical to those in the experimental condition of Experiment 1, except that no objects were drawn from Boxes 1 through 3. Infants in the color condition were shown test events identical to those in the experimental condition of Experiment 2, except that no objects were drawn from Boxes 1 through 3. (See Fig. S2 in the Supplemental Material available online for a schematic representation of the test events in the shape and color conditions of Experiment 3.)

Results

Preliminary analyses found no effect of gender or test-trial order. Subsequent analyses were collapsed over these variables. All infants were observed off-line by a second observer who was completely blind to condition and test-trial order. Interscorer reliability averaged 90%.

Shape condition. Infants in the shape condition looked marginally longer at two same-shaped objects ($M = 9.13$ s, $SD = 4.48$; expected outcome) than at two different-shaped objects ($M = 6.28$ s, $SD = 2.89$; unexpected outcome) drawn from the test box, $t(11) = 1.88, p = .09$. This looking pattern is the reverse of that found in Experiment 1. Performance in the shape condition of Experiment 3 was compared with performance in the experimental condition of Experiment 1 by means of a 2×2 repeated measures ANOVA with outcome (expected vs. unexpected) as a within-subjects factor and study (Experiment 1 vs. Experiment 3) as a between-subjects factor. This analysis revealed a significant Outcome \times Study interaction, $F(1, 34) = 8.04, p = .01, \eta_p^2 = .19$.

Color condition. Infants in the color condition looked for equivalent durations upon seeing two different-colored objects ($M = 7.75$ s, $SD = 3.82$; unexpected outcome) and two same-colored objects ($M = 7.55$ s, $SD = 4.58$; expected outcome) drawn from the test box, $t(11) = 0.15, p = .88$. Performance in the color condition of Experiment 3 was compared with performance in the experimental condition of Experiment 2 by means of a 2×2 repeated measures ANOVA with outcome (expected vs. unexpected) as a within-subjects factor and study (Experiment 2 vs. Experiment 3) as a between-subjects factor. The interaction between outcome and study was not significant, $F(1, 30) = 2.49, p = .12, \eta_p^2 = .08$, but there was a

trend for the significant difference in looking obtained in Experiment 2 to be reduced in Experiment 3.

Discussion

In contrast to infants in the experimental conditions of Experiments 1 and 2, infants in Experiment 3 did not look longer at the different-shaped or different-colored test objects than at the same-shaped or same-colored test objects. These findings indicate that the results of Experiments 1 and 2 were not driven by a first-order generalization formed over the outcomes of the test box alone, as infants in the control experiment were presented with test events identical to those in the previous two experiments. Experiment 3 provides evidence that the results of the first two experiments were due to infants' ability to form the relevant overhypothesis based on the pattern of objects sampled from the first three boxes.

General Discussion

Infants were able to make a principled generalization about a class of entities (i.e., boxes and the nature of the objects they contain) on the basis of scant data. After receiving limited evidence about the contents of the first three boxes (i.e., a random sample of four objects from each box), 9-month-olds expected the contents of a new box, with novel objects, to accord with an abstract pattern. The infants' performance is impressive considering that, in order to succeed, they were required to make both a first-order generalization regarding the contents of individual boxes (i.e., Box 1 contains sphere-shaped objects) and a second-order generalization, or overhypothesis, about the contents of the boxes in general (i.e., boxes contain uniformly shaped objects). It is even more impressive that the infants were able to succeed in the first two experiments considering that the objects presented differed along two perceptual dimensions (shape and color). Thus, the infants were required to form the overhypothesis across a relevant perceptual dimension while ignoring another salient perceptual feature.

Previous inferential-learning studies with infants have focused on how infants employ intuitive statistics to use a small amount of data in order to make inductive inferences about larger populations and, conversely, to make inferences from populations to samples (Denison & Xu, in press; Xu & Denison, 2009; Xu & Garcia, 2008). Studies of intuitive statistics examine infants' ability to form first-order generalizations about the expected composition of a population on the basis of a small sample drawn from that population. The current study focused on how infants are able to go beyond these first-order generalizations in order to make a second-order generalization about the composition of all populations of like kind. Thus, after seeing samples drawn from several boxes, infants are able to make an inductive inference about the expected composition of the objects in a new box on the basis of sampling of a single (novel) object.

The current study also differs from research investigating infants' ability to detect and generalize rules or concepts from

visual stimuli (e.g., Saffran, Pollak, Seibel, & Shkolnik, 2007; Tyrrell, Stauffer, & Snowman, 1991; Tyrrell, Zingardo, & Minard, 1993). For example, Tyrrell et al. (1991) showed that 7-month-olds were sensitive to "same" and "different" relations; that is, when familiarized to the relation of sameness (e.g., two identical toys, AA), infants looked longer at a different relation (e.g., two different-looking toys, EF) than at the same relation (two other identical toys, DD) at test, and vice versa. The current study goes beyond demonstrating that infants can generalize the concept of "sameness" and apply it to novel stimuli. If the results of Experiments 1 and 2 were driven by a generalization of "sameness," the infants should have behaved equivalently in the experimental and control conditions, as the visual pattern of sampled objects was identical in these conditions. This was not the case, which suggests that the infants tracked both the pattern of drawn objects and sampling information (i.e., the location from which the test object was drawn) and used both cues in service of their inference. This is critical for formation of an overhypothesis—a second-order inductive generalization that involves postulating two variables (e.g., bags and colors of marbles) and some correspondence rule to link the specific values of the two variables.

The present study provides evidence that as early as 9 months of age, infants are able to make second-order inductive generalizations. Given evidence from a few members of a category, infants are able to make metageneralizations allowing them to make predictions about new object categories on the basis of scant data. Future research is needed to understand the nature of the underlying inductive learning mechanism, which may be responsible for the acquisition of several presumed-innate inductive biases in a number of knowledge domains.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at <http://pss.sagepub.com/content/by/supplemental-data>

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