



Infant categorization

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In this article, we review the principal findings on infant categorization from the last 30 years. The review focuses on behaviorally based experiments with visual preference, habituation, object examining, sequential touching, and inductive generalization procedures. We propose that although this research has helped to elucidate the ‘what’ and ‘when’ of infant categorization, it has failed to clarify the mechanisms that underpin this behavior and the development of concepts. We outline a number of reasons for why the field has failed in this regard, most notably because of the context-specific nature of infant categorization and a lack of ground rules in interpreting data. We conclude by suggesting that one remedy for this issue is for infant categorization researchers to adopt more of an interdisciplinary approach by incorporating imaging and computational methods into their current methodological arsenal. © 2010 John Wiley & Sons, Ltd. *WIREs Cogn Sci* 2010 1 894–905

INTRODUCTION

The study of categorization—especially its emergence in the first years of life—has potential to become an archetypal endeavor of Cognitive Science. First and foremost, infant categorization—and the concepts or *mental representations* that it is based on—provides insight into one of the most enduring philosophical and psychological questions at the core of Cognitive Science, namely, what are the origins of knowledge. Over the last 30 years, infancy researchers have predominantly studied early categorization with only one of the tools of Cognitive Science, namely, behavioral methods. On the one hand, this approach has led to the emergence of a large database on *what* categories infants can form and *when* in developmental time they are able to do so. In so doing, it has provided the kind of information that is necessary for cognitive scientists to describe any mental phenomena and the behavior that stems from it. On the other hand, it has also led to increasing polarity among researchers about *how* infants categorize, that is, what are the mechanisms that underpin classification in the first years of life. This debate began with the Greek philosophers over 2000 years ago, and it remains today one of the thorniest and fractious issues within developmental and Cognitive Science.

In this article, we will review a number of primary findings generated in the last three decades via a

variety of infant-appropriate methods. We will show that although much is known about the ‘what’ and ‘when’ of early categorization, researchers have struggled to find theoretical consensus about mechanisms for three reasons. First, infant categorization is highly context specific and is affected not only by the choice of stimuli but also the method used. Second, there are no ground rules for the interpretation of behavioral studies, which often leads to unwarranted assumptions about how infants categorize. Third, those in the field have not, as yet, adopted a truly interdisciplinary approach by using and interrelating findings from behavioral studies with brain imaging and computational modeling. We conclude by discussing a number of promising future avenues that may lead to a more coherent view of early categorization.

WHAT IS INFANT CATEGORIZATION?

There is no single definition of *categorization*. Broadly speaking, it is the ability, shared by human and nonhuman animals, to mentally group together things that exist in the world. More formally, to categorize is to group discriminable properties, objects, or events into classes by means of some principle or rule and to respond to them in terms of their class membership instead of as an individual.^{1–3} It is related to, but different from, the ability to *discriminate* a single object or thing as different from another object or thing, and from *induction* or *inductive inference* whereby prior experience is used to decide how far to generalize or extend a particular observation to a novel instance.

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According to most researchers, categorization and induction rely on *concepts* or *mental representations* in the brain that encapsulate or summarize the properties, features, and structures that exist among category members in the world. In this way, the mind reduces considerably the information-processing demands on inherently limited memory storage and perceptual processes. Concepts also underpin language learning in that they allow labels to be attached to categories of things.^{4,5} The study of infant categorization, then, provides insight not only into the origin of concepts and knowledge—which may act as the foundation for later learning—but also helps cognitive scientists to understand the development of memory, encoding, and language.

The period of infancy is often considered over at the onset of language; after all, the etymology of the term ‘infant’ comes from the Latin word meaning ‘unable to speak.’ Nonetheless, for many infancy researchers, ourselves included, the ‘onset’ of language occurs during the rapid acceleration of naming called the *vocabulary spurt* or *naming explosion* that occurs between 18 months and 2 years of age.^{6–8} Thus, in the current article, we will review evidence from studies performed on children prior to their second birthday.

RESEARCH FINDINGS

Until relatively recently, it was generally assumed that the categorizing abilities of infants were fairly limited.^{9,10} For instance, Sugarman wrote that although 1- to 2-year-old infants sequentially manipulate objects of a given type, ‘...no definitive evidence exists that the children link these objects mentally’ (Ref 11, p. 12). This view changed, however, with the emergence of novel infant-oriented methodologies—for example, visual preference,¹² habituation,^{13,14} object examining,¹⁵ sequential touching,^{8,16} and inductive generalization¹⁷—that were combined with experimental designs suitable to study early categorization. In this section, we outline the major findings that emerged on infant categorization from the last 20 years using these methods.

Visual Preference

In this procedure, infants are first presented with successive pairs of images from a single category for a fixed number of trials. During the test phase, infants are presented with a novel pair of images: one from the familiar category and one from a novel category. Fixation times to each image are measured. An infant is judged to have formed an exclusive category when the proportion of time spent looking at the novel

category exemplar relative to the familiar category member during the test phase is significantly greater than chance of 0.50.¹²

The visual preference procedure is particularly useful for studying categorization in infants from birth onward. Using this method, it has been shown that newborns who were familiarized with either triangles, squares, circles, or crosses were able to form global categories such as open (e.g., crosses) and closed shapes (e.g., triangles, squares, circles) but were unable to form distinct shape categories (e.g., triangles vs. squares).¹⁸ More impressive perhaps, by 3 and 4 months of age infants are able to form prototypes—or representational averages—of basic shapes such as triangles and squares.¹⁹ Following familiarization with shapes that deviated from the prototype to different degrees, infants looked longer at a previously seen shape than at a previously unseen prototype. This suggests that they generated a mental representation of the prototype based on the familiarization stimuli and found it more familiar than a shape they had viewed earlier.

The visual preference procedure has also been used to demonstrate that by 3 months of age infants can form categorical representations at the adult-like global level of mammals that exclude nonmammalian animals and furniture, and of furniture that excludes vehicles and mammals.²⁰ There is also evidence that infants at this age form an exemplar-based global category of humans that includes other animals such as cats and horses.²¹ This categorical representation is asymmetrical such that the categories of horses and cats exclude the category of humans. According to the authors, this pattern occurs because infants’ global representation of humans provides a basis for a global category of animals. Studies that further examined basic-level categorization showed that infants form categories for dogs and cats by 3 months of age, with a similar asymmetry such that the category of cats is subsumed by the category of dogs.¹² Infants form the same categories even when presented with silhouettes of the animals or silhouettes of their heads, which suggests that the shape of the animal’s head gives sufficient information to provide a basis for categorization.^{22,23}

The asymmetrical nature of the cat and dog categories is explained by the fact that the distribution of the external features of dogs has a greater range and overlaps with the distribution of the external features of cats; category boundaries are therefore dependent on the feature distribution of the particular stimulus set.²⁴ This pattern is only present for a few months, however. Furrer and Younger,²⁵ for example, demonstrated that the asymmetry disappears

by 10 months of age such that infants succeeded at categorizing cats as different from dogs even when the number of stimuli in the familiarization phase was greatly reduced. They argued that this effect occurs because older infants have greater experience with the two categories and not because of more efficient processing as compared to 4-month-olds.

In addition to the findings with respect to asymmetry, visual preference studies have demonstrated other changes in category formation with development. For instance, infants form subordinate categories of cats and dogs by 7 months of age that are asymmetric such that the category of Siamese cats is exclusive of Tabby cats but the category of Tabbies is inclusive.²⁶ Developmental changes are also evident in the ability to separate stimuli into two separate categories during familiarization such that 10-month-olds, but not younger infants, form two separate categories when exposed to both pictures of cats and horses or male and female faces during familiarization.²⁷

Finally, an interesting developmental trend has been observed in infants' formation of spatial relation categories. Using the visual preference procedure, infants were familiarized with a shape (or a series of shapes) in a particular spatial location of a bar, followed by a test phase where infants viewed the shape in the familiar and novel locations. Infants formed categories for above and below²⁸ and left and right²⁹ when just one shape was used during familiarization. It is not until 6 or 7 months of age that they could abstract the categories of above and below when multiple shapes were used during familiarization.³⁰ Taken together, these findings show that there is a developmental trend that proceeds from forming narrow categories for spatial relations of specific objects to forming more broad categories that include similar spatial relations of diverse objects.

Habituation Studies

In the habituation procedure, stimuli from the same category are presented serially in succession. The procedure is infant controlled such that each trial ends when the infant looks away for a fixed amount of time, and the habituation phase ends when a predetermined decrement in looking time is reached. In the test phase, infants serially are shown a novel stimulus from the familiar category and a novel stimulus from a different category. Longer looking at the novel out-of-category exemplar relative to the novel in-category exemplar is interpreted to mean that the infant has formed a categorical representation for the habituation category. One primary advantage of the habituation procedure, relative to the visual preference procedure,

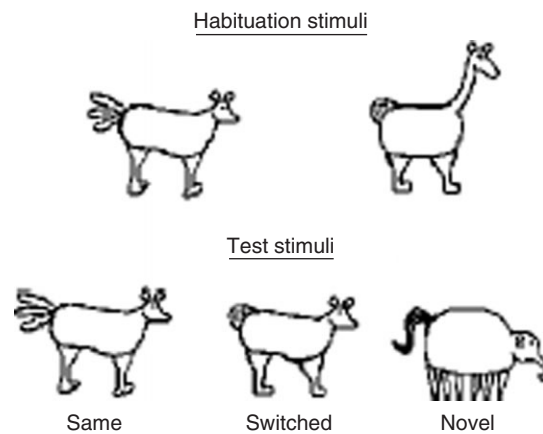


FIGURE 1 | Habituation and test stimuli used by Younger and Cohen.¹⁴ Infants at 10 months of age looked longer at the switched stimulus than the familiar stimulus, which indicated that they learned the correlation between the type of tail and the length of the neck of the schematic animals.

is that it is sensitive to individual differences in learning rates among infants. In addition, it decreases the possibility of a familiarity rather than a novelty preference in the test trials, which can occur with insufficient exposure to a stimulus.³¹

The primary finding of experiments with the habituation procedure is that over developmental time infants become sensitive to, and can form categories based on, different kinds of correlated attributes (e.g., things with feathers have wings and claws). One of the first studies to examine this issue was performed by Younger and Cohen.¹⁴ Infants at 4, 7, and 10 months of age were habituated to line drawings (Figure 1) of novel animal stimuli that could be grouped into categories on the basis of correlated features (e.g., legs and tails). They were then tested with a familiar correlated stimulus as well as a 'switch' uncorrelated stimulus that paired one feature from each of the habituation categories. Across a number of experiments, it was found that 10-month-olds, but not 4- or 7-month-olds, were sensitive to, and encoded, the correlated attributes embedded in a category context and generalized this correlation to a novel exemplar. This basic finding has since been replicated and extended with 10-month-olds in habituation studies with realistic color photographs of animals.³²

Infants are not only sensitive to categories defined by correlations among static features, however. A number of recent experiments have examined whether infants can form categories on the basis of correlations between static and dynamic features such as action, function, or motion. Horst, Oakes, and Madole³³ (see also Ref 34), for example, found that

infants who were familiarized to appearance-based categories (e.g., purple things) first learned the features of the individual exemplars and only later learned the common feature. In contrast, infants familiarized to functional categories (e.g., things that squeak when squeezed) first formed a summary representation and only later learned the individual items. In a related set of studies, Madole and Cohen³⁵ habituated 14- and 18-month-olds to objects that could be categorized on the basis of correlations between an object feature (e.g., wheels) and a function (e.g., rolling). Across a number of experiments, the authors found that 14-month-olds form categories on the basis of form–function correlations that make sense (e.g., when the form of a feature predicts its function) as well as those that do not make sense (e.g., when the form of a feature predicts another feature’s function). In contrast, 18-month-olds formed categories with only those form–function correlations that were consistent with the real-world.

A similar pattern of behavior—younger infants learning ‘more’ than older infants—has also been found in noncategorization studies on infants’ ability to learn correlations between object features and self-propulsion and agency,^{36,37} as well as studies on speech perception and gesture.^{38,39} One possibility is that this developmental trajectory occurs because the same general learning mechanism operates across these different domains.³⁷

Object Examination

In this method, objects from the same category—typically novel or scale model toys—are presented to the infant one at a time with a fixed trial length and number of trials. The manipulation time for each object is measured. In the test phase, the infant is presented with a novel object from the familiar category and an object from a novel category. The examining times are compared between the two test trials. Categorization is inferred when the examining time for the novel category object is longer than for the familiar category object.^{15,40} This method is suitable for infants older than approximately 9 months of age because it requires sufficient motor skills to hold and inspect objects.

Mandler⁴¹ the object examination task taps conceptual knowledge that visual familiarization tasks fail to access. Mandler and McDonough⁴⁰ showed that 9- and 11-month-old infants categorized at the global level—toy animals as different from toy vehicles—during object examination, and they could further categorize vehicles but not animals at the subordinate level. The authors argued that this

categorization was not perceptually based because infants were able to categorize birds as different from airplanes, despite both types of objects sharing external features. Further evidence for this claim comes from a study in which 10- and 11-month-old infants were presented with animal and furniture replicas that had high between-category similarity and low within-category similarity. Despite the perceptual similarity between animals and furniture, infants still formed global category boundaries similar to those of adults, suggesting a conceptual basis for categorization.⁴²

Several studies have provided evidence for the counterargument that category formation in the object examination task does not differ from visual familiarization and depends on the distribution of features in the familiarization stimuli rather than conceptual knowledge. The asymmetry in the cat and dog categories found using the visual preference procedure has also been demonstrated in 7- and 9-month-old infants with the object examination procedure.⁴³ In addition, infants can use correlations among the perceptual features of the input stimuli to categorize, such that 12-month-olds examine an animal that violates correlations presented during familiarization longer than an animal that is consistent with those correlations.⁴⁴ It has also been shown that category boundaries are determined by the frequency with which infants are exposed to typical versus atypical category members.⁴⁵ At 10 months of age, infants formed separate land and sea animal categories when an exemplar that was similar to the other members of its category was presented on multiple trials; infants failed to do so when the frequently appearing animal was dissimilar. In conjunction, these studies suggest that it remains an open question whether infants’ basis for categorization in object-examining tasks is perceptual or conceptual.

Sequential Touching

In the sequential touching procedure, the infant is simultaneously given multiple objects from two categories—typically four from each class—and is encouraged to play with them for a fixed period of time while touching behavior is recorded. Systematic touching of objects from the same category relative to chance is interpreted as providing evidence for categorization. This procedure can be used to study categorization in infants as young as 10 months of age.^{46,47}

Using those procedure, Mandler and Bauer⁴⁸ found that 16- and 20-month-olds categorize at the *global* level (e.g., dogs vs. cars) but only the older age

group classified successfully at the basic level (e.g., dogs vs. horses). In follow-up experiments, Mandler et al.,⁴⁶ showed that 18-month-old infants categorize at the global level (e.g., animals vs. vehicles) but not at the low or moderate basic-level contrasts within these domains (e.g., dogs vs. horses, dogs vs. rabbits). Two main conclusions were drawn from these data. First, infants' categorization develops in a global-to-basic trend and not the other way round, as first proposed by Rosch and Mervis.^{49,50} Second, infants' ability to form global categories of animals and vehicles must be based on conceptual knowledge of category relations, motion properties, or other nonperceptual cues because animals (and vehicles) look different from one another.

Evidence that infants use perceptual features and not conceptual knowledge to categorize has been provided in Rakison and Butterworth.⁵¹ They found that when 14- and 18-month-old infants were presented with objects from two different global level categories that either shared parts (such as legs in animals and furniture) or had distinct parts (such as legs and wheels in animals and vehicles), they categorized only when objects did not share parts. Furthermore, when half of the animals and vehicles in each category were modified to have parts of the other category (e.g., a tractor with legs; Figure 2), 14- and 18-month-olds categorized according to parts rather than at the global level. A follow-up study revealed that category distinctions were not made on the basis of parts *per se* but on the canonical structure that is generated by parts.⁵² Taken together, these two studies provide evidence that infants categorize on the basis of readily available perceptual features, such as legs and wheels, rather than conceptual knowledge about the motion properties of objects.

The sequential touching paradigm has also been used to demonstrate the flexibility of infants' basis for categorization. Ellis and Oakes,⁵³ for example, found that 14-month-old infants switched from categorizing a set of objects according to shape (balls vs. blocks) to categorizing them according to material (soft vs. hard) after the experimenter tried to compress each object in front of the infant. This effect, however, was found only in infants with high productive vocabularies and those who successfully made global level distinctions between animals and vehicles. This implies that flexibility in attending to different bases for categorization is related to other emerging cognitive abilities.

Inductive Generalization

In this procedure—also known as *generalized imitation*—the infant is first provided with two or more



FIGURE 2 | Example of stimulus used by Rakison and Butterworth.⁵¹ Infants at 14 and 18 months of age categorized such stimuli on the basis of their parts (e.g., legs).

objects (typically scale model toys) and a prop and is encouraged to play with them. Following this baseline phase, the objects are removed and the experimenter models an action with the prop and a novel object that is from the same category as one of the baseline objects. After this demonstration, the infant is once again given the baseline objects and the prop and is encouraged to imitate the action. Infants' choice of object is examined to determine whether they extend the behavior to the within- or out-of-category object. This procedure has been used with infants as young as 9 months of age and children as old as 26 months of age^{17,54,55}.

Mandler and McDonough^{17,54,56} used this methodology to investigate whether infants between 9 and 14 months of age understand that animals and vehicles engage only in category-appropriate actions. They found that infants between 9 and 14 months of age generalized animal properties to novel animals (e.g., drinking from a cup) and vehicle properties to novel vehicles (e.g., starting with a key), and they did so for prototypical (e.g., a car) and nonprototypical category members (e.g., a plane). They also found that 14-month-olds generalized domain-general actions—those typical of both animals and vehicles (e.g., being washed)—to animals as well as vehicles,⁵⁶ though infants first imitated with an exemplar from the same category member as the model exemplar. Finally, to examine the effect of the model exemplar on infants' behavior, Mandler and McDonough¹⁷ used both an appropriate and an inappropriate exemplar to demonstrate an action. Under these conditions, 14-month-olds were more likely to choose an appropriate exemplar than an inappropriate exemplar for their first action. Note,

however, that infants also performed a high number of actions with the inappropriate exemplar. More recently, Poulin-Dubois, Frenkiel-Fishman, Nayer, and Johnson⁵⁷ found that 14-month-olds generalize bodily (e.g., going to bed) and sensory properties (e.g., looking in a mirror) to animals and not vehicles, and that 16- and 20-month-olds extended motion (e.g., jumping over a wall) and sensory properties from a person to other mammals but not to vehicles.

Importantly, Mandler and McDonough^{17,56} proposed that infants' behavior in the task is guided by their conceptual knowledge about category relations. For instance, they argued that infants' imitations 'are based on their conceptual interpretations of what they have observed, not the physical appearance of the items per se.' (Ref 56, p. 37). A number of studies have recently tested this assumption. Furrer, Younger, and Johnson,^{58,59} for example, examined whether infants chose the test exemplar that was perceptually similar to the model exemplar. They found that 14- and 16-month-olds enacted events with an appropriate category member when the experimenter modeled the event with a conventional object (e.g., a bus starting with a key) but used an inappropriate category member when the event was modeled with a counter-conventional item (e.g., a dog starting with a key). In support of this finding, Johnson, Younger, and Furrer⁶⁰—using a different methodology—found that 16-month-olds show no evidence that they understand that actions performed with scale model toys are related to the corresponding real-world actions. Finally, there is evidence that infants' inductive generalization for motion properties is not grounded in conceptual knowledge of category membership but rather the features or parts of the objects that move in specific ways. For instance, using the generalized imitation procedure Rakison³⁶ found that 18-month-olds generalize land motions such as walking or rolling to objects on the basis of parts (e.g., things with legs—including tables—walk), and Cicchino and Rakison⁵⁵ showed that even 26-month-olds generalize goal-directed motion on the basis of such parts. In conjunction, these studies suggest that perceptual features and not conceptual knowledge about categories may act as the basis for induction generalization in infancy.

UNRESOLVED ISSUES

Mechanisms for Categorization: Specific or General?

The preceding review—which only skims the surface of an extensive literature—illustrates that a good deal

is now known about the 'what' and 'when' of infant categorization. At the same time, it also highlights that caution is necessary in the interpretation of a number of findings, particularly in regard to how infants form categories or the mechanism that underpins learning. This is not to say that categorization theorists have found no common ground. They agree, for example, that infants use general mechanisms to categorize such as prototype formation¹⁹ and the ability to extract clusters of correlated features.¹⁴ Theorists also concur that the categories formed in the first months of life—such as those in the visual preference studies by Quinn and colleagues—are likely based on perceptual cues.^{61,62}

There are, however, also widely disparate views about how and when infants learn about, and use as the basis for categorization, category relatedness as well as the less obvious dynamic properties of objects such as motion or action. According to one view, infants possess domain-specific learning mechanisms, principles, or modules that facilitate early learning about these properties of objects and events in the world.^{41,42,63,64} There are two corollaries of this perspective. First, infants have two mechanisms for concept formation, one perceptual and one conceptual; second, infants are precocious concept formers and use conceptual knowledge (e.g., animals are the 'same kind of thing,' animals act as agents) to categorize. According to a second view, infants use general mechanisms—those that are applied across a multitude of domains such as associative learning and habituation—to learn about the static and dynamic properties of things in the world.^{61,65–67}

This theoretical polarity is not uncommon in the study of object concept development, and is ongoing in the domains of math,^{68,69} object physics,^{70,71} and action.^{72,73} We propose that these fierce debates continue—at least within the infant categorization literature but probably in many other areas besides—for at least two reasons. We outline these below.

Infant Categorization Is Context and Procedure Dependent

One problem with interpretation for many categorization studies stems from the fact that infants' performance is highly task dependent. The cognitive demands of the task with respect to memory and attention heavily influence the category boundaries that are formed, and as a result performance in the laboratory may not be indicative of how infants categorize objects in the real-world. For example, visual familiarization procedures can be conducted by presenting single images or pairs of images in succession.

A comparison of category learning under these two methods showed that 4-month-olds were able to form exclusive categories of cats and dogs in the paired presentation only.⁷⁴ One explanation for this difference is that visual preference allows infants to make direct comparisons between two exemplars of a category, thereby reducing the memory load for individual exemplar features.

While infants demonstrate the ability to form basic-level animal categories early in development when tested with the visual preference procedure, similar categorization performance is not achieved in other tasks until much later. Younger and Furrer,⁷⁵ for example, found that 9-month-old infants successfully formed exclusive categories of dogs and horses when the stimuli were presented using visual familiarization, but they failed to do so in the object examination procedure. However, it was found that performance could be equated for the two tasks when the object examination test trials were presented as a pair rather than in succession. According to the authors, infants' attention during physical object examination may be captured by irrelevant features of the familiarization objects (such as texture or weight) that may be shared with the contrasting category. This would lead to a failure to form a category boundary. In contrast, paired presentation of the test stimuli allows infants to make multiple comparisons between the two objects so that they would be more likely to pay attention to the contrasts.

In comparison to visual preference and object examination, categorization in the sequential touching procedure places even greater demands on attention and working memory. Oakes, Plumert, Lansink and Merryman⁷⁶ found that infants categorized animals and people at an earlier age when tested with the object examination procedure as compared to sequential touching because of this additional information-processing load. In the sequential touching procedure, two categories are presented simultaneously and infants must track multiple features that are similar within a category but different across the categories. In contrast, the infant's attention in the object examination task is directed to the relevant similarities of a single group of objects during familiarization to only one category. During the test phase, infants must simply compare their representation of the object features presented during familiarization to those presented in the test phase. Taking these findings in conjunction with those on the distribution of features²⁴ and exemplars⁴⁵ during familiarization suggests that category boundaries that infants demonstrate in these procedures are not fixed; rather, they are formed on-line during the course of the experiment.

There Are No Ground Rules for Interpreting Infant Categorization Experiments

In any domain of psychological study, virtually any data can be interpreted in more than one way. However, in our view it is not uncommon for researchers who study infant categorization—as well as those in the field of object concept development more broadly—to make unwarranted assumptions and overreach their findings in terms of mechanism. There are two general lines of reasoning that often lead to these erroneous conclusions. First, it is often argued that rapid or early learning about object properties must be driven by domain-specific mechanisms. Yet, domain-general learning need not be slow, and there are many experimental findings that show it can be incredibly fast. For example, in visual preference experiments infants at 3 months of age categorize cats as different from dogs with only 12 training exemplars,¹² and by 10 months of age infants form categories based on correlated attributes after only 7 or 8 training exemplars.¹⁴

Second, it is often assumed that if there is no obvious perceptual cue for infants to categorize then they must rely on conceptual knowledge acquired through domain-specific learning. This conduct is particularly rife in infant categorization experiments with scale model toys, in which the basis for categorization is often inferred rather than studied empirically. For example, it was concluded that infants' categorization of animals as different from vehicles in the sequential touching procedure could not have resulted from perceptual similarity—because animals look different from one another, as do vehicles—and it therefore must have been based on conceptual knowledge.⁴⁶ Similarly, it was argued that infants' categorization of birds as different from airplanes in the object-examining procedure must also be based on conceptual understanding because birds and airplanes look alike.⁴⁰ Finally, it was assumed that infants' induction must be conceptually based if they generalize an observed action from, for example, one animal to another.⁴⁰ As we outlined earlier, in each of these cases there is empirical evidence that demonstrates that these assumptions are mistaken.

How are these errors to be avoided in the future? One obvious guideline is that researchers need to eliminate empirically all perceptual bases for categorization before jumping to the conclusion that infants' behavior is conceptually driven. In addition, it is necessary to adopt a developmental approach by studying multiple ages rather than just the one at which infants are capable of categorizing a set of stimuli. Finally, and perhaps most importantly, it is vital to design experiments that can provide insight

into the basis and mechanism that underpins category formation. It is not sufficient to show that infants can form categories for specific stimuli such as cats and dogs; instead, it is imperative to show empirically how they are able to classify these stimuli into distinct groupings.

THE WAY FORWARD: THE ADOPTION OF A MULTIDISCIPLINARY APPROACH

One of the tenets of Cognitive Science is to incorporate findings from a wide range of fields and methods to the study of the mind and brain. We have reviewed in this article a number of behavioral methods for studying infant categorization, which have provided illuminating data about a number of developmental phenomena. In our view, however, the field remains primarily an endeavor of psychology—or more specifically developmental science—and researchers remain wary of integrating research from nonbehavioral methods. We outline here two areas that have recently begun to show their potential with regard to the study of infant categorization, and in particular for the clarification of the mechanisms that underpin it.

EEG/ERP

Event-related potentials (ERPs) are the changes in baseline electrical activity in the brain as measured by an electroencephalogram (EEG) in response to particular stimuli. ERPs are obtained by collecting measurements from multiple locations on the scalp and averaging them over many trials. Waveforms at particular times are assumed to correspond to separate cognitive processes, with waveform information reported in terms of polarity and latency.⁷⁷ Although ERPs allow for the study of brain processes that do not have a directly observable behavioral component, there are multiple disadvantages in using ERPs with infants.⁷⁸ Infant ERPs are highly variable and change rapidly with development, thereby making comparisons between infants of even slightly different ages difficult.⁷⁷ In addition, infant ERP patterns are difficult to compare with the current findings for adults because of the greater latency as well as polarity inversion that occur for some waveforms.⁷⁸

ERP studies with infants have started recently to isolate distinct waveforms for different phases of the categorization process. Quinn, Westerlund, and Nelson⁷⁹ familiarized 6-month-old infants with 36 cat images, followed by a mix of 40 novel cat and novel dog images. The EEG data revealed three waveforms. First, there was a negative slow wave (NSW) recorded

for initial presentations of cats and dogs, indicating the infants' representation of a novel basic-level category. Second, a negative central component was recorded during the presentation of dogs after infants were familiarized with cats, indicating the detection of a contrast category. Finally, a positive slow wave (PSW) was recorded during the first half of the familiarization with cats only, indicating the formation of a global category—that included novel cats and dogs—during the second half of the familiarization phase. The PSW was recorded 200 ms prior to the NSW, indicating a global-to-basic categorization pattern.

EEG recordings have also been used to examine the organization of word categories in infants. Torkildsen and colleagues⁸⁰ presented 20-month-olds with images of objects along with a verbal label for the objects; the label was either correct, incorrect but from the same global category (within-category violation), or incorrect but from a different global category (between-category violation). A negative waveform of greater amplitude and earlier onset was found for the between-category violation as compared to the within-category violation for the recordings over the left hemisphere; a negative waveform was present in the recordings over the right hemisphere for the between-category violation only. For both the between- and within-category violations, the negativity was greater for the correct label. Based on these findings, the authors conclude that by 20 months infants have organized words into semantic clusters, such that label violations within the same global level cluster lead to less negative waveforms than violations between clusters. These studies provide evidence for the various components of the categorization process that may not—or cannot—be directly evident from behavioral observation. They are an excellent demonstration of how brain imaging studies with infants can, if used appropriately, provide insight into the mechanisms of categorization.

Computational Modeling

The rationale for creating a computational account of a theory is that it forces the researcher to make explicit the hypotheses of the theoretical account.⁸¹ In addition, computational models often generate concrete predictions that can be tested empirically, which in turn can unify incongruent findings under a shared framework (for a discussion, see Ref 82). Note that although a computational model is only a sufficiency proof—it shows whether particular theoretical assumptions can (but not do) lead to observed patterns of behavior—it offers cognitive scientists with a more explicit way of formulating and testing their theories about mechanism.

There are a number of notable implementations of parallel distributed processing (PDP) models that have advanced researchers' understanding of early category development. Mareschal and colleagues,^{83,24} for example, used a PDP model to show that young infants' categorization of cats and dogs, as described by Quinn et al.,¹² can be explained by bottom-up associative processes and is based on the feature values of the stimuli. Similarly, Cohen, Chaput, and Cashon⁸⁴ showed that information-processing principles implemented in a PDP architecture can explain how infants learn about and categorize causal events. Finally, Rakison and Lupyan⁶⁶ showed that general learning processes are sufficient to account for how and when infants form categories on the basis of correlations between object features and how those objects move in the world. These studies demonstrate that computational modeling can offer infant categorization researchers something that behavioral studies cannot, that is, a way to address and test ideas about mechanism.

CONCLUSION

In this article, we have reviewed a number of key findings in the infant categorization literature with the aim of demonstrating both the consensus and lack thereof that exist within the field. Researchers have made considerable headway in the relatively short time that the appropriate methodologies have been available; yet a number of key issues—particularly, in our view, relating to mechanism—remain hotly debated. We have suggested a number of reasons why these issues remain under debate. Most notably, in our opinion it is the failure of many developmental scientists who study infant categorization to adopt the tools and approach of Cognitive Science. We believe that this is the way forward for infant cognition researchers, and it is only when this transition occurs that cognitive scientists will have a coherent and cohesive understanding of the what, when, and how of infant categorization.

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