Reproducibility and a Unifying Explanation: Lessons from the Shape Bias

Sarah C. Kucker; Oklahoma State University

Larissa K. Samuelson; University of East Anglia

Lynn K. Perry; University of Miami

Hanako Yoshida; The University of Houston

Eliana Colunga; The University of Colorado Boulder

Megan G. Lorenz; The University of Iowa

Linda B. Smith; Indiana University

Authors Note

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Abstract

The goal of science is to advance our understanding of particular phenomena. However, in the field of development, the phenomena of interest are complex, multifaceted, and change over time. Here, we use three decades of research on the shape bias to argue that while replication is clearly an important part of the scientific process, integration across the findings of many studies that include variations in procedure is also critical to create a coherent understanding of the thoughts and behaviors of young children. The "shape bias," or the tendency to generalize a novel label to novel objects of the same shape, is a reliable and robust behavioral finding and has been shown to predict future vocabulary growth and possible language disorders. Despite the robustness of the phenomenon, the way in which the shape bias is defined and tested has varied across studies and laboratories. The current review argues that differences in performance that come from even seemingly minor changes to the participants or task can offer critical insight to underlying mechanisms, and that working to incorporate data from multiple labs is an important way to reveal how task variation and a child's individual pathway creates behavior—a key issue for understanding developmental phenomena.

Keywords: reproducibility, shape bias, task effects, word learning, individual differences

Highlights

- Individual experiments and replications form the basis of scientific inquiry, but limits inherent in a single result only advance science so far.
- We advance science through deep, unified understanding of phenomena, gained through integrating across multiple studies.
- Here, we highlight four lessons for science, using the shape bias as an example.
- Valid conclusions require attention to, and unified explanations of, *all* the data.

Reproducibility and a Unifying Explanation: Lessons from the Shape Bias

What is the goal of science? Science is not simply about experiments; it is about gaining knowledge. It is about building deep, coherent, and unified explanations of multiple phenomena. Such explanations allow control and prediction of outcomes in new experiments; they provide new understanding of old findings and support the mining, and comprehension, of old data. The best explanations, however, do more than this—they make connections to new domains, allowing control and prediction in translation, whether in medicine, in teaching, or in engineering. What role does the replication of individual experiments play in all this? All scientific progress relies on our faith in the phenomena and the effects to be explained because science is incremental, with new advances building on and incorporating the past. Thus, our conclusions from individual experiments must be valid. In psychology, there are increasing suggestions that what we have previously taken to be foundational findings are not replicable. But how do you know which findings—the old or the new—are closer to the truth? Replication and open science approaches—which make the data and procedures available to everyone— are two useful and, we suspect, field-changing approaches (Open Science Collaboration, 2015; Klein et al., 2014; Zwaan, Etz, Lucas, & Donnellan, 2017). But there is a third approach, which fits with the larger goal of science itself and, we believe, needs continued attention and emphasis - a holistic, integrative approach.

Our aim in this essay is to elevate the current discussions and emphases on reproducibility back to the level of the goal of science. We argue that the larger goal of science is not really about individual experiments or about the ability to exactly reproduce the results of other laboratories. Precisely redoing experiments may cull bad experiments but does not advance nor expand the dataset that must be explained. Accordingly, we ask how we should think about experiments—their individual results and their individual conclusions—in the context of building a larger, more valid, more coherent understanding of developmental science, and how doing so will assist other efforts to ensure that our science and our conclusions are on solid ground. We examine this question through an example case: 30 years of data on the shape bias. We compare older and newer findings and discuss how explanations of the bias and our understanding of the underlying cognitive processes have evolved and changed—not by throwing out data, but by seeking an all-encompassing explanation that remains coherent. We believe continued emphasis of this larger goal offers a third essential approach to replication and open science initiatives.

Examining "best practices" through 30 years of research on the shape bias

Experiments often begin with a question or hypothesis. For example, one might propose (as was once suggested, MacNamara, 1972, 1982) that very young children know from the start of word learning that nouns refer to objects. What experiment would test that idea? There are lots of choices, and many critical gaps in our expertise. As we all learned in Experimental Design 101, we need to operationally define our terms—"know", "noun", "object". We need to determine which experimental factor can be manipulated so as to provide insight into the causal factors implied by our hypothesis. As developmentalists we need to decide which age or level of children to test. Finally we need an experimental task that the population we have chosen can do and that provides easily interpretable dependent variables. Since the conceptual hypothesis is about "knowing at the start," we might do a quasi-experiment manipulating age or vocabulary. We decide on a task that is close to the real-world behavior in question: We will provide a noun (a name) or an object (an individual, solid, 3-dimensional entity) and then ask children which other objects can also take that name ("Which is a dax?"). We will define "knowing" as being able to systematically apply the new name to other objects in a way similar to adults. We will also test that this is really about "nouns" by using the same objects in a no-name version of the task wherein children (and adults) are asked which things are "alike." We will use novel objects so as to equate participants' prior experience with the specific stimuli. Clearly, the choice of test objects for generalization is critical. Recent work (at the time) had suggested that many basic-level categories are organized by similarity in shape (Rosch, 1973) so we will include test objects that match in shape, but also other perceptual properties such as material or color (see Figure 1).

The experimental hypothesis for the first shape bias experiment was thus: Children at the earliest stages of word learning will, like adults, generalize novel names systematically and exclusively to test objects that match the named exemplar's shape, but will be less systematic when the objects are not named. The finding was that by around 2 years of age children systematically generalize the object name to the same-shaped test object rather than the same-material or same-size object. This result was initially interesting because it showed that children have expectations about the kinds of categories to which object names refer. However, there are many grounds on which to attack this experiment and the conclusions. Is generalization by "shape" really what it means to know a noun or an object? The current answer is probably "no," and there are many studies with results indicating that those original results are not replicable, such as when using other definitions of object (Davidson & Gelman, 1990; Gelman & Markman, 1986), other kinds of nouns (Hall, 1991), and other control comparisons (Cimpian & Markman, 2005; Diesendruck, Gelman, & Lebowitz, 1998; Gelman & Bloom, 2000; Kemler Nelson, 1995; Kemler Nelson, Russell, Duke, & Jones, 2000). Did the way we asked children the question influence the outcome? There are many studies showing that the answer to this is "yes" (see lesson 2 below). Were the effects sizes robust, was the sample size big enough, were the statistical tests powerful enough? The answer is “no” to these in today’s terms (see Oakes, 2017, for similar cases).

Not surprisingly, in the early days of the shape bias, there were a number of contrasting hypotheses, arguments, and claims about its meaning and basis. In the 30 years since the original finding by Landau, Smith, and Jones (1988), however, the combined evidence has made clear that not only is children’s tendency to pay attention to shape when learning new names a robust experimental effect, it is strongly linked to the processes of word learning outside of the lab at the level of both individual children and groups of children. Specifically: (1) the shape bias is better predicted by a child’s productive vocabulary than by age (Gershkoff-Stowe & Smith, 2004; Perry & Samuelson, 2011; Samuelson & Smith, 1999); (2) within individual children, the emergence of a robust shape bias co-occurs with an acceleration of new nouns in his/her productive vocabulary (Gershkoff-Stowe & Smith, 2004); (3) experimentally teaching young children a precocious shape bias increases the rate of noun vocabulary growth outside of the laboratory (Perry, Samuelson, Malloy & Schiffer, 2010; Samuelson, 2002; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002); and (4) children who are delayed in early language learning, late talkers (Jones, 2003; Jones & Smith, 2005; Colunga & Sims, 2017), children with Specific Language Impairment (Collisson, Grela, Spaulding, Rueckl, & Magnuson, 2015), and children with Autism Spectrum Disorder (Potrzeba, Fein & Naigles, 2015; Tek, Jaffery, Fein, & Naigles, 2008) do not show the same shape bias seen in children on the more typical vocabulary development trajectory. Clearly, performance in these artificial noun learning experiments measures something that matters to everyday word learning and, in particular, to object name learning. In fact, the accumulated research suggests that the shape bias has connections beyond the scope of the initial hypotheses—it is probably not just about the meaning of “nouns” or the meaning of “objects.”

These points notwithstanding, we also know that the bias children demonstrate in experimental tasks is subtly but informatively linked to the exact way an experiment is done. The results depend on all those specific decisions that experimenters make in trying to test their not-totally-right conceptualization of the problem (Zwaan et al., 2017). But our understanding of the shape bias, what it says about object noun learning and learning in general, is advanced by trying to understand *all* the data—the subtle effects of different methods, the seeming non-replications given slightly different experimenter decisions, and the cases where there were no reliable effects. We believe there are larger lessons here for developmental science. Below we examine the accumulated literature on the shape bias, proposing four “best practice” lessons it suggests for infant work: 1) Examine multiple factors and multiple paths, 2) Pay attention to the task, 3) Balance individual differences and generalizability, and 4) Be inclusive and play well with others outside your main domain of inquiry. These lessons are highlighted across multiple studies examining children’s generalization of novel nouns by similarity in shape. These studies show that the shape bias arises out of the interaction of a child’s early experience with systematic input from multiple domains, leading to individual differences which interact with the *immediate* task context. We argue that seeing this higher-order, coherent big picture only comes from appreciation of *all* the individual experiments.

Lesson 1: Examine multiple factors and multiple paths

Individual experiments are not enough to give us big picture understanding in science because causes are complex. This is certainly true in cognitive development. There is not one single cause for each behavior, nor even a sole pathway by which all children develop. For example, children learn to walk in very different ways, some crawl first, some just stand up, some cruise. These are not irrelevant variations but different trajectories of development that influence and depend on individual changes in physiological structures, and also on cognitive and perceptual processing of the environment, neurological advances for coordination and balance, likely some encouragement from mom and dad, and a lot of practice (Thelen, 1992). Indeed, even a single individual does not walk in exactly the same way every time; a skilled walker can flexibly adapt to terrain, shoes, slopes, and obstacles (Adolph, 2008). Learning a word or recognizing a referent also has different routes. We can recognize a dog from a silhouette of its shape, from a caricature (as in a cartoon dog), from a simple 3-dimensional model, or from a paw sticking out from a blanket (Smith, 2003). Not all of these involve shape. In the early days of shape bias research, the phenomenon was often countered by individual experiments showing that there were contexts in which young children did not attend to shape when mapping a known noun or generalizing a novel name to new instances (Gelman, Croft, Fu, Clausner, & Gottfried, 1998; Gelman & Markman, 1986; Prasada, Ferenz, & Haskell, 2002; Waxman & Namy, 1997). Rather than arguing about which set of findings is correct, really understanding children's noun learning requires understanding why and how changes in method yield different results.

After many more experiments, we now know at least this: Early in word learning, around the first birthday, when children are just beginning to produce object names, they rely heavily on category specific features and parts to recognize objects—duck bills, cat whiskers, the wheels on cars (Rakison & Butterworth, 1998; Smith, 2003, 2009). Learning to abstract the 3-dimensional shapes that characterize object categories emerges later in development, closer to age 2 or so, after a robust vocabulary has developed. The development of a shape bias depends on adding this shape-based pathway to visual object recognition (Pereira & Smith, 2009; Smith, 2003, 2013; Yee, Jones, & Smith, 2012). However, we also know that being skilled at object recognition means having more than one path from stimulus to recognition, and critically, each of these paths have their own developmental course. Further, data now suggest that some paths to visual object recognition, and thus the shape bias, are more likely to falter in children with atypical language development (see lesson 3 below; Jones & Smith, 2005). We also now know, precisely because there are multiple paths to visual object recognition, that children (and adults) are more likely to attend to shape when generalizing a name for a novel category than for a well known one (Cimpian & Markman, 2005; Gelman et al., 1998; Waxman & Namy, 1997; Yoshida & Smith, 2003b). We now know that the shape bias is more about the first stage of learning an object name—the first best guess about the category. We end up knowing a lot more about cups, about purses, about pickles than just their characteristic shape (Gelman & Markman, 1986). No one experiment—showing or not showing a shape bias—can tell us all this. No set of experiments that keep reproducing the very same results can tell us all this. Rather, this larger understanding results from the accumulation of multiple studies, examining multiple pathways and multiple factors.

There are also multiple routes and complex developmental pathways on the language side and multiple ways in which language directs the learner's attention to some properties over others upon hearing an object name. All the nameable things in the world differ in a variety of their properties—solidity, holdability, moveable parts, size, complexity, and stability of shape. Languages often talk about these properties in different ways, creating more and less systematic correlations between the words and syntactic frames used to label and talk about an object and the likelihood that shape is important in recognizing instances of a category. In the early research, with its focus on single causes, syntactic frames were pitted against perceptual properties (Soja, Carey, & Spelke, 1992), and children learning different languages were compared in the search for universal and language specific effects (Barner, Li, & Snedeker, 2012; Colunga, Smith, & Gasser, 2009; Gathercole, Evans, & Thomas, 2000; Gathercole & Min, 1997; Imai & Gentner, 1997).

These data sets are rich and complex, showing some strong and nuanced effects and many interactions between the language being learned, the words used by the experimenter in labelling an object, and the perceptual properties of objects. We know that the syntactic context in which a novel word is presented to a child alters their subsequent decisions about the generalizability of that novel label. A count noun (e.g., "*a* dax") leads a child to generalize to a shape-matching item, regardless of whether the items are solid or non-solid (Soja, 1992). A mass noun (e.g., "*some*" dax), however, will bias an English-speaking child's attention toward material only if the objects are non-solid substances (Colunga & Smith, 2005; Landau et al., 1988; Subrahmanyam, Landau, & Gelman, 1999). In the English language, though, count nouns often refer to items that are organized in the world by shape, such as cups, tables, and chairs. Mass nouns on the other hand, identify items that are not countable in the same way and are used with objects that are typically organized by similarity in material, such as oatmeal, sand, and milk (Samuelson & Smith, 1999). The variations seen across studies that defined "noun" and "object" in different ways, revealed the nuanced fit between children's generalization behavior and the language they are learning outside the laboratory. In this way, then, one can start to see how disagreements about the "shape bias" may be understood as reflections of children's learning about the statistical regularities in language and in the visual world. These regularities create contextually sensitive and nuanced – smart – biases in learning and interpreting nouns. These insights require that we not reify tasks nor definitions, and remind us that even when we do everything right and the statistics are right, the findings from one method cannot provide us with a complete understanding of a phenomenon. Evidence for this nuanced intelligence is also evident in studies that pushed the definition of “object” to the boundary between things and animals, and in cross-linguistic comparisons of the generalizations produced by children whose languages differed in the regularities used to mark that boundary. These studies highlight how different kinds of cues—language, perceptual, and contextual—interact to direct children’s attention and determine the nature and strength of their bias. Specifically, 2-year-old English-learning children attend to shape even when extending names for objects with perceptual cues suggestive of animacy (e.g., shoes, rounded body, googly eyes; Jones & Smith, 1998; Jones, Smith, & Landau, 1991; Yoshida & Smith, 2001), but 3-year-old English-learning children find shape sufficient only when extending names for objects presented *without* features suggesting animacy (Jones & Smith, 1998; Jones et al., 1991; Ward, Becker, Hass & Vela, 1991; Yoshida & Smith, 2001). Instead, older children extend names for objects with animacy cues conservatively to instances that are similar to the original exemplar on multiple properties including shape and texture.

In contrast, 2-year-old children learning Japanese attend not just to shape, but shape and texture when extending names for objects that have animacy cues (Yoshida & Smith, 2001). This matches the linguistic features of Japanese which does not have the pervasive count/mass distinction seen in English but rather offers pervasive linguistic cues predictive of an animate-object distinction (i.e., *iru/aru* distinction). Furthermore, these cross-linguistic differences in name extensions by English-speaking and Japanese-speaking children with animate-inanimate perceptual cues correspond to vocabulary differences reported by parents. Japanese-speaking children with more balanced vocabularies between animate and inanimate names seem to know more about the different organizations that characterize animal versus object categories (Yoshida & Smith, 2001).

Finally, the strength of the connection between the child's language knowledge and perceptual cue use depends not just on the relatedness of those two cues but also on all the other cues to which they are related. Japanese-speaking children presented with objects that had minimal perceptual cues suggestive of animal categories (i.e., 4 short pipe cleaners that could be seen as limbs), and with the corresponding animate-object linguistic cues (i.e., *iru/aru*), extended new names more narrowly (Yoshida & Smith, 2003a). Their generalization exclusively to test objects that matched in both shape and texture suggested that they interpreted the objects as depictions of animals. In contrast, English-speaking children presented with the same stimuli formed a broader category based on shape, a pattern consistent with the interpretation of the objects as artifacts.

These variations within and across studies suggest that the degree of early attention to shape reflects learned correlations among perceptual properties of things in the world, category structures, language structure, vocabulary, and immediate in-task cues; all indicating potential developmental processes through which the shape bias and category knowledge may emerge. To some, these studies are evidence that the shape bias is not universal as the size of the effect (attention to shape) varies across populations, contexts, stimuli, and task. However, we view these "non-replications" as fitting with a larger body of work demonstrating that human learners are sensitive to the statistical regularities in their learning environments. They show that the statistical regularities experienced between heard words and visual attention are particularly powerful across development. Thus, the shape bias—and its variants—is one highly relevant real-world example of how such naturalistic statistics of the learning environment enable words to guide visual attention across many contexts (Altmann & Kamide, 2009; Benitez & Smith, 2012; Darby, Burling, & Yoshida, 2014; Eberhard, Spivey-Knowlton, Sedivy, & Tanenhaus, 1995; Goldenberg & Sandhofer, 2013; Neider & Zelinsky, 2006; Torralba, Oliva, Castelhano, & Henderson, 2006; Vales & Smith, 2015). But this larger picture is only seen when we extend our view of the shape bias past the original question and findings to examine connections, explore boundary conditions, do experiments in different ways, and, when results do not come out the way we expected, determine why by taking *all* the data seriously. Focusing on single experiments, rejecting or not rejecting a single null hypotheses, *will not get us what we need to know*. We create experiments under the guise of testing hypotheses, and yes we should all adhere to best practices in doing so. But we also need to acknowledge that given our imperfect understanding of the complex phenomena we investigate, the best we can do in these experiments is probe the world, and hope it will give us back clues from which to form better hypotheses. Thus we need to listen carefully to *all* that it tells us as we strive for more complete and unified understandings.

Lesson 2: Pay attention to the task

As experimenters, we design our tasks with at least two different requirements in mind: 1) the operationalization of stimuli, conditions, and measures with respect to our conceptual hypotheses and 2) the construction of a task context that is understandable to the young child. The latter requirement is fraught with problems and has been the subject of fruitful discussions in the field since its inception (see Frank et al., 2017). However, these discussions tend to start from a view that the experimenter's goal is to find the right task that correctly taps into children's knowledge. What is underappreciated is how the multiple seemingly small decisions we make as experimenters actually shape children's behavior and subsequent demonstrations of their knowledge (see also, *Infancy* special issue, 2017; Frank et al., 2017). Imagine this: you are a 2-year-old child brought to a strange place with tables and cameras and nice people you don't know who show you funny toys you've never seen before and use strange words you've never heard before. They hold a simple object made of sponge up and say "This is my dax. Can you find your dax?" What do you do? It is likely that you use whatever cues you can find. Some may be what the experimenter had in mind, others may not be. Perhaps the experimenter holds up a second object made of the same material but a different color and different shape. She says "Is this a dax?" It matches in material so you say "yes." She then holds up another object that is made of wood but is the same shape as the object she originally named; "Is this a dax?" You again say "yes." Both objects match the named exemplar in some way, so why not? But what if she had instead named the first object and then presented both the material and shape matching test objects at the same time, saying, "Can you get the dax?" Now you have to pick. You have to decide: Is shape or material more important for daxes?

The literature reveals that children do not demonstrate the same biases in these two cases. Children learning the same language, who are the same age, and have the same-sized vocabulary generalize novel names for deformable things more narrowly—by shape—in forced choice tasks and more broadly—by shape or material—in yes/no tasks (Samuelson, Horst, Schutte, & Dobbertin, 2008; see Landau et al., 1988, for related results). Furthermore, a computational model of these data suggests differences in the underlying decision processes that are created by the interaction of the stimuli in the task (Samuelson, Schutte, & Horst, 2009). One could ask which task better taps children's underlying knowledge or competence. But human competence lies in its adaptive ability to adjust to context, to smartly integrate multiple sources of information, and not simply to do the same fixed thing over and over. And young children are remarkably adept at this. Children's behavior in an experiment is tuned by all the subtle details of the experiment--the kind of question, the syntactic frame, the contrasting stimuli, who is asking the question, etc. Some of these we explicitly manipulate to test our ideas, but children do not know what factors are the manipulations they should attend to and what are the irrelevant details. They just respond (if we're lucky), based on any and all available cues. For instance, Samuelson and Horst (2007) demonstrated that how you tell the child what the game is during the warm-up trials can change the biases they demonstrate. If the experimenter started the task for one child by presenting a rubber duck, saying "see my duck", and then asking the child to "get your duck," from a selection of a matching duck and a red wooden block, that child is likely to think that shape is the critical factor when presented with novel objects on subsequent trials. In contrast, a child presented with several small balls of blue PlayDough, and then asked to get her PlayDough from a selection of several other balls of PlayDough or balls of peanut butter, is more likely to attend to material substance on subsequent novel noun trials (Samuelson & Horst, 2007).

Even decisions about more removed aspects of the experimental context, such as the chair a child is seated in, can affect a child's behavior and subsequent generalization. A context (such as a highchair and bib) that encourages messy play with non-solids will direct attention to material substance and reduce shape choices. This is because the majority of non-solid substances children learn to name early, name foods (e.g., applesauce, milk), and what children learn about material and generalization is initially constrained to, and supported by, the mealtime context. When 16-month-olds sit in a highchair in the laboratory, the same context in which they typically learn about non-solids and material at home, they are more likely to messily explore and touch the stimuli, subsequently showing more of a material bias than their peers seated at a more standard laboratory table (Perry, Samuelson, & Burdinie, 2014). Much like the case of syntax and perceptual cues in lesson 1, children here are learning about the statistics of their world. Nearly every time children are in their highchairs, they will encounter a material-based substance (food). In many of these cases, they will also hear associated labels (e.g., applesauce) and those associated labels will more than likely be presented along with a mass noun ("Here's *some* applesauce.").

Children are smart and adaptive. Explaining human cognition requires understanding this, and understanding this requires taking all the data seriously, including when we cannot reject the original null hypothesis. Thus, we should not reify tasks. Instead, we should reject the notion that there is only a single way to experimentally test an idea. If we do not, then we are just studying the task and not the underlying processes that we want to understand. The tasks we choose are the path to understanding human intelligence.

Lesson 3: Balance individual differences and generalizability

Development and human intelligence emerge from complex interactions. Different pathways to knowledge (lesson 1) merge with the unique particulars of the immediate context or task to activate knowledge (lesson 2), forming the basis of learning itself. But as variation across tasks is meaningful so is variation across individuals—this variance, however, limits effect sizes and reproducibility. One thing that we as experimenters do—that could be encouraged by the focus on replication—is to actively and purposely create tasks that *reduce variability among* *children* in order to increase the reproducibility of results. We try to find tasks that make all children perform the same way. Is this really what we ought to do?

One individual difference that is particularly relevant to the shape bias is children's vocabulary as measured by parent report (Fenson et al., 1994). Vocabulary varies greatly both in size and content across individual children and is strongly predictive of concurrent behavior in many tasks and in future outcomes, including success in school (Duff, Reen, Plunkett, & Nation, 2015; Morgan, Farkas, Hillemeier, Hammer, & Maczuga, 2015). For both typically and atypically developing children, novel noun generalization is better predicted by vocabulary size then by age (Samuelson & Smith, 1999; Colunga & Sims, 2017). Late talking children, those who are significantly delayed in their productive vocabulary (e.g., below the 30th percentile in age norms for expressive language), show either a very weak shape bias or even a strong texture bias (Jones, 2003; Jones & Smith, 2005). These children also fail to recognize abstract shape caricatures of highly familiar objects in contrast to typically developing children who succeed (Jones & Smith, 2005), a finding that can indicate both disrupted visual object recognition as well as delayed lexical learning.

How are we to understand these differences? The texture bias shown by some late talkers does not reliably characterize the group as a whole. Should we ignore it as an oddity (despite the fact that this oddity repeatedly shows up in a non-reliable subset of children)? If this was not discovered by first forming a testable hypothesis and experimentally rejecting a null hypothesis, can we even think about it? This unique finding in a subset of late talkers may be deeply informative, both about why some children falter in building early noun categories and about how all children learn object names. If the shape bias is the product of learning—aggregations over the statistical structure of individual experiences—then the object names and categories an individual child learns will matter. A number of studies have shown that the individual structure of children's noun vocabulary predicts how they generalize newly learned object names to new instances (Colunga & Sims, 2017; Perry & Samuelson, 2011; and see e.g., Perry, Axelsson, & Horst, 2016). Although the average vocabulary is dominated by the names of solid objects in categories organized by similarity in shape (e.g., ball, chair), some children happen to know more names for solid objects in categories organized by similarity in material (e.g., chalk, ice). The more of this latter type of words children know, the less likely they are to show a shape bias and the more likely they are to show a material bias for novel solid objects (Perry & Samuelson, 2011). This relation between vocabulary structure and word learning characterizes both ends of the language proficiency spectrum—late talkers and early talkers (Sims, Schilling & Colunga, 2013; Colunga & Sims, 2017). Late talkers and early talkers have vocabularies dominated by names of solid categories organized by similarity in shape, but late talkers also know plenty of names for non-solid substances organized by similarity in material. Correspondingly, both the late talkers and early talkers show a robust shape bias for solids, and early talkers also show a material bias for non-solids (Colunga & Sims, 2017). For individual children, there is a fit between how they generalize novel labels and the nouns they already knew.

There are many other informative examples (Perry & Saffran, 2017; Perry et al., 2010) including training experiments that altered the individual trajectories of individual children with long term outcomes on their later developmental trajectory (Smith et al., 2002; Samuelson, 2002). Because the shape bias is a product of the individual's learning history and because different cultures and languages present the learner with different statistical regularities, there are marked cultural and language effects in the development of the "shape bias." These differences show the multiple pathways to the same knowledge (lesson 1) and the interactive effects of different kinds of information (and task effects; lesson 2), as well as the effects of the long term developmental history of the child (lesson 3). This is seen when the count/mass and object/substance distinction seen in English-speaking children is compared to the regularities provided in Japanese. Originally, the question of interest in these cross-linguistic comparisons was whether there were underlying universal differences or not (Imai, Gentner, & Uchida, 1994). But the experiments (Yoshida & Smith, 2003a, 2003c, 2005) show many similarities and differences across cultures, perhaps best explained in terms of a consortium of linguistic (this is a__, some__, *iru*, *aru*) and perceptual cues (e.g., wearing shoes, having eyes, being angular), and the category organization patterns (e.g., similarity in shape). One could view all these interactive effects as just a mess or as a non-replication of a single conclusion. Or, one could look for a higher-order, coherent explanation that unifies across these studies and finds support for a single causal mechanism: interactive integration and differential weighting depending on the strength of the statistics provided by the language environment. This explanation has been supported by training experiments that shifted the statistical strength of some cues to category structure over others (Yoshida & Smith, 2005) and by studying children who learn English in different environments, for example bilingual vs. monolingual (Brojde, Ahmed, & Colunga, 2012).

The lesson is this: Each child develops as an individual, on their own journey, through their own set of experiences and intrinsic differences. Psychology is not yet at the point that we can explain or predict all individual patterns of development, but surely that is where we should be headed.

Lesson 4: Be inclusive and play well with others

Developmental change is multiply determined, the aggregate product of many nested processes operating over many time scales and interacting across many levels of analysis (from genes, to parent behaviors, to the language environment, and to social groups). Because of this, there is nontrivial causal spread in which seemingly unrelated systems play influential, critical, modulating or permissive roles in the development of other systems (Smith, 2013; Smith & Thelen, 2003). In the case of the shape bias, we now know that non-linguistic factors such as hand-eye coordination, sleep, and cognitive control both affect and are affected by language development.

Early eye-hand coordination in object play sets the stage for (and predicts) later word learning (Iverson, 2010; James, Jones, Swain, Pereira, & Smith, 2014; James, Jones, Smith, & Swain, 2014; Yu & Smith, 2012). Toddlers' handling of objects generates dynamic and sequenced visual information about shape (Pereira, James, Jones, & Smith, 2010), changes the way children perceive the shapes of things (Smith, 2007) and may play a crucial role in an early stage of visual learning, essential to showing the shape bias in the experimental task. Recent findings from separate areas of research may be related: infants at risk for or diagnosed with ASD show atypical object manipulation and hand-eye coordination (Koterba, Leezenbaum, & Iverson, 2012). Object manipulation segregates objects from scenes and teaches the visual system about 3-dimensional shape (Farivar, 2009; Graf, 2006). The representation of the abstract 3-dimensional geometry of multi-part shapes depends on the visual experiences generated by actively handling and looking at objects (Bushnell & Boudreau, 1993; James et al., 2014; Yu, Smith, Shen, Pereira, & Smith, 2009). The shape bias depends on aggregating over these more abstract 3-dimensional representations (Smith, 2009). Thus, the connective hypothesis is that atypically developing children with atypical sensory-motor coordination patterns may not develop a shape bias because they do not generate the quantity or quality of dynamic visual experiences upon which robust 3-dimensional object representations, and aggregations across those representations, depend. This hypothesis is based on a deep understanding of the visual-learning side of the shape bias but only comes about when we take a wider perspective and seek to understand how data from seemingly different domains play together.

In another example, sleep patterns (both those deriving from the intrinsic dynamics of the developing child and those resulting from chaotic parenting) play a causal role in the development of the neural systems underlying behavioral control (e.g., Goodnight, Bates, Staples, Pettit, & Dodge, 2007). Sleep patterns also play a role in supporting consolidated but abstract memories, the kinds of memories that support generalization (Werchan & Gomez, 2013; Williams & Horst, 2014). Moreover, sleep interacts with hippocampal processes and by newer accounts, the operations of the two complementary systems that rapidly form specific memories versus slower more abstract and generalizable memories (Schapiro, Turk-Browne, Botvinick, & Norman, 2016). These advances would seem to have direct implications for why children in some novel word learning tasks do well when asked to find the referent of novel names, but show no generalizable or long term knowledge (Horst & Samuelson, 2008; McMurray, Horst & Samuelson, 2012); why repeated experiences of word and objects are critical at first (Horst, Parsons, & Bryan, 2011); and why pre-familiarization with the visual objects supports long term retention (Kucker & Samuelson, 2012).

Finally, the multi-causal nature of language means it also plays a well-documented role in cognitive control (Bohlmann, Maier, & Palacios, 2015). Young children and adults with language impairments have difficulties with nonlinguistic tasks that require them to selectively attend to some task-relevant information to the exclusion of some task-irrelevant information.

When typically developing adults engage in verbal interference (Lupyan, 2009) or undergo noninvasive brain stimulation over cortical areas associated with verbal labeling, but not cognitive control processes (Perry & Lupyan, 2013; 2014; 2016)—in other words making it difficult for them to use language—they too have difficulty selectively attending to relevant information. Conversely, making it easier for children to use language by presenting labels in otherwise nonlinguistic tasks helps children selectively attend to relevant information (Perry & Samuelson, 2013). When children hear the name of the target prior to search in a visual search task, they are faster to locate the target then when they see a picture of what they are looking for (Vales & Smith, 2015). Having children label pictures in a dimensional change card sort task makes them better able to switch and attend to relevant dimensions (Kirkham, Cruess & Diamond, 2003).

In these cases, and in the case of the shape bias, hearing words directs attention and they do so because of past co-occurrences and predictive relations between what we hear and what we visually attend to (Brojde, Porter, & Colunga, 2011; Perry & Lupyan, 2014). This is because even as the child is learning language, she is building statistics not just about the words or referents in the world, but about multiple variables (lesson 1), the context and setting (lesson 2), and her own and others' behaviors in response to each experience (lesson 3). This accumulation of statistical relations builds on a larger network of knowledge that goes beyond language. The data reviewed here highlight a potential causal role for word learning in the development of cognitive control brain networks--especially in light of increasing evidence that the development of cognitive control depends on long reaching brain networks, rather than simply frontal lobe maturation (Buss & Spencer, 2017; Fair et al., 2007). In brief, the shape bias is not just about nouns or objects. It is about how our whole system works—memory, attention, object recognition, statistical learning—and should inform and be informed by advances in all those areas of research.

For all phenomena, not just the shape bias, we can be more confident that our conclusions are right when they fit into current findings and advances in the whole of our science. The larger point emergent from this and the three prior lessons is that the complexity and multiple timescales of biological development, and the complexity and multiple timescales of learning and behaving in a real world, gives rise to a tangle of inter-related causes and effects that require multiple measures, large data sets, and analytic approaches beyond a single experiment, beyond a rejection of a single null hypothesis. To understand development, we need to go both deep and wide. We need to integrate data from multiple studies that vary in the depth of their details—different tasks, with different definitions of the main variables, and we need to test children of different ages, from different cultures, language backgrounds, and abilities. And we need to connect widely and play with others by paying attention to advancing findings in other domains and at other levels of analysis than our own. We need to help integration and translation by formulating our hypotheses and the measures in our experiments in terms better defined and more defensible than folk-psychological terms. This work goes beyond replications of a given study (though that is a starting point), to seeking understanding of why differences arise between studies and what that means for the behavior observed. The starting hypothesis for the shape bias in the 1980s—that very young children know from the start of word learning that nouns refer to objects—has no place in 21st century psychology and cognitive science because we have moved beyond the old definitions of terms such as “know”, “nouns,” and “objects” that had no direct connections to the processes of perceiving, remembering, or learning at a cognitive or neural level.

Conclusions

Our goal in science is to advance the field through valid conclusions that can do real work. Experimental approaches are always a work in progress, always needing to be revised and sometimes to be changed in major ways. Alas, scientists are people with all the strengths, weaknesses, ambitions, and honest (and sometimes, but quite rarely, dishonest) aspirations, and these factors can lead to non-replicable studies. The current crisis has put much needed attention on the issue of whether individual phenomena are reproducible—whether exact replications yield the same result and whether there is over-enthusiasm when an effect is first discovered. But the greatness of science is that it forces us to correct our misunderstandings and it does so by requiring us to consider all the data and find a way to fit it all together, whether it shows what we expected or not. We still think this is the right approach: take all our experiments and all the data seriously —those that support our hypotheses, those that do not, and even the experiments and data that seem to show no effects at all. What are the data trying to tell us?

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Figure 1.

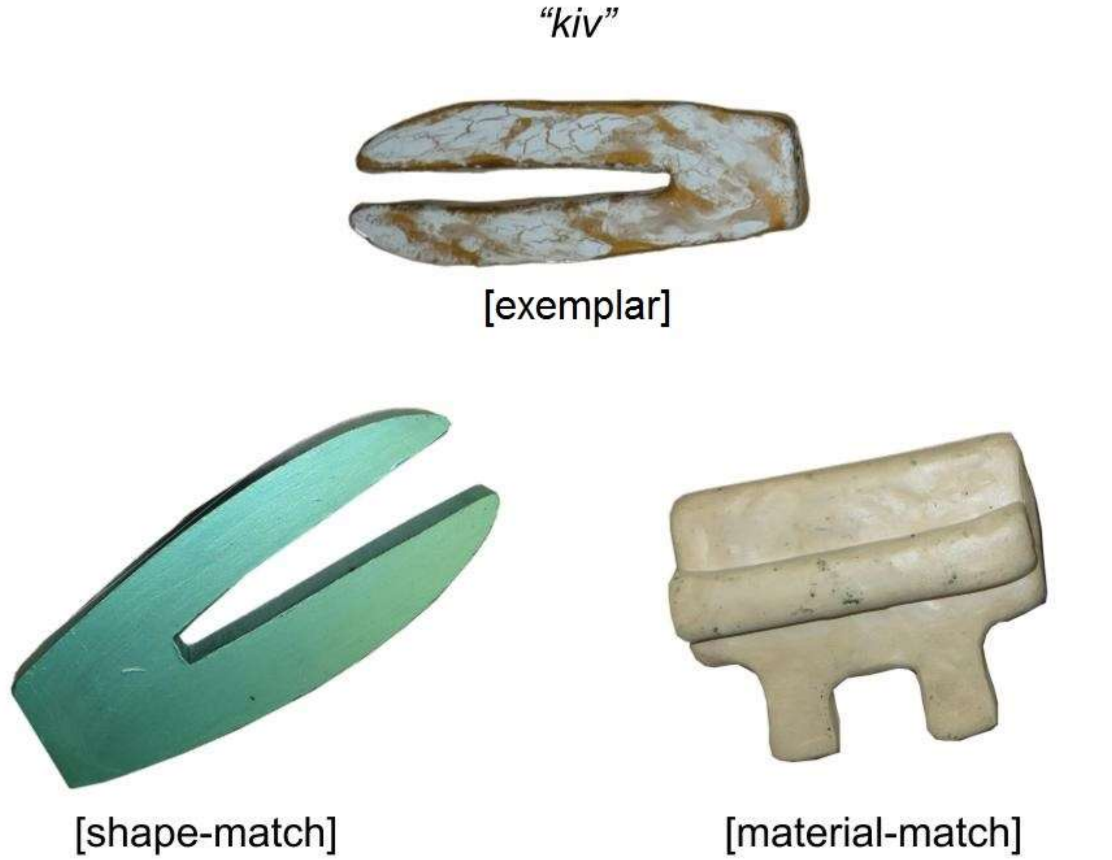

Figure 1. Standard example of a novel noun generalization task.