

A Quantitative Synthesis of Early Language Acquisition Using Meta-Analysis

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Abstract

replicability, etc.

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Introduction

To learn to speak a language, a child must acquire a wide range knowledge and skills: the sounds of the language, the word forms, and how words map to meanings, to name only a few. How does this process unfold? Our goal as psychologists is to build a theory that can explain and predict this process in a way that is both precise but also highly generalizable. The challenge we face, however, is that we must build this theory on the basis of very limited data, and, as a consequence, we must rely on error-prone inductive reasoning strategies to build our theories. In this paper, we consider the domain of language acquisition and demonstrate how meta-analytic methods can support the inductive theory-building process.

Meta-analysis is a quantitative method for aggregating across experimental findings. The fundamental unit of meta-analysis is the *effect size*: a scale-free, quantitative measure of “success” in a phenomenon. Importantly, an effect size provides an estimate of the *size* of an effect, as well as a measure of uncertainty around this point estimate. With such a quantitative measure of success, we can apply the same reasoning we use to aggregate noisy measurements over participants in a single study: By assuming each *study*, rather than participant, is sampled from a population, we can appeal to the classical statistical framework to combine estimates of the effect size for a given phenomenon.

Meta-analytic methods support theory building in several ways. First, they provide a way of evaluating which effects in a literature are “real,” and thus should constrain the theory. This is particularly important in light of recent high-profile evidence in the field that an effect observed in one study may not replicate in another (“replication crisis,” Ioannidis, 2005; Open Science Collaboration, 2012, 2015). Failed replications are difficult to interpret, however, because they may result from a wide variety of causes, including an initial false positive, a subsequent false negative, or differences between initial and replication studies, and making causal attributions in a situation with two conflicting studies is often difficult (Anderson et al., 2016; Gilbert, King, Pettigrew, & Wilson, 2016). Meta-analysis can allow

researchers to address this set of issues in a principled way by aggregating evidence across studies and assuming that there is some variability in true effect size from study to study. In this way, meta-analytic methods can provide more veridical description of the empirical landscape, which in turn leads to better theory-building.

Second, meta-analysis supports theory building by providing higher fidelity descriptions of phenomena. In addition to providing a quantitative estimate of success, meta-analytic methods provide a method for quantifying the amount variability around this point estimate. Furthermore, the quantitative framework allows researchers to detect potential moderators in effect size. This is particularly important for developmental phenomena because building a theory requires, ~~critically~~, a clear description of ~~the~~ changes in effect size across development. Typically, individual papers describe an effect size within the same paradigm, across 1-3 age groups. To the extent that the effect size at *each* of these developmental timepoints is a noisy sample from the true underlying effect size, it may be quite difficult to detect developmental trends in effect sizes from individual papers. By aggregating across papers through meta-analytic methods, however, we can provide a more precise description of the empirical phenomena.

In addition to providing a quantitative measure of success, effect size estimates also provide a common language for comparing *across* phenomena. This common language allows us to meaningfully consider the relationship between different phenomena in the language acquisition domain (“meta-meta-analysis”). Through cross-phenomena comparisons, we can understand not only the trajectory of a particular phenomenon, like word learning for example, but also how this phenomenon might depend on other skills, such as sound learning, gaze following, and many others.

Finally, in addition to these theoretical motivations, there are practical reasons for conducting a quantitative synthesis. When planning an experiment, an estimate of the size of an effect on the basis of prior literature can inform the sample size needed to achieve a desired level of power. Meta-analytic estimates of effect sizes can also aid in design choices:

If a certain paradigm tends to have overall larger effect sizes than another, the strategic researcher might select this paradigm in order to maximize the power of a study.

While meta-analytic methods are likely helpful for many psychological literatures, we believe language acquisition is a particularly informative application for this tool. One reason is that language acquisition may be uniquely vulnerable to false findings because running children is expensive, and thus sample sizes are small and studies are underpowered (Ioannidis, 2005). In addition, the difficulty in running participants means that replications are relatively rare in the field. Finally, there has been attention to developmental psychology research practices more broadly, suggesting evidence of experimenter bias (Peterson, 2016).

We take as our ultimate goal a single overarching theory of language acquisition that can explain and predict all the relevant phenomena. Toward this end, we developed a dataset of effect sizes in the language acquisition literature across 12 different phenomena (Metalab; <http://metalab.stanford.edu/>). We demonstrate how meta-analysis supports building this theory in two ways. We first use meta-analytic techniques to evaluate the evidential value of the empirical landscape in language acquisition research. We find broadly that this literature has strong evidential value, and thus that the effects report in the literature should constrain our theory of language acquisition. We then turn to synthesizing these findings across phenomena and offer a preliminary theoretical synthesis of the field.

Method

We analyzed 12 different phenomena in language acquisition. These phenomena were selected opportunistically, based on their availability in the literature and feasibility of conducting meta-analysis for a particular phenomenon. The phenomena cover development at many different levels of the language hierarchy, from the acquisition of prosody and phonemic contrasts, to gaze following in linguistic interaction. This wide range of phenomena allowed us to compare the course of development across different domains, as well as explore questions about the interactive nature of language acquisition (Table 1).

To obtain estimates of effect size, we coded papers reporting experimental data. Within each paper, we calculated a separate effect size estimate for each experiment and age group (“condition”). In total, our sample includes estimates from 269 papers, 981 different conditions and 12,029 participants. The process for selecting papers from the literature differed by domain, with some individual meta-analyses using more systematic approaches than others (see SI).

Replicability of the field

To assess the replicability of language acquisition phenomena, we conducted several diagnostic analyses: Meta-analytic estimates of effect size, fail-safe-N (Orwin, 1983), funnel plots, and p-curve (Simonsohn, Nelson, & Simmons, 2014b, 2014a; Simonsohn, Simmons, & Nelson, 2015). These analytical approaches each have limitations, but taken together, they provide converging evidence about the replicability of a literature. Overall, we find evidence of bias in our meta-analyses, suggesting that the language acquisition literature likely describes real psychological phenomena and should therefore provide the basis for theoretical development.


Meta-Analytic Effect Size

To estimate the overall effect size of a literature, effect sizes are pooled across papers to obtain a single meta-analytic estimate. This meta-analytic effect-size can be thought of as the “best estimate” of the effect size for a phenomenon given all the available data in the literature.

Table 2, column 2 presents meta-analytic effect size estimates for each of our phenomena. We find evidence for a non-zero effect size in 11 out of 12 of our phenomena, suggesting these literature provide evidential value. In the case of phonotactic learning, however, we find that the meta-analytic effect size estimate does not differ from zero, suggest that this literature does not describe a robust effect. [Remove it from analyses below?].

Level	Phenomenon	Description	N papers (conditions)
Prosody	IDS preference (Dunst, Gorman, & Hamby, 2012)	Looking times as a function of whether infant-directed vs. adult-directed speech is presented as stimulation.	16 (50)
Sounds	Phonotactic learning (Cristia, in prep.)	Infants' ability to learn phonotactic generalizations from a short exposure.	15 (47)
	Vowel discrimination (native) (Tsuji & Cristia, 2014)	Discrimination of native-language vowels, including results from a variety of methods.	40 (167)
	Vowel discrimination (non-native) (Tsuji & Cristia, 2014)	Discrimination of non-native vowels, including results from a variety of methods.	21 (72)
	Statistical sound learning (Cristia, in prep.)	Infants' ability to learn sound categories from their acoustic distribution.	11 (40)
	Word segmentation (Bergmann & Cristia, 2015)	Recognition of familiarized words from running, natural speech using behavioral methods.	68 (296)
Words	Mutual exclusivity (Lewis & Frank, in prep.)	Mapping of novel words reflecting children's inference that novel words tend to refer to novel objects.	20 (60)
	Sound Symbolism (Lammertink et al., in prep.)	Non-arbitrary relationship between form and meaning ("bouba-kiki effect").	10 (42)
	Concept-label advantage (Lewis & Long, unpublished)	Infants' categorization judgments in the presence and absence of labels.	16 (100)
	Online word recognition (Frank, Lewis, & MacDonald, 2016)	Online word recognition of familiar words using two-alternative forced choice preferential looking.	12 (32)
Communication	Gaze following (Frank, Lewis, & MacDonald, 2016)	Gaze following using standard multi-alternative forced-choice paradigms.	15 (45)
	Pointing and vocabulary (Colonesi et al., 2010)	Longitudinal correlations between declarative pointing and later vocabulary.	25 (30)

Table 1
Overview of meta-analyses in dataset.

While the measure of effect size is itself quantitative, meta-analytic estimates of effect size provide only categorical information  the evidential value of a literature: the effect is real, or not. But, a more powerful method of assessing evidential value would tell us the

degree to which a literature has evidential value, and thus the degree to which it should constrain our theory building. In the following three analyses—fail-safe-N, funnel plots, and p-curves—we attempt to quantify the evidential value of these literatures.

Fail-safe-N

One approach for quantifying the **reliability** of a literature is to ask, How many missing studies with null effects would have to exist in the “file drawer” in order for the overall effect size to be zero? This is called the “fail-safe” number of studies (Orwin, 1983). To answer this question, we estimated the overall effect size for each phenomenon (Table 2, column 2), and then used this to estimate the fail-safe-N (Table 2, column 3).

Because of the large number of positive studies in many of the meta-analyses we assessed, this analysis suggests a very large number of studies would have to be “missing” in each literature ($M = 3634$) in order for the overall effect sizes to be 0. Thus, while it is possible that some reporting bias is present in the literature, the large fail-safe-N suggests that the literature nonetheless likely describes a real effect.

One limitation of this analysis, however, is that it assumes that all reported effect sizes are obtained in the absence of analytical flexibility: If experimenters are exercising analytical flexibility through practices like p-hacking, then the number and magnitude of observed true effects in the literature may be inflated. In the next analysis, we examine this possibility through funnel plots.

Funnel Plots

Funnel plots provide a visual method for evaluating whether variability in effect sizes is due only to differences in sample size. A funnel plot shows effect sizes versus a metric of sample size, standard error. If there is no bias in a literature, we should expect studies to be randomly sampled around the mean, with more variability for less precise studies.

Figure 1 presents funnel plots for each of our 12 meta-analyses. These plots show evidence of asymmetry (bias) for several of our phenomenon (Table 2, column 4). However,

an important limitation of this method is that it is difficult to determine the source of this bias. One possibility is that this bias reflects the heterogeneity in phenomena (e.g. different ages). P-curve analyses provide one method for addressing this issue, which we turn to next.

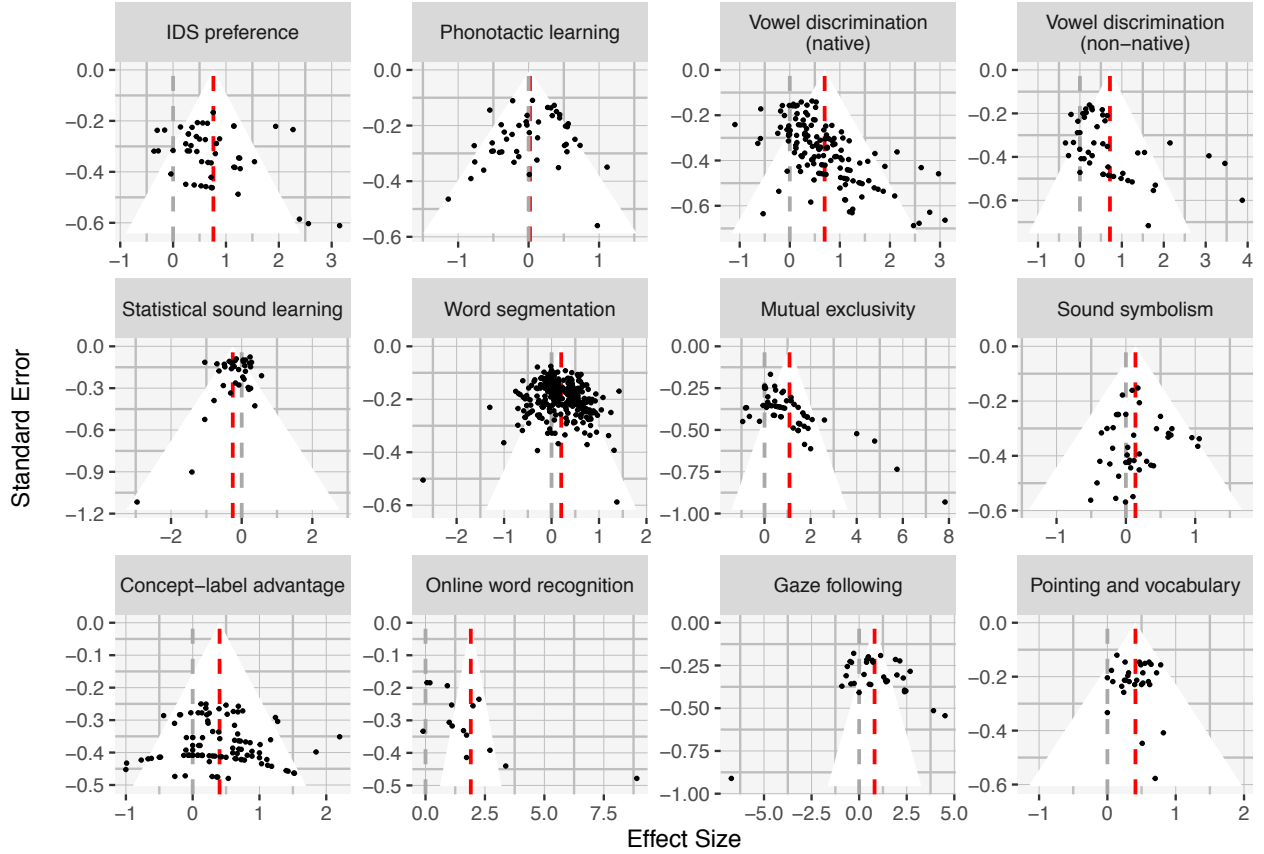


Figure 1. Funnel plots for each meta-analysis. Each effect size estimate is represented by a point, and the mean effect size is shown as a red dashed line. The funnel corresponds to a 95% (narrow) and 99% (wide) CI around this mean. In the absence of true heterogeneity in effect sizes (no moderators) and bias, we should expect all points to fall inside the funnel.

P-curves

A p-curve is the distribution of p-values for the statistical test of the main hypothesis across a literature (Simonsohn et al., 2014b, 2014a, 2015). Critically, if there is a robust effect in the literature, the shape of the p-curve should reflect this. In particular, we should expect the p-curve to be right skewed with more small values (e.g., .01) than large values (e.g., .04). An important property of this analysis is that we should expect this skew

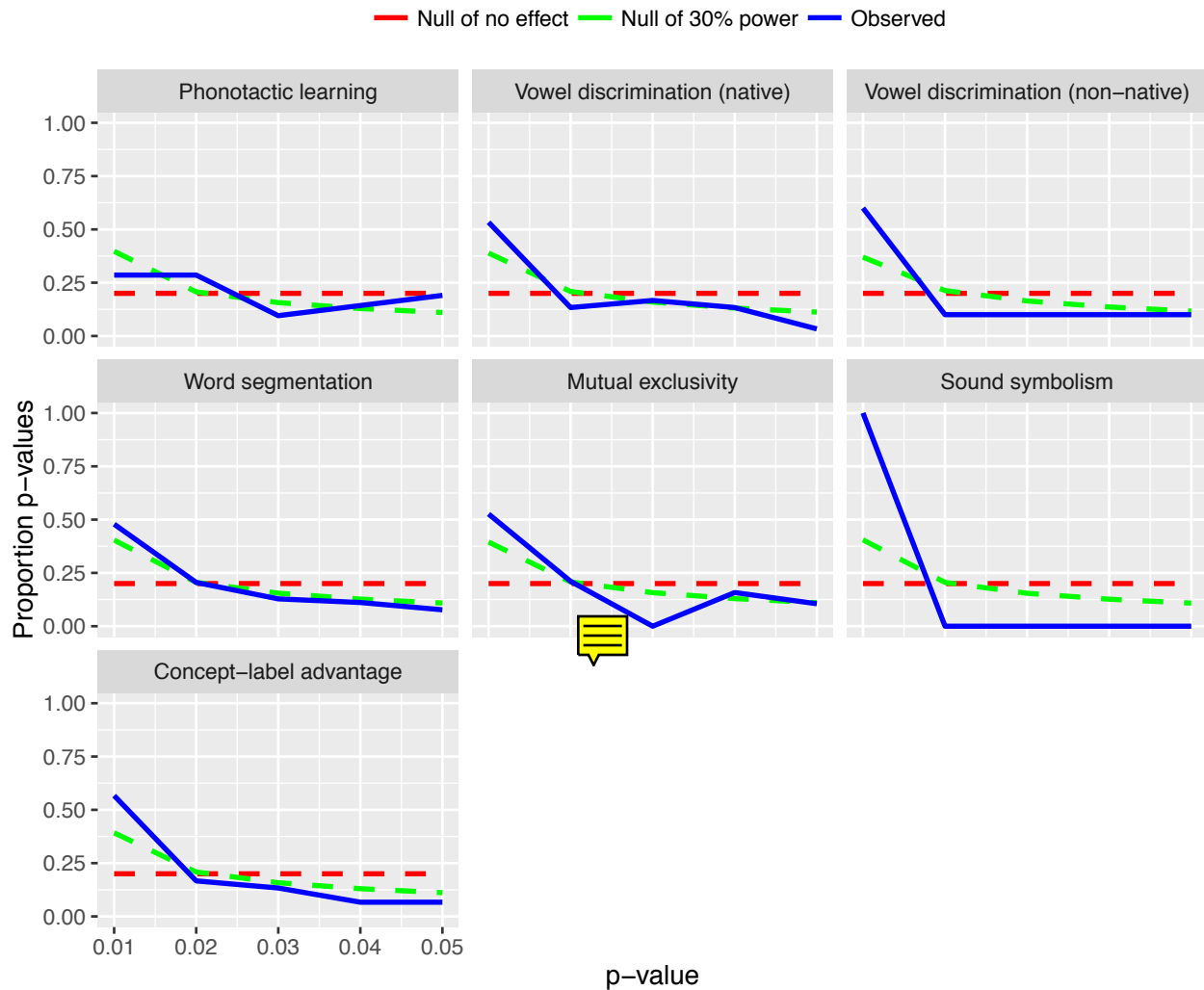


Figure 2. P-curve for each meta-analysis (Simonsohn, Nelson, & Simmons, 2014). In the absence of p-hacking, we should expect the observed p-curve (blue) to be right-skewed (more small values). The red dashed line shows the expected distribution of p-values when the effect is non-existent (the null is true). The green dashed line shows the expected distribution if the effect is real, but studies only have 33% power.

Phenomenon	<i>d</i>	fail-safe-N	funnel skew	p-curve skew	power
IDS preference	0.71 [0.53, 0.89]	3762	1.88 (0.06)		
Phonotactic learning	0.04 [-0.09, 0.16]	45	-1.08 (0.28)	-1.52 (0.06)	0.14
Vowel discrimination (native)	0.6 [0.5, 0.71]	9536	8.98 (0)	-5.42 (0)	0.67
Vowel discrimination (non-native)	0.66 [0.42, 0.9]	3391	4.13 (0)	-3.24 (0)	0.78
Statistical sound learning	-0.14 [-0.27, -0.02]	Inf	-1.87 (0.06)		
Word segmentation	0.2 [0.15, 0.25]	5645	1.54 (0.12)	-9.67 (0)	0.56
Mutual exclusivity	1.01 [0.68, 1.33]	6443	6.25 (0)		
Sound symbolism	0.15 [0.04, 0.26]	538	-1.32 (0.19)	-2.16 (0.02)	0.96
Concept-label advantage	0.4 [0.29, 0.51]	3928	0.31 (0.76)	-6.15 (0)	0.69
Online word recognition	1.89 [0.81, 2.96]	2843	2.92 (0)		
Gaze following	0.84 [0.26, 1.42]	2641	-1.69 (0.09)		
Pointing and vocabulary	0.41 [0.32, 0.49]	1202	0.59 (0.55)		

Table 2

Summary of replicability analyses. d = Effect size (Cohen's d) estimated from a random-effect model; fail-safe- N = number of missing studies that would have to exist in order for the overall effect size to be $d = 0$; funnel skew = test of asymmetry in funnel plot using the random-effect Egger's test (Stern & Eggers, 2005); p-curve skew = test of the right skew of the p-curve using the Stouffer method (Simonsohn, Simmons, & Nelson, 2015); power = power to reject the null hypothesis at the 5% significance level based on the p-curve (Simonsohn, Nelson, & Simmons, 2014); Brackets give 95% confidence intervals, and parentheses show p-values.

independent of any true heterogeneity in the data, such as age. Evidence that the curve is in fact right-skewed would suggest that the literature is not biased, and that it provides evidential value for theory building.

Figure 2 shows p-curves for 7 of our 12 meta-analyses.¹ With the exception of phonotactic learning, all p-curves show evidence of right skew. This is confirmed by formal analyses (Table 2, column 5).

P-curves also provide a method for calculating the overall power of a literature, based on the shape of the p-curve (Simonsohn et al., 2014a). Intuitively, when power is high and

¹We did not conduct p-curves on all meta-analyses because previously published meta-analyses did not include test statistics and the key test statistics in some others were inappropriate for p-curve.

effect is real, we should be more likely to observe an effect size “further” from the null. This means that we will observe more small effect sizes. Thus, the higher the power, the more right skewed the p-curve will be. Table 2 (column 6) presents estimates of power for each meta-analysis based on p-curve. With the exception of phonotactic learning (*power* = .14), literatures appear to have acceptable power.

In sum, then, meta-analytic methods, along with our dataset of effect sizes, provide an opportunity to assess the replicability of the field of language acquisition. Across a range of analyses, we find that this literature shows some evidence for bias, but overall, is quite robust.

Theoretical development

~~The replicability analyses suggest that the raw material for theory building experimental data reflect, for the most part, real psychological phenomena. Given this, we now turn to how these data can be used to constrain and develop theories of language acquisition.~~

~~At the most basic level,~~ meta-analytic methods provide a precise, quantitative description of the developmental trajectory of individual phenomena. Figure 3 presents the developmental trajectories of the phenomena in our dataset at each level in the linguistic hierarchy.² By describing how effect sizes change as a function of age, we can begin to understand what factors might moderate that trajectory, such as aspects of a child’s experience or maturation. For example, the mutual exclusivity meta-analysis suggests a steep developmental trajectory of this skill. We can use these data to then build quantitative models to understand how aspects of experience (e.g. vocabulary development) or maturational constraints may be related to this trajectory (e.g., M. C. Frank, Goodman, & Tenenbaum, 2009; McMurray, Horst, & Samuelson, 2012).

[There are also large differences in the relative magnitude of ES of different skills.

²The Pointing and Vocabulary dataset is excluded from this analysis because it does not contain effect sizes at multiple ages.

Theoretical point about overt skills have larger ES]

~~But~~, acquiring a language requires not just learning isolated skills; acquiring a language is the result of the integration of a range of skills across the language hierarchy. Consider, for example, a child understanding the word “dog:” If the child is unable to segment “dog” from natural speech, a child cannot be expected to understand the meaning of this word. Given these types of interdependencies, we can therefore usefully think of language acquisition as a *system* where different skills interact and depend on each other. In building a theory of this system, a pragmatic and necessary research strategy has been to study these skills primarily in isolation, describing the developmental trajectory of individual phenomena in separate research programs. However, if it is indeed the case that there are dependencies between these skills, then we may not be able to ultimately understand one skill without having a more complete picture of other skills, as well as a common language for talking about their relationship.

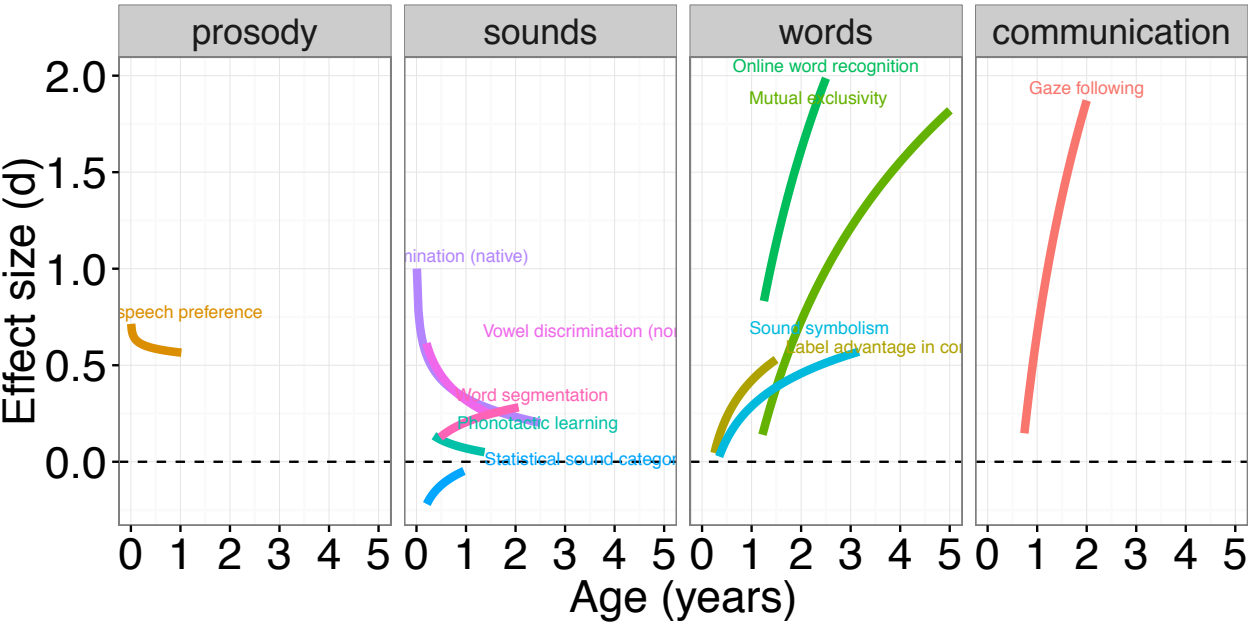


Figure 3. Effect size plotted as a function of age across all developmental meta-analyses in our dataset. Lines show logarithmic model fits.

A useful analogy is thermodynamic processes in weather. A meteorologist can carefully describe changes in temperature over the course of a day in a particular location. But, to



explain and predict those changes, the meteorologist needs to know about other variables in the system, like atmospheric pressure. Quantitative models can then be applied to understand the relationship between the two. Similarly, to predict and explain a child’s understanding of the word “dog,” we need not only to describe the child’s competency in understanding this word, but also the child’s competency in other skills like phonemic knowledge, word segmentation, and pragmatic reasoning. Like in the case of thermodynamics, quantitative methods provide a rich toolkit for relating these phenomena

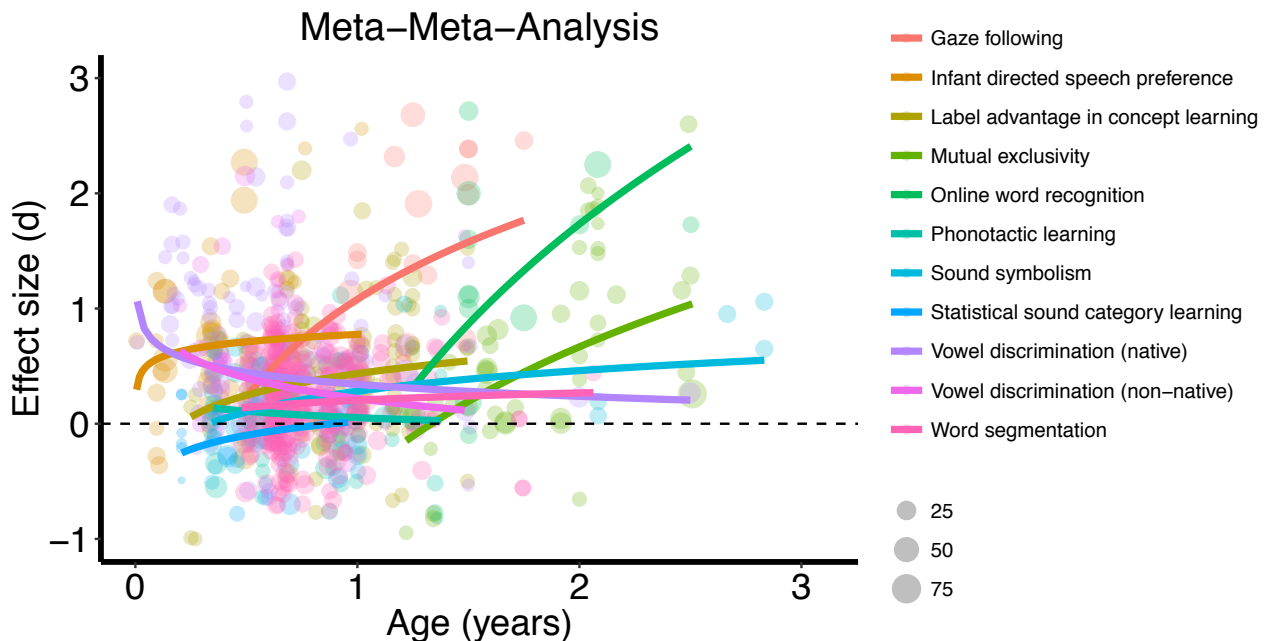


Figure 4. Effect size as a function of age from 0-3 years, across 11 different phenomena. Each point corresponds to a condition, with the size of the point indicating the number of participants. Models show logarithmic fits. These developmental curves suggest there is interactivity across language skills, rather than sequential learning of the linguistic hierarchy

We suggest that meta-analytic methods provide an approach for synthesizing across different linguistic skills via the language of effect sizes. The ultimate goal is to use meta-analytic data to build a single, quantitative model of the language acquisition system, much like those developed for individual language acquisition phenomena, like word learning. Developing a single quantitative model is a lofty goal, however, and will likely require much more precise description of the phenomena than is available in our dataset. Nevertheless, we can use our data to distinguish between broad meta-theories about the relationship between

different skills.

There are two existing meta-theories in the literature about the dependencies between different skills in language acquisition. The first—the “bottom-up” theory—proposes that linguistic skills are acquired sequentially beginning with skills at the lowest level of the linguistic hierarchy. Under this theory, once a skill is mastered, it can be used to support the acquisition of skills higher in the linguistic hierarchy. In this way, a child sequentially acquires the skills of language, “bootstrapping” from existing knowledge at lower levels to new knowledge at higher levels. There is a wide range of evidence consistent with this view. For example, there is evidence that prosody supports the acquisition of sound categories [CITE], word boundaries [CITE], and even word learning (e.g., Shukla, White, & Aslin, 2011).

A second possibility is that there is interactivity in the language system such that multiple skills are learned simultaneously across the system. Under this proposal, a child does not wait to begin learning the meanings of words until the sounds of a language are mastered, for example; rather, the child is jointly solving the problem of word learning in concert other language skills. This possibility is consistent with predictions of a class of hierarchical Bayesian models that suggest that more abstract knowledge may be acquired quickly, before lower level information, and may in turn support the acquisition of lower information (“Blessing of abstraction,” Goodman, Ullman, & Tenenbaum, 2011). There is evidence for this proposal from work that suggests word learning is supported the acquisition of lower-level information like phonemes (Feldman, Myers, White, Griffiths, & Morgan, 2013). More broadly, there is evidence that higher level skills like word learning may be acquired relatively early in development, likely before lower level skills have been mastered (e.g., Bergelson & Swingley, 2012)

Within the meta-analytic framework of effect-sizes, we can represent these two theories schematically in figure 4a (bottom-up) and 4b (interactive) [A figure here?]. This framework also allows us to specify a much larger space of possible theories, however. By specifying

several parameters of the framework, such as the shape of the developmental trajectory (e.g., linear or logarithmic), direction of the trajectory (upward or downward) and the age at which acquisition begins, we can consider many possible meta-theories of development.

Our data allow us to begin to differentiate between this space of theories. Figure 5 presents a holistic representation of the developmental trajectories of all the skills in our dataset. We find strong evidence for interactivity—children begin learning even high-level skills like the meanings of words early on in development, and even low-level skills like sound categories show a protracted period of development. Moving forward, we can use this approach to distinguish between a larger space of meta-theories and, ultimately, build a single quantitative theory of language acquisition.

Discussion

Building a theory of a complex psychological phenomenon requires making good inductive inferences from the available data. We suggest that meta-analysis can support this process by allowing the researcher to verdically describe the to-be-explained behavior, and to do so with high-fidelity. Here, we apply the meta-analytic toolkit to the domain of language acquisition—a domain where there are concerns of replicability, and where high-fidelity data is needed to explain its complexity. We find that the existing literature in this domain describe robust phenomena and thus should form the basis of theory development. We then offer a preliminary synthesis of the field by aggregating across language acquisition phenomena. We find evidence that linguistic skills are acquired interactively rather than in a strictly bottom-up fashion.

There are a number of important limitations to the meta-analytic approach as a theoretical tool. First, this method relies on researchers conducting replications of the same study across a range of ages and, critically, reporting these data so that they can be used in meta-analyses. To the extent that researchers do not conduct these studies, or report the necessary statistics in their write-ups (e.g., means and standard deviations), the

meta-analytic method cannot be applied. Second, the meta-analytic method, as for qualitative forms of synthesis (e.g. literature review), is limited by the potential presence of bias, which can come from a ranges of sources including non-representative participant populations, failure to publish null findings, and analytical degrees-of-freedom. To the extent these biases are present in the literature, methods of synthesizing these findings will also be biased.

In addition, there are a number of more substantive concerns with this method. One possibility is that the magnitude of effect may be more related to the method than the psychological phenomenon. While this may be true to some extent, we find that method does not have a large impact on effect size for a phenomena, relative to other moderators like age (see SI). Another issue is that meta-analysis usually measures signal to noise, not units of interest (e.g. ability in an absolute sense) there could be important confounds with respect to this.

Future directions:

- Educational tool - presage/link to other paper
- Contributions, CAMAS
- Other domains – language acquisition as a case study

Author Contributions.

Acknowledgments.

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