

A synthesis of early cognitive and language development using (meta-)meta-analysis

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Abstract

Young children acquire and develop a wide range of linguistic and cognitive skills in the first three years of life. Decades of experimental work have established a solid empirical foundation for our understanding of cognitive development in early childhood. However, most experimental studies are limited in statistical power and focus on specific psychological constructs, thus making them unsuitable for describing developmental growth at scale. Here, we turned to meta-analyses of experimental research. We conducted a meta-meta-analysis to consolidate and integrate 23 meta-analyses compiled on MetaLab, a community-augmented meta-analysis platform. We found great diversity in the best-fitting functional forms of the age model across different research areas. In some domains, the effect size of the experimental phenomenon increases substantially with age (e.g. Online word recognition), whereas in other domains the effect size remains constant throughout early childhood (e.g. Sound symbolism). In addition, we evaluated the impact of a range of methodological factors, including behavioral measures, exposure phase, stimuli naturalness, and whether the study is produced by a prominent author in the particular research area. We showed that these moderators have diverse influences on the effect sizes of the studies. Overall, our work sheds light on the heterogeneous nature of developmental trajectories and the subtle interactions between research methods and experimental outcomes.

Keywords: meta-analysis; cognitive development; language learning

Introduction

In the first three years of life, children undergo a plethora of developmental changes, transitioning from newborn infants who possess a limited understanding of language and categories to toddlers who are able to master a wide range of linguistic and cognitive skills. Despite a wealth of research examining cognitive development, constructing a comprehensive theory of cognitive development remains a formidable challenge. Research in this area generally falls under two categories: observational research and experimental research. Observational studies using instruments like the Bayley Scales can provide a holistic picture of an individual child's development [e.g. @bayley2006bayley], but it is a challenge to move from global developmental milestones to underlying mechanisms. In contrast, experimental research allows causal tractions on potential mechanisms, but experiments typically focus on one single construct and does not reveal the connections between different processes and mechanisms. In this paper, we aim to provide a quantitative synthesis of experimental work across multiple areas of devel-

opmental psychology, providing insights into the interrelatedness between psychological constructs. We achieve this goal by consolidating and integrating 23 meta-analyses of cognitive and language development compiled on MetaLab, a community-augmented meta-analysis platform.

Statistical meta-analysis, the technique of aggregating effect sizes across a systematic sample of experiments, has some unique advantages as a source of data about developmental processes in early childhood. First and foremost, it allows researchers to explore questions that are difficult to address with individual studies. One such example is the functional form of developmental curves, or how different psychological processes change over time. Many developmental studies use linear regression models with age as a predictor, but this assumption of linearity may not capture the complexities of developmental processes, especially as they interact with developmental changes in measurement. For example, some cognitive abilities – such as relational reasoning – might follow an inverted-U shape (Carstensen et al., 2019; Walker, Bridgers, & Gopnik, 2016), while others – like early vocabulary size – show an exponential increase (Frank, Braginsky, Yurovsky, & Marchman, 2021). These non-linear trends can be challenging to identify and interpret with limited data from individual studies, but meta-analytic methods can provide a large amount of data across a broad age range, enabling researchers to evaluate and compare different functional forms of developmental trajectories.

Meta-analysis can also shed light on the relationships between methods and theories. Research methods and theories are fundamentally intertwined, and this is especially true for developmental psychology (Dale, Warlaumont, & Johnson, 2022). Developmental theories are often based on interpretations of experimental results, which are produced by methods that even small changes to the parameters would substantially change the outcomes. One example is the influence of familiarization time. It has been proposed that the amount of exposure infants have prior to the test events can influence infants' direction of preference (i.e. novelty preference or familiarity preference) (Hunter & Ames, 1988). Although the empirical evidence for this theory is mixed, this ambiguity has significant downstream consequences on our understanding of infants' cognitive capabilities (Bergmann & Cristia, 2016). Debates about infants' arithmetic competencies or their evaluations of social agents are often centered around the direction

of preferences (Infants arithmetic competencies: Clearfield & Westfahl, 2006; Wakeley, Rivera, & Langer, 2000; Wynn, 1993; Evaluation of social agents: Hamlin, Wynn, & Bloom, 2007; Salvadori et al., 2015). Due to the time and resources required for developmental studies, it is often difficult to directly evaluate the impact of subtle changes in parameters. Therefore, meta-analytic methods provide a unique opportunity to investigate the effects of methodological factors on research findings.

Last but not least, meta-analytic methods make it possible to compare and connect research findings across research areas. The use of effect size as the fundamental unit of analysis allows for comparisons across different domains and research areas. These comparisons can provide insight into how different processes facilitate learning at different stages of development and can aid in the development of data-driven cognitive development theories (Cao & Lewis, 2022; Lewis et al., 2016). However, a synthesis across multiple domains requires a database of multiple meta-analyses. Towards that aim, MetaLab was established to provide an open database of meta-analyses (Bergmann et al., 2018). Developmental researchers are invited to deposit their meta-analysis dataset into MetaLab, and they are encouraged to use the datasets for custom analyses. As of November 2022, Metalab contains X effect sizes from 30 different meta-analyses. This resource allows the beginnings of a quantitative synthesis across different research areas in developmental psychology.

In particular, we address three separate questions. First, we would like to investigate the shape of developmental curves across domains. The form of growth curves has been of interest in a lot of areas of developmental research (e.g., exponential growths in vocabulary: McMurray, 2007; asymptotic decreases in reaction time: Kail, 1991). These nuanced descriptions of developmental trajectories allow for a more precise understanding of the underlying mechanisms driving these changes. We aim to provide these quantitative descriptions for more research areas. Second, we hope to understand how research methods moderate the strengths of the findings. Increasingly, developmental research methods are scrutinized for their mechanisms and scientific rigors (Paulus, 2022; Stahl & Kibbe, 2022). With MetaLab, the fields are ripe for a more systematic understanding of how different design choices in experiments could influence the results. Finally, we would like to offer a birds-eye view of the field by integrating the growth curves across multiple domains. This view would provide an empirical foundation for creating a synthesized theory of cognitive development.

The plan for this paper is as follows. We first describe the datasets included in the current synthesis, including our selection criteria and the descriptive statistics associated with our final dataset. We then turn to model comparison, comparing the fits of age models under different functional forms. Next, we present methodological moderators analysis. Four methodological moderators are selected due to their theoretical relevances: behavioral measure type, exposure phase

type, stimuli naturalness, and major author effect. Finally, we present a synthesis of the developmental curves across all of the domains considered. We end the paper by discussing the implications and limitations of our current work.

Methods

Datasets Datasets were retrieved from `metalabr`, the R package built from Metalab. As of November 2022, the package includes 30 individual meta-analysis datasets covering different research domains in language learning and cognitive development. We removed 5 datasets from the final analysis, including 2 with data quality issues (Word segmentation neuro; Phonotactic learning), 3 due to being observational studies or including studies with quasi-experimental design (Pointing and vocabulary concurrent; Pointing and vocabulary, longitudinal; Video deficit)). We modified 2 datasets to reflect a more accurate representation of the literature and combined two pairs of datasets because they measure theoretically identical constructs. To minimize the heterogeneity in our datasets, we also excluded effect sizes calculated from participants with clinical diagnoses.

The final dataset contained 23 meta-analyses. Table 1 provides a summary of the, along with the number of effect sizes and participants included in each dataset.

The final dataset and analysis scripts are available at X.

Analytic Methods All analyses were conducted in R using the `metafor` package (Viechtbauer, 2010). We specified multi-level random effect models with random effect structures that included grouping by paper and by participant group. We removed the clustering if grouping information was missing from the dataset. All moderators were included as fixed effects. Unless otherwise specified, all model comparisons were based on the corrected Akaike Information Criterion (AICc).

Results

Functional form of developmental curves

Our first research question was about the functional form of the developmental trajectories we observed. We considered four specific forms: linear, logarithmic, quadratic, and constant, each considered as an age-related fixed effect. We evaluated the models based on the corrected AICc (Table 1). 10 out of the 23 datasets had the constant model as the best-fitting model. 7 and 5‘ datasets’ best-fitting models are the Quadratic model and logarithmic model, respectively. Finally, among all datasets considered, Online Word Recognition was the only domain in which the linear age model provides the best fit. Model evaluation based on Bayesian Information Criterion (BIC) yielded similar results with little discrepancy.

Methodological Moderators

In this section, we considered methodological moderators shared by multiple datasets. Given the limited number of studies conducted with neuroimaging methods, we focused

Dataset	N ES	N Participants	ES estimates	Linear	Log	Quad.	Const.
Label advantage in concept learning	100	1644	0.36 [0.23,0.48]	169	169	170	171
Vowel discrimination (native)	143	2418	0.59 [0.43,0.75]	256	256	258	255
Vowel discrimination (non-native)	49	600	0.65 [0.2,1.1]	73	73	73	72
Statistical word segmentation	103	804	-0.08 [-0.18,0.02]	129	129	129	128
Online word recognition	14	330	1.37 [0.78,1.96]	47	47	47	49
Mutual exclusivity	131	2222	1.27 [0.99,1.56]	422	416	433	453
Sound symbolism	44	425	0.16 [-0.01,0.33]	58	58	59	61
Categorization bias	80	382	0.25 [-0.54,1.05]	300	300	300	301
Familiar word recognition	34	586	0.54 [0.38,0.69]	27	28	27	29
Abstract rule learning	95	1123	0.22 [0.07,0.37]	141	141	140	141
Switch task	143	2764	-0.16 [-0.25,-0.06]	205	205	205	204
Mispronunciation sensitivity	249	2122	0.45 [0.24,0.66]	620	628	614	644
Prosocial agents	61	1244	0.4 [0.29,0.52]	82	82	82	80
Simple arithmetic competences	14	369	0.25 [0.04,0.46]	23	23	23	16
Symbolic play	196	7148	0.63 [0.53,0.72]	234	234	234	234
Natural speech preference	55	786	0.44 [0.23,0.65]	111	112	111	112
Cross-situational word learning	48	2241	0.67 [0.5,0.84]	80	82	80	84
Language discrimination and preference	153	2060	-0.13 [-0.26,0]	265	266	263	265
Syntactic bootstrapping	60	832	0.24 [0.03,0.44]	107	107	108	107
Statistical sound category learning	11	350	0.56 [0.19,0.93]	33	35	33	30
Gaze following	81	1407	0.81 [0.61,1.01]	152	160	149	193
Word Segmentation	315	2910	0.2 [0.14,0.26]	329	329	329	328
Infant directed speech preference	83	985	0.47 [0.28,0.65]	70	71	70	69k

Table 1: This table summarize the number of effect sizes *ES* and the number of participants included in each meta-analysis dataset. The ES estimates represent the aggregated effect sizes and their 95% confidence intervals from each dataset. The last four columns include the values of corrected Akaike Information Criterion *AICc* for the age model with different functional forms: Linear, Logarithmic, Quadratic and the Constant. The values were rounded to integers and the bold values are the smallest values among the four functional forms before rounding.

our analyses on studies conducted with behavioral methods. Therefore, we excluded studies that were conducted with either fNIRS or EEG. Moreover, to minimize age-related heterogeneity, we only included studies with participants' mean age below 36 months. All analyses were conducted on the subset of research domains with multiple levels for the moderator of interests.

Figure 1 provides a summary of the estimates for moderators.

Behavioral Measures Meta-analyses have very heterogeneous moderators coded, but many included coding of which behavioral response measure was used in the original study: looking-based behaviors (e.g., looking time or other eye-tracking measures), sucking (as in the high amplitude sucking procedure), and manual behaviors (e.g., pointing, exploration). We thus added behavioral measure as an additional fixed effect to the age model with the best-fitting functional form from the previous analysis.

In general, nearly all effects were weakly positive such that sucking and manual response modes yielded slightly larger effect sizes, though these effects were not always significant. Behavioral measure was a significant predictor of effect sizes in only two domains, Vowel Discrimination (Na-

tive) and Sound Symbolism. In Vowel Discrimination (native), studies with Manual or Sucking behavioral measure has larger effect sizes than studies using looking as the behavioral measure (Manual: $\beta = 0.58$ [0.33, 0.82], $z = 4.6$, $p < 0.01$; Sucking: $\beta = 0.96$ [0.53, 1.4], $z = 4.34$, $p < 0.01$). Similarly, in Sound Symbolism, studies with manual behavioral measures also yield larger effect sizes than looking studies ($\beta = 0.61$ [0.24, 0.97], $z = 3.29$, $p < 0.01$).

We also explored whether there would be an interaction between the research methods and the age of participants. There was limited evidence for such interaction. The inclusion of interaction terms only improved the *AICc* in 3 domains (Label advantage in concept learning; Language discrimination and preference; Mutual exclusivity). Of all the interaction models, only the Language discrimination and preference showed a significant positive interaction effect between the manual behavioral measure and age ($\beta = 0.01$ [0, 0.02], $z = 2.19$, $p = 0.03$).

Exposure Phase Exposure phase refers to the type of exposure infants have during the experiments prior to the test events. There are typically four types of exposure phase: 1) an infant would be conditioned to show an orienting behavior (conditioning); 2) an infant would be exposed to a stimulus

for a constant amount of time (familiarization); 3) an infant would be shown some stimulus repeatedly until the magnitude of response drops below a threshold (habituation); 4) no exposure to the stimulus at all; the infant would be tested immediately (test-only). We coded these four types of exposure phases as four levels in the moderator exposure phase.

Exposure phase is a significant predictor of effect sizes in four domains. In Language Discrimination and Preference, habituation studies yield smaller effect sizes than conditioning studies ($\beta = -0.3 [-0.55, -0.04]$, $z = -2.28$, $p = 0.02$). A similar trend is found in Vowel discrimination (native), where both habituation studies and familiarization studies have smaller effect sizes than conditioning studies (Habituation: $\beta = -0.71 [-1.11, -0.31]$, $z = -3.48$, $p < 0.01$; Familiarization: $\beta = -0.43 [-0.87, 0.01]$, $z = -1.94$, $p = 0.05$).

Interestingly, the results of the comparison between familiarization studies and conditioning studies are mixed. In the Vowel discrimination (non-native) dataset, both familiarization and test-only studies produce smaller effect sizes than the conditioning studies (Familiarization: $\beta = -1.4 [-2.35, -0.46]$, $z = -2.93$, $p < 0.01$; Test-only: $\beta = -1.26 [-2.42, -0.1]$, $z = -2.13$, $p = 0.03$). However, the opposite trend is found in Natural Speech Preference, with familiarization studies producing larger effect sizes than the conditioning studies ($\beta = 1.65 [0.33, 2.97]$, $z = 2.44$, $p = 0.01$).

Stimuli Naturalness Next, we considered the effect of stimuli type. We focused on one key dimension: naturalness. For primarily visual stimuli, we considered “naturalness” to mean stimuli that use real-world objects (e.g. puppets, blocks). We compared these natural stimuli with representation-type stimuli, such as pictures, videos, or drawings. In primarily auditory stimuli, we compared natural speech with synthesized stimuli.

We found that naturalness is a significant predictor for Label advantage in concept learning, with natural stimuli yielding larger effect sizes than representation-type stimuli ($\beta = 0.23 [0.01, 0.45]$, $z = 2.06$, $p = 0.04$). Similarly, in both Statistical word segmentation and Abstract rule learning, we found a natural speech advantage (Statistical word segmentation: $\beta = 0.47 [0.23, 0.72]$, $z = 3.8$, $p < 0.01$; Abstract rule learning: $\beta = 0.27 [0.05, 0.5]$, $z = 2.35$, $p = 0.02$).

Major author Margoni & Surian (2018) found evidence for an author-based bias in Prosocial Agents, where results produced by certain authors were consistently larger than others. We evaluated how prevalent this phenomenon was in the literature by coding a “major author” moderator. Authors are considered to be a “major author” if they are listed as authors in more than 15% of the papers in the literature.

We found evidence for a major author effect in 7 datasets, where studies produced by the major author were larger than the rest of the papers. In 3 datasets, however, we also found the opposite patterns, where certain authors produced on average smaller effect sizes than the rest of the literature.

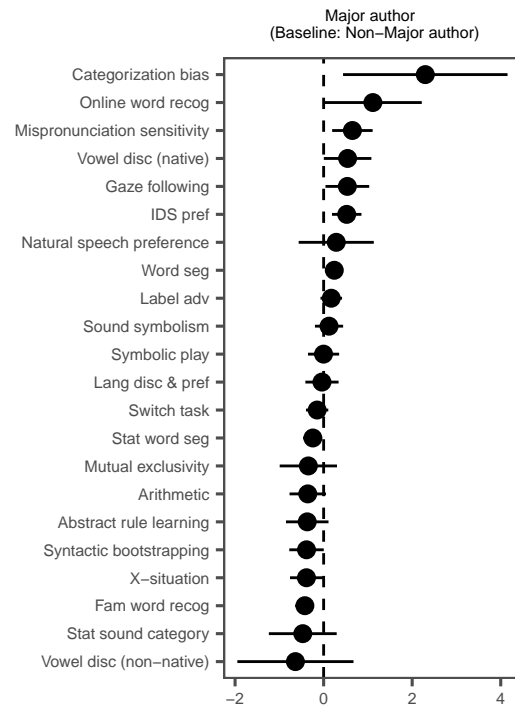


Figure 2: Each dot represents the estimate for studies produced by major author in the particular research area, compared to other studies in the same research area.

Synthesis

Finally, we synthesized all 23 datasets by grouping them based on the type of theoretical constructs they represented: Cognitive, Communication, Sounds, and Words. We integrated the predictions from the best-fitting age-based models in Figure 2, showing predictions across the range of measured phenomena. We found a striking range of functional forms in the developmental trajectories across all types of theoretical constructs. In particular, the magnitudes of some phenomena – online word recognition, gaze following, and mutual exclusivity, for example – increased substantially over development. In contrast, others – sound symbolism, categorization bias, and others – stayed constant at a measurable level without showing developmental increases. We considered several explanations for these differences: one is that these meta-analyses might correspond to relatively more experience-independent biases. On the other hand, we cannot rule out cross-experiment confounding wherein experimenters test progressively harder stimuli with development, thus counteracting any developmental gains that might otherwise be measured.

Discussion

How can we quantitatively describe developmental growth at scale? Meta-analysis is one promising method. In this paper, we presented a bird-eye view of developmental psychology by synthesizing 23 meta-analyses available on MetaLab. We found great diversity in the shapes of the best-fitting mod-

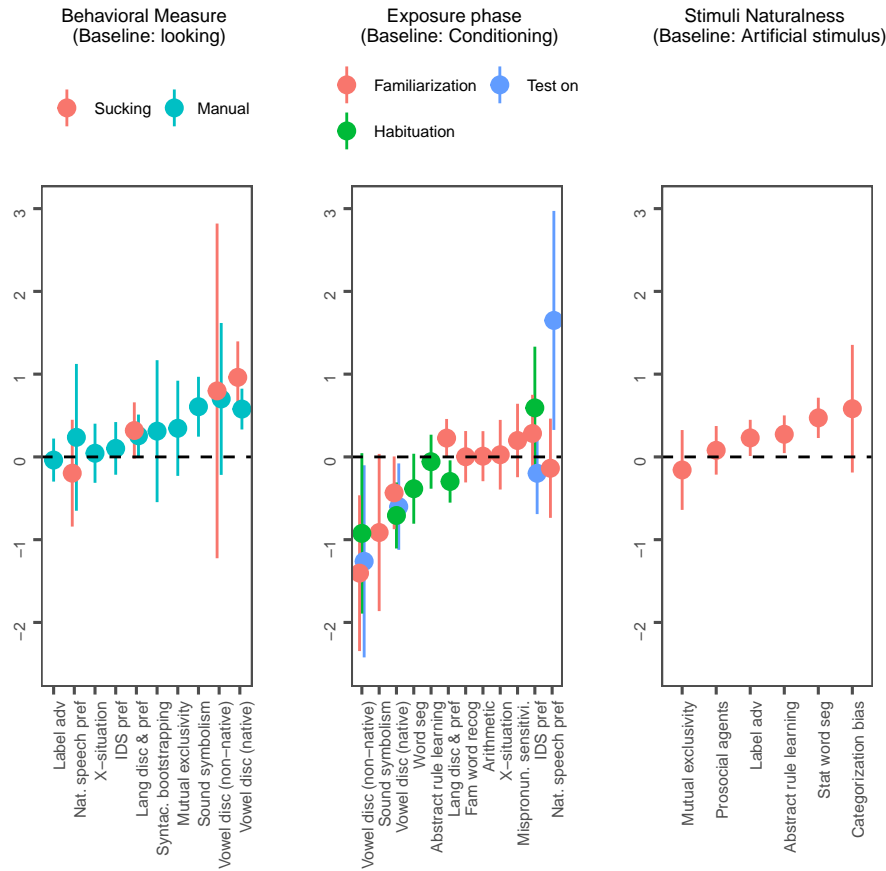


Figure 1: Each panel shows the moderator estimates. Each dot represents the estimate of the particular moderator level compared to the baseline. For behavioral measure, the baseline level is looking. Red dots indicate the estimate for studies using sucking measure, and the teal dots indicate the estimates for studies using manual measure. For exposure phase, the baseline level is conditioning. Red, blue, and green represent the estimates for studies using familiarization, test-only, and habituation in exposure phase, respectively. For stimuli naturalness, the dots represent the estimate for studies using natural stimuli (e.g. real-world objects; natural speech) compared to studies using artificial stimuli (e.g. pictures, synthetic speech).

els for each domain – while some phenomena showed larger and larger effects with development, quite a number of others stayed constant, suggesting a distinction between small but measurable in-lab effects and behaviors that can easily be observed in individual children (effect sizes > 2). We also considered the moderating effects of different methodological factors, including the type of behavioral measure, the type of exposure phase, stimuli naturalness, and whether the work is done by a “major author”. These factors moderate effect sizes from different domains in heterogeneous ways, though we did find evidence for naturalistic stimuli leading to larger effects in a number of studies.

This current synthesis highlights the variation in developmental trajectories, challenging the traditional “milestone” view of cognitive development. Under the milestone view, infants would acquire different cognitive and linguistic skills as they grow (Meylan & Bergelson, 2022; Wilks, Gerber, & Erdie-Lalena, 2010). Our findings suggest that this view is missing two important details. First, at any given age, psychological constructs could have a wide range of effect sizes.

For example, at 15 months of age, the predicted effect sizes for communication skills range from X (DOMAIN NAME) to X (DOMAIN NAME). The differences between the strengths of the effect may reflect the differences in how these skills contribute to communication, with some playing a more significant role than others. In addition, the development of these skills could follow significantly different trajectories, with some increasing exponentially with age and others staying constant throughout early childhood. The heterogeneity of the developmental process calls for developing a more nuanced and integrated developmental theory.

The heterogeneity can also partly be attributed to the wide variety of research methods. In the current analysis, we focused on in-lab experimental work, and thus the effect sizes may as well reflect how well the research methods capture the phenomenon of interest. Indeed, we have shown that subtle experimental procedure changes (e.g. exposure phase) could significantly alter the effect sizes. Moreover, methods’ impact varies across domains, with some domains being more susceptible to methodological factors than others. Therefore,

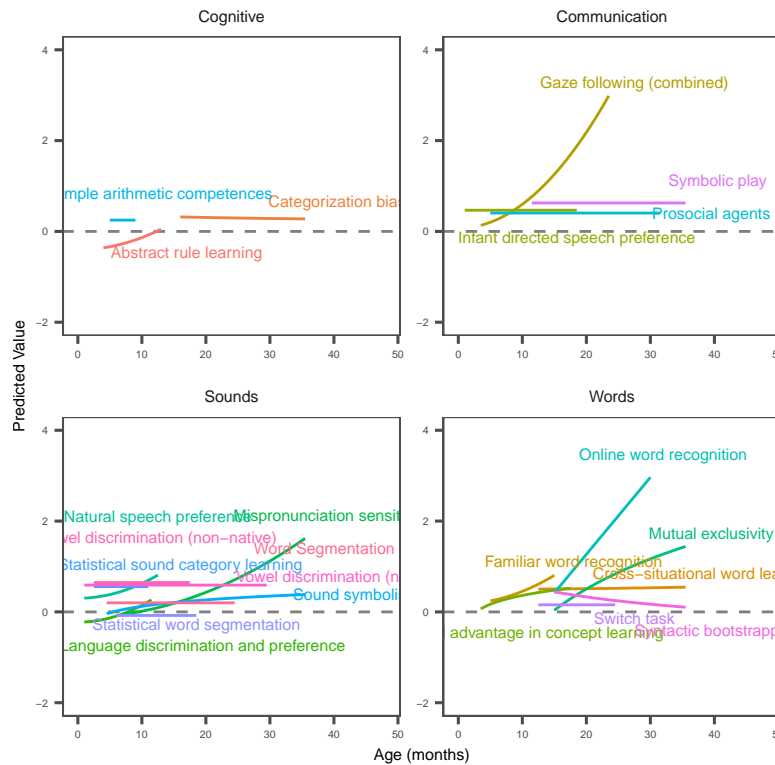


Figure 3: Predictions of the best-fitting functional forms of the age model. X-axis is age in months. Y-axis is effect size. For each research area, we plotted the predicted values for the age range included in the dataset.

the developmental trajectories that we document could be influenced by researchers adapting their methods to participants of different ages. In fact, we have found that the inclusion of methodological moderators could change the functional form of the best-fitting models. For example, in Infant Directed Speech preference, the winning functional form for an age-only model is constant (STATS?). However, when the Exposure Phase moderator is included, the best-fitting model includes age as a linear term (STATS?). Our findings call attention to the importance of understanding methods’ nuances: rather than treating methods as a perfect mirror perfectly reflecting the phenomenon, they should be regarded as an imperfect lens that could distort our perception of the phenomenon.

Of course, the same can be said about meta-analysis. Meta-analysis is not a perfect tool, and can often produce effect sizes significantly larger than a comparable large-scale replication (Kvarven, Strømland, & Johannesson, 2020). Part of the discrepancy can be attributed to the heterogeneity of research methods that are often minimized in a large-scale replication (Lewis, Mathur, VanderWeele, & Frank, 2020). While we have included methodological moderators in our analysis, it is highly likely that the coded moderators did not fully reflect the subtlety of research methods. However, the “Major author” effect found in many research domains could provide a window into understanding the workings of the research method. In the future, we could compare and con-

trast the methods used by “major authors” and those by others. Doing so would allow us to pinpoint the differences and understand which aspects of the methods really matter, and which do not.

Our ultimate goal is to offer a data-driven synthetic theory of cognitive development. Here we have made our first step toward that goal by offering a synthesis of meta-analyses across 23 different research domains. Moving forward, we aim to expand and refine our synthesis by including more research areas, correcting potential publication biases, and accounting for more detailed methodological factors. We would also like to make more connections between our meta-analysis-based work and the many ongoing analyses based on large-scale multi-site replication projects (e.g. ManyBabies: Frank et al., 2017). Ultimately, we hope our analysis could provide a solid empirical foundation to help us to better understand the complex and diverse processes involved in cognitive development.

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