Quantifying the syntactic bootstrapping effect in verb learning through meta-analysis

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Abstract

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Introduction

In order to become fluent users of language, children must learn the names not only for concrete nouns, like “ball” and “apple”, but also verbs like “eat” and “throw”. Learning the meaning of a verb presents a particular challenge to learners because the perceptual information about a verb’s meaning is complex – it is ephemeral and temporally dynamic. How are children able to overcome this perceptual ambiguity in order to learn verb meanings? One of the central theoretical proposals is that children use syntactic information in a verb’s linguistic context to infer its meaning (Gentner, 2006; Gentner & Boroditsky, 2001), a phenomenon known as “syntactic bootstrapping” (Brown, 1957; Gleitman, 1990; Landau & Gleitman, 1985). For example, if a child hears the sentence “Mom pilked the apple”, the child can use knowledge about the language’s syntax to infer that “pilked” refers to an event where “Mom” is an agent acting on a patient, “the apple”, thereby constraining the hypothesis space of possible referents. A large body of empirical literature over the past twenty years has experimentally tested children’s ability to use syntactic information to infer verb meanings. The goal of the current paper is to synthesize this literature quantitatively using meta-analytic methods in order to evaluate the evidential value of this literature and understand theoretical and methodological moderators of the strength of the effect.

The earliest work on syntactic bootstrapping demonstrated that children were able to use course-grain syntactic information to constrain word meaning. Brown (1957) presented 3- to 5-year-old children with sentences containing a novel word in different syntactic categories (e.g.,“ Do you know what it means to sib?” (verb) vs. “Do you know what a sib is?” (noun)), and found that children were able to use the novel word’s grammatical class to infer the correct referent (action versus noun). Subsequent studies demonstrated that children are able to use more nuanced syntactic information to infer a word’s meaning. In particular, this work focused on the distinction between transitive and intransitive verbs, and found that children were able to successfully map a transitive sentence to a two-agent causative event, and an intransitive sentence to a non-causative event.

In the canonical version of the syntactic bootstrapping paradigm, children are presented with two visual stimuli simultaneously, along with a sentence (Naigles, 1990). One visual stimulus depicts two characters doing a causative action (e.g., pushing), and the other depicts one or more characters doing a non-causative action (e.g., waving). Children then hear a transitive (e.g., "The duck is gorping the bunny") or intransitive sentence (e.g., "The duck and the bunny are gorping") with a novel verb, and then are asked to find the novel verb ("Where's the gorping now?"). Children's fixation time or pointing selections are then measured. A longer looking time for either of the screen indicated a match between the children's conceptual representations of the novel verbs and the action on the screens. Evidence for syntactic bootstrapping is found when children in the transitive condition look longer at the causal action than the non-causal action, and the children in the intransitive condition show the opposite pattern. This pattern is taken as evidence that children can use syntactic structure to inform the meanings of novel verbs in a surprisingly detailed way.

The body of empirical literature investigating syntatic bootstrapping has demonstrated that children are able to successfully use syntatic information to bootstrap verb meaning given a range of linguistic () and visual stimuli (), and under a range of methodological implementations (). These studies provide a binary description of the effect ("there is an effect") with various samples of children under various condition, but do not quantify the *strength* of the effect. Quantifying the strength of the effect allows researchers to assess the degree to which a learning strategy can be used by young learners to acquire verb meanings. Further, quantifying the size of an effect allows for the quantitative comparision to other proposed learning mechanisms for infering the meaning of a word in a local context. For example, children may be able to infer a word's meaning by using co-occurrence statistics between words and referents ("cross-situational learning"; Smith & Yu, 2008; Yu & Smith, 2007), or by relying on knowledge that each word in a language tends to only have one meaning ("mutual-exclusivity"; Lewis, Cristiano, Lake, Kwan, & Frank, 2020; Clark, 1987; Markman & Wachtel, 1988). While these learning strategies, and others, could in principle be applied to verbs, there is reason to think that these strategies may be better suited for concrete nouns, where the perceptual information is less complex. Consistent with this prediction, verbs are typically learned later in development than verbs (e.g. XXX, Frank, Braginsky, Marchman, & Yurovsky, 2019). Understanding the the relative strength of various learning strategies for mapping word forms to word meanings could shed light on the source of the developmental lag in verb learning.

In addition to uncertainty about the overall size of the syntactic bootstrapping effect, there are a number of open theoretical questions about the nature of the effect. First, how does the strength of the effect change across development? One possibility is that the ability to use syntactic bootstrapping to learn novel verbs is available early on in development as soon as the relevant syntactic information is represented, and the ability does not strengthen with development. An alternative possibility is that the effect becomes stronger with maturation and experience. There are a range of reasons to think that the effect might strengthen. For example, with development, children's vocabulary size increases, making it more likely they will know the nouns in the linguistic input containing a novel verb. If the effect becomes stronger with development, this would suggest that syntactic bootstrapping might become an increasingly powerful learning mechanism for children as they learn more words. [learning to learn stuff] Prior work has examined the syntactic bootstrapping effect within a few age groups (e.g., XXX), but it is unclear what the developmental trajectory of this effect looks like. Characterizing this developmental change is important to understanding the role that different word learning strategies play across the development.

Second, how robust is the effect to different kinds of linguistic input? Syntactic bootstrapping is theorized to be a general learning mechanism that could in principle be applied to the range of syntactic structures in children's input. However, some experiments have found a syntactic bootstrapping effect for transitive sentences, but not intransitive sentences (Arunachalam & Waxman, 2010; Yuan, Fisher, & Snedeker, 2012), whereas others find the opposite pattern (Bunger & Lidz, 2004; Naigles & Kako, 1993). Plausible explanations for both patterns have been proposed. For example, the effect may be stronger for transitive sentences relative to intransitives, because intransitive sentences are relatively more flexible in their usage. Consider, for instance, the sentence "the girl is daxing." This sentence could describe either a scene in which a girl is doing a transitive action (e.g. patting a boy) or a scene in which the girl is doing an intransitive action (e.g. jumping). In contrast, the sentence "the girl is daxing the boy" could only describe a scene in which the girl is doing a transitive action (e.g. patting the boy). This asymmetry may lead children to treat the syntactic information in sentences with transitive novel verbs as a stronger cue to a word's meaning, relative to sentences with an intransitive novel verb. On the other hand, intransitive sentences have fewer processing demands relative to transitive nouns (Lidz, Bunger, Leddon, Baier, & Waxman, 2009), thereby potentially making syntactic bootstrapping easier for intransitive nouns and predicting that the effect should be stronger for intransitives, relative to transitive stentences.

The literature has also revealed conflicting findings about the robustness of syntactic bootstrapping to different types of noun phrase structures. In everyday discourse, people and objects are often referred to by pronouns (e.g., "she") instead of descriptive nouns ("the girl"). There is some evidence in the literature that semantically rich, descriptive nouns are beneficial for verb learning because the semantic content of the surrounding nouns can help scaffold the interpretation of the verbs (Arunachalam & Waxman, 2011, 2015; Fisher, Hall, Rakowitz, & Gleitman, 1994; Gillette, Gleitman, Gleitman, & Lederer, 1999; Gleitman, Cassidy, Nappa, Papafragou, & Trueswell, 2005; Imai et al., 2008; Piccin

& Waxman, 2007). Others, however, have found that pronouns reduce processing load, thereby facilitating syntactic bootstrapping (Childers & Tomasello, 2001; Lidz et al., 2009). In the case of both sentence structures and noun phrase structures, it is difficult to evaluate the robustness of syntactic bootstrapping to variability in the linguistic input without a clear understanding of the empirical pattern.

The meta-analytic method provides a powerful analytic tool for quantifying theoretically important effects, and has increasingly been used in the language acquisition literature (Bergmann et al., 2018). Meta-analysis involves quantifying the size of an effect in individual experiments with a standardized measure (such as Cohen's d), and then aggregating across studies statistically to estimate an overall effect size. Because a meta-analysis reflects estimates from many more participants than an individual study, the meta-analytic method has greater power to detect a true effect and precisely quantify it. The meta-analytic method also allows researchers to explore moderators of an effect. Detecting a moderator to a small effect requires large sample sizes, but infant experiments, like those investigating syntactic bootstrapping, typically have small sample sizes (Bergmann et al., 2018; Oakes, 2017). These small sample sizes mean that individual studies have low power to detect a true moderating effect, creating the potential for many null and conflicting effects for moderating influences. Meta-analysis addresses this limitation by providing a high-powered test of theoretically important moderators factors, as well as revealing variability in effect sizes due to methodological variability across studies.

The plan for the paper is as follows. We first describe our method for conducting a meta-analysis of the syntactic bootstrapping effect. We then assess the evidential value of this literature by evaluating the influence of publication bias. Next, we characterize the size of the effect with respect to other word learning phenomena. We then examine the moderating influence of experience, sentence structure, and noun phrase structure on the syntactic bootstrapping effect, and the relationship between theoretical moderators and methodological variability in our meta-analytic data. We find some evidence for publication bias in the syntactic bootstrapping literature, but that there is nevertheless a small syntactic bootstrapping effect. The effect is larger for transitive sentences, relative to intransitive sentences, but does not appear to be influenced by experience, noun phrase structure, and a range of methodological factors. In the General Discussion, we discuss the implications of our findings for theories of verb learning.

Method

Literature Search

We conducted a literature search of the syntactic bootstrapping literature following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist (PRISMA; Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2009). We identified relevant papers by conducting a keyword search in Google Scholar with the phrase "syntactic bootstrapping" and a forward search on papers that cited the seminal paper, Naigles (1990) (total records identified: N = 3,339; retrieved between May 2020 and July 2020; Figure 1). We screened for relevance the abstracts of the first 60 pages of the keyword search results (N = 600) and the first 10 pages of the forward search results (N = 100). The screening processes ended because we could no longer identify relevant, non-duplicate papers from consecutive pages. Additional papers were identified by consulting the references section of the most recent literature review (N = 155; Fisher, Jin, & Scott, 2020) and experts in the field (N = 11). Our sapmle included published journal articles, conference proceedings, doctoral dissertations, and unpublished manuscripts. These will be collectively referred to as "papers" in the following sections. Each paper may include multiple experimental conditions, and thus provides multiple effect sizes for the final analysis.

We restricted our final sample to papers that satisfied the following criteria: First, the experimental paradigm involved a two-alternative forced-choice task in which participants were instructed to identify the scene that matched the linguistic stimuli. Second, the visual stimuli were two events displayed side-by-side on a computer monitor. The two events included one depicting causative action (e.g. one agent causes the other to move), and one non-causative action (e.g. two agents move simultaneously but do not causally interact with each other). We included studies with either videos of live actors or animated clips. Third, the linguistic stimuli included at least one novel verb embedded in a syntactically informative frame. For example, "Look, it's kradding!" embeds the novel verb in an intransitive syntactic frame that is informative about the meaning of the novel verb "kradding". In contrast, "Look, kradding!" does not provide informative syntactic information. Finally, we restricted our sample to studies with English-speaking, typically-developing children. Papers that satisfied these constraints reflected a range of methodological implementations which we examine analytically below (see moderators).

Our final sample included 18 individual papers, corresponding to 60 individual effect sizes and 730 unique infants (Mean age: 758.77 days).

Data Entry

For each paper, we entered the paper's metadata (e.g., citation), information to calculate effect sizes, and moderators. We entered a separate effect size for each experimental condition and age group per paper. Most papers therefore contained multiple effect sizes.

Calculating individual effect sizes. In order to calculate each effect size, we recorded the sample size of each condition, the group mean, and the across-participant standard deviation. The mean and standard deviation were obtained from one of the four methods: a) retrieved from the results section or the data-presenting tables (N = 37); b) recovered from the plots (N =10); c) contacted the original authors (N = 12); d) imputed using values from studies with similar designs (N = 1, Hirsh-Pasek, Golinkoff, & Naigles

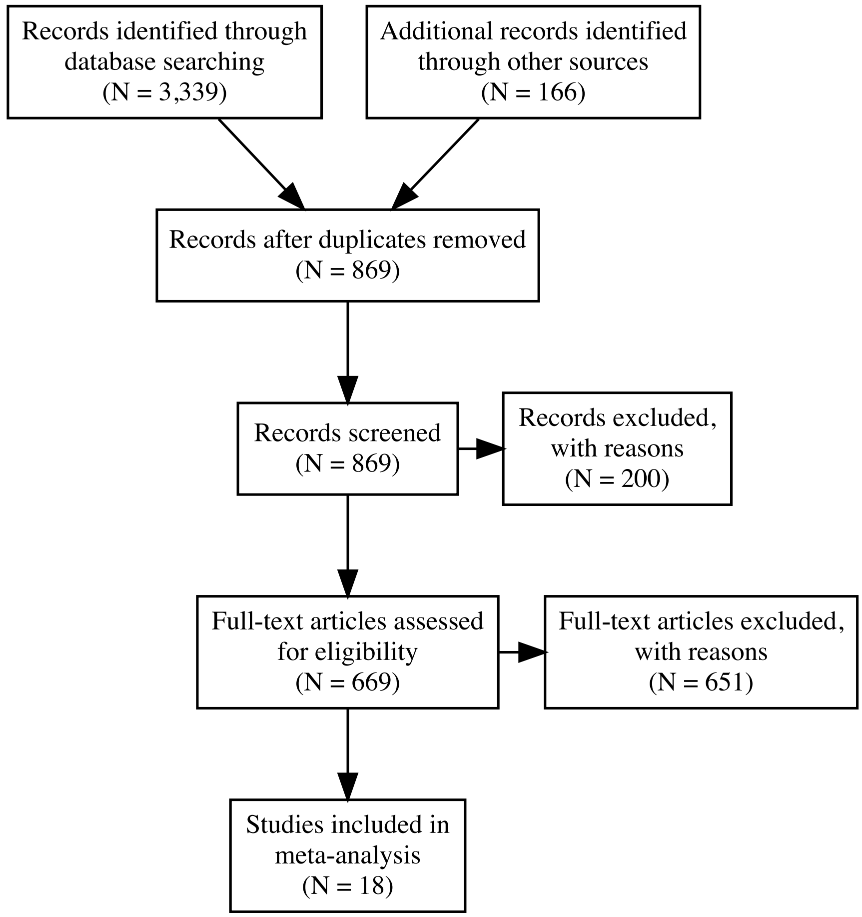


Figure 1. PRISMA plot showing...

(1996); the missing SD values were imputed from Naigles (1990)). Previous work suggests using imputed values from highly similiar studies improves the accuracy of effect size estimates (Furukawa, Barbui, Cipriani, Brambilla, & Watanabe, 2006). The reported results do not qualitatively change when conditions from Hirsh-Pasek et al. (1996) are excluded from our sample (see SI).

Using the raw coded data, we calculated an effect size estimate for each condition as Cohen's d. Cohen's d was calculated as the differemce between the proportion correct responses and chance (.5), divided by a pooled estimate of variance (see SI for example calculation). Note that we assume baseline performance to be .5 in all cases, even when an empirical baseline was reported ($N = 6$ conditions). This analytical decision was made in order to standardize the effect size estimate across all conditions in our sample, most of which did not report an empirical baseline.

Moderators. For each effect size in our sample, we coded several theoretical and methodological variables. The information was either retrieved from the methods section of the paper or obtained by contacting authors.

Four theoretical variables were coded: participant age, participant vocabulary size, sentence structure type, and noun phrase type. Participant age was entered in mean age in days ($N = 60$). Vocabulary size was recorded as the median productive vocabulary measured by MacArthur-Bates Communicative Development Inventories (CDI) Words and Sentences (Fenson, 2000; $N = 32$). Sentence structure was coded as either transitive ($N = 30$) or intransitive ($N = 30$). Noun phrase type encoded information about the agent verb argument of the sentence stimulus. The agent of the sentence was coded as either as being either noun (e.g., "the girl"; $N = 26$) or pronoun ("she"; $N = 34$). A condition was coded as "pronoun" if it contained at least one instance of a pronoun refering to the agent.

In addition to the theoretical variables, we coded a range of methodological variables that varied across the studies in our sample. First, we coded whether the paradigm included a practice trial prior to the testing phase. A study was coded as having a practice trial if there was at least one trial in which children were presented with a familiar verb and asked to identify a familiar action (e.g. "Find jumping"; N with practice phase $= 36$). Second, we coded whether or not the paradigm involved trials in which children were prompted to identify the nouns in the testing events (e.g., "Where's the bunny?"; N with character identifcation phase $= 16$). Third, we coded whether the linguistc and visual stimuli were presented synchronously with each other ("Stimuli Synchronicity"). An experimental condition was coded as "asynchronous" if the linguistic stimulus was first paired with an irrelevant visual scene (e.g. a person on the phone talking), and the matching visual stimulus was not shown until the training phase is over ($N = 37$); a condition was coded as "simultaneous" if the very first training sentence was presented along with the visual stimuli depicting relevant action or along with an attention-getter or a blank screen, immediately followed by the relevant action ($N = 23$). Fourth, we coded coded the temporal distribution of the training and the testing trials (Mass: $N = 28$; Distributed: $N = 32$). A procedure was categorized as "mass" if participants were trained exclusively on one novel verb and tested on the same verb. Finally, we coded how many times each novel verb was spoken in a syntactically-informative way during training.[1]

Analytic Approach

We analyzed the data using multi-level random effect models implemented in the metafor package in R (Viechtbauer, 2010). The random effect stucture included groupings by paper and participant group in order to account for the clustering of effect sizes in our sample. Moderator variables were included as additive fixed effects. All estimate ranges correspond to 95% confidence intervals, unless otherwise noted. Data and analysis scripts are available at XXXX, and the dataset can be interactively explored at XXXX.

Results

Figure 2 shows effect size estimates for all conditions in our sample. The weighted mean effect size was 0.25 [0.06, 0.45], which significantly differed from 0 ($Z = 2.51$; $p = 0.01$).

Evidential value of the syntactic bootstrapping literature

We first evaluated the evidence for publication bias in order to determine the evidential value of the literature. Publication bias refers to the tendency to selectively publish positive findings, which inflates meta-analytic estimates of effect size and threatens the evidential value of the literature. We present two analyses of publication bias: a classic

[1] See SI for additional methodological moderators.

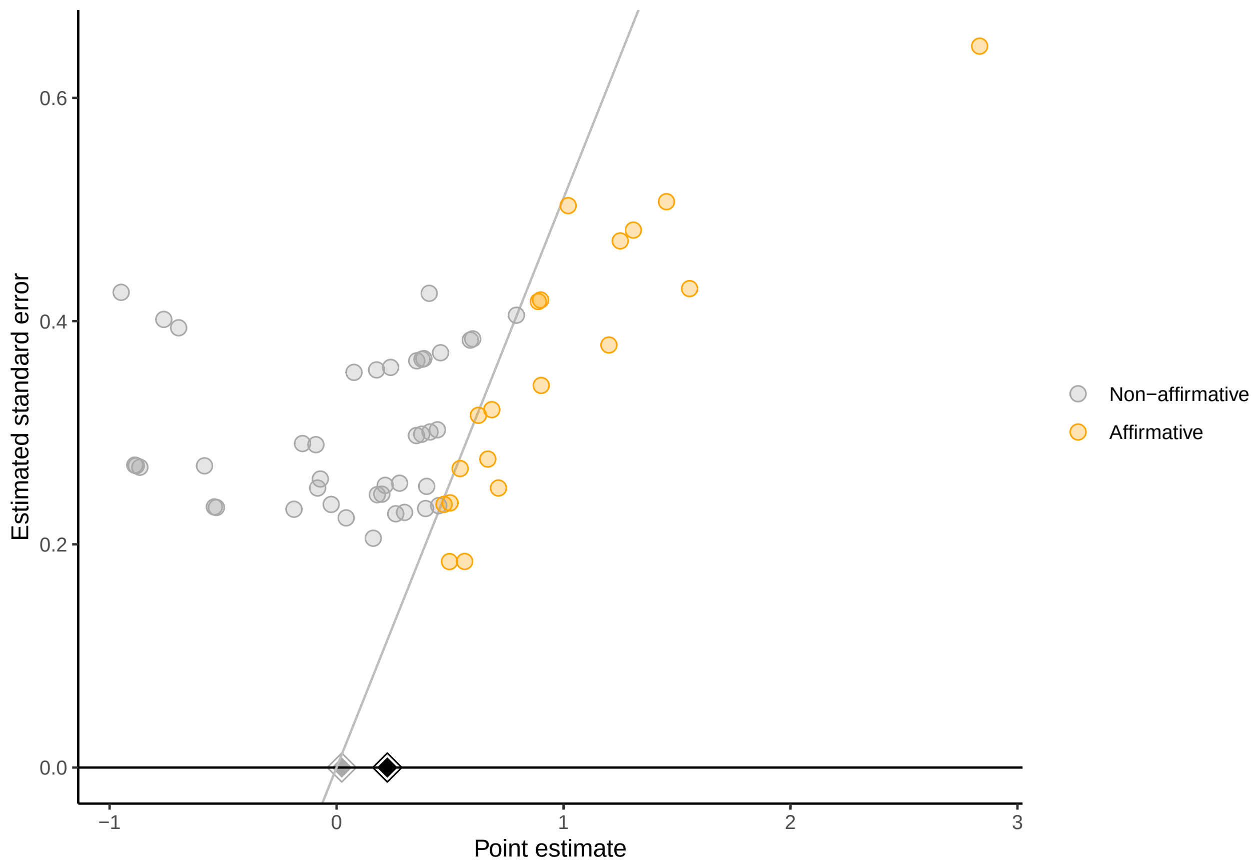
funnel plot analysis, and a sensitivity analysis that assumes a more plausible model of publication bias.

Figure 3 presents the funnel plot for the effect sizes in our sample. A funnel plot shows estimates of effect size variance (plotted with large values lower on the axis) as a function of the magnitude of the effect size (cite egger 1997). Under a model of publication bias in which researchers decide whether or not to publish a study based on the magnitude of its effect size (larger effect sizes being more likely), effect size estimates should fall symmetrically around the grand effect size estimate. Evidence of asymmetry around the grand mean, particularly more large, positive effect sizes, suggests that the literature reflects a biased sample of studies. A formal test of asymmetry in our sample revealed evidence for asymmetry (Egger's test: $Z = 3.91$; $p < .0001$).

The funnel plot analysis provides some evidence for publication bias, but the intreprtation of this analysis is limited by the fact that it assumes a relatively implausible model of how researchers decide which studies to make public (CITE): the criteria for publishing a study in a journal is typically not the size of the effect, as assumed by the funnel plot analysis, but rather whether or not the p-value of the hypothesis test for that effect is below some threshold (usually .05). We therefore conducted a second analysis of publication bias, called a sensitivity analysis (Mathur & VanderWeele, 2020), that assumes that publication bias operates overthe size of the p-value, rather than the magnitude of the effect size.

The intuition behind the sensitivity analysis…

Instead, it estimated the severity of publication bias by considering how much more likely the "affirmative studies" will be published than the "non-affirmative studies". Furthermore, it calculated the severity of publication bias needed in the literature to attenuate the meta-analytic effect size down to zero.


0.6
0.4
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Estimated standard error
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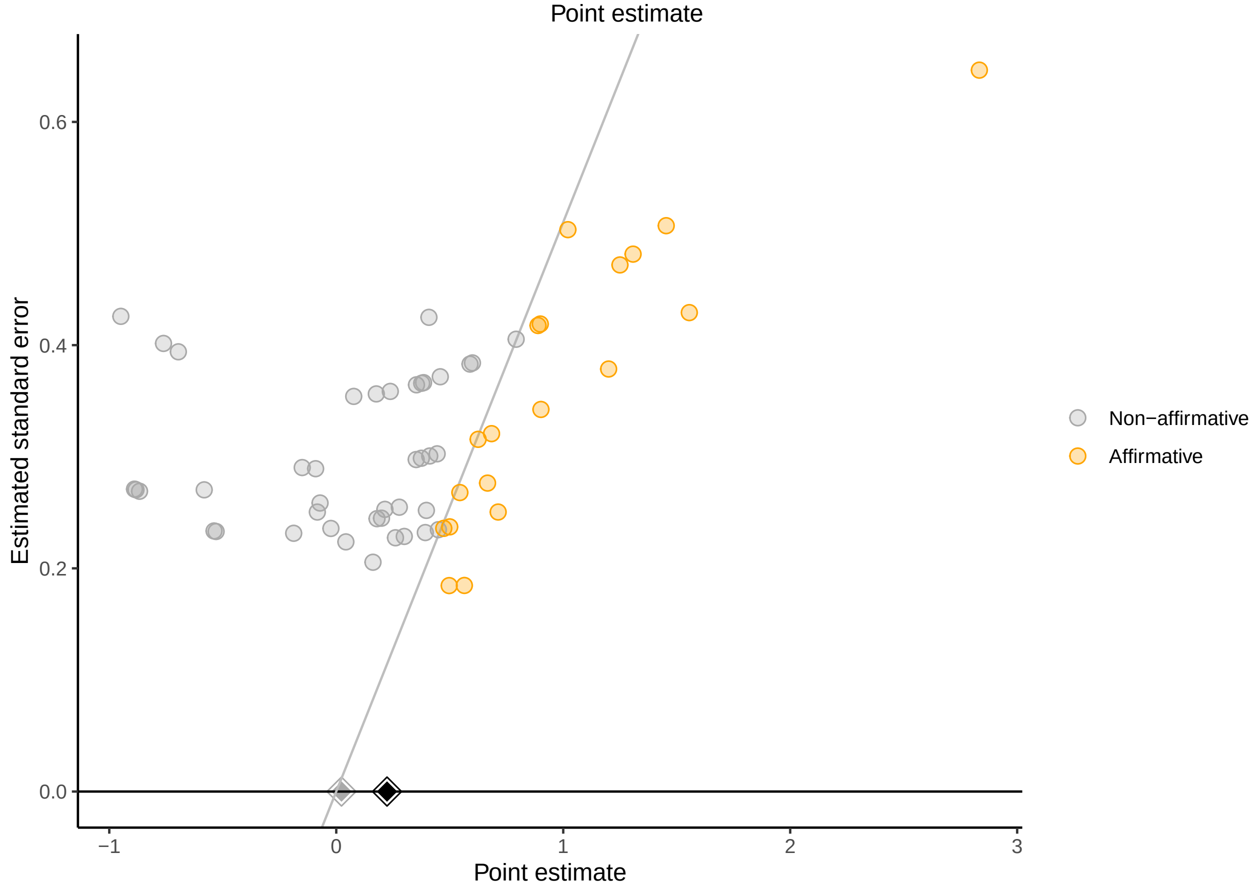

0.6
0.4
0.2
0.0
Estimated standard error
−1
0
1
2
3
Point estimate
Non−affirmative
Affirmative

We ran the analysis using the PublicationBias package (Mathur & VanderWeele, 2020). In this analysis, we considered the worst-case scenario when the publication bias is most severe. To do so, we ignored all the positive findings and considered only the negative findings. However, under this condition, the meta-analytic effect size is still above zero. This result can also be seen in the modified funnel plot (Figure @ref(fig:moderated_funnel)). In plot, the x-axis represents the point estimate of Cohen's *d*. The y-axis represents the estimated standard error. The gray line represents studies with a p-value of 0.05. To the left of the line are the non-affirmative studies (represented by gray dots), and to the right are the affirmative studies (represented orange dots). The diamonds near the x-axis are meta-analytic effect sizes. Note that the black one is pooling from all studies, whereas the gray one is only pooling from the non-affirmative studies. Although the gray diamond is closer to the significance line than the black diamond, it does not cross the gray line. Therefore, even in the scenarios with the worst publication bias, where we only consider the non-affirmative studies results, the meta-analytic effect size of syntactic bootstrapping still has a positive value.

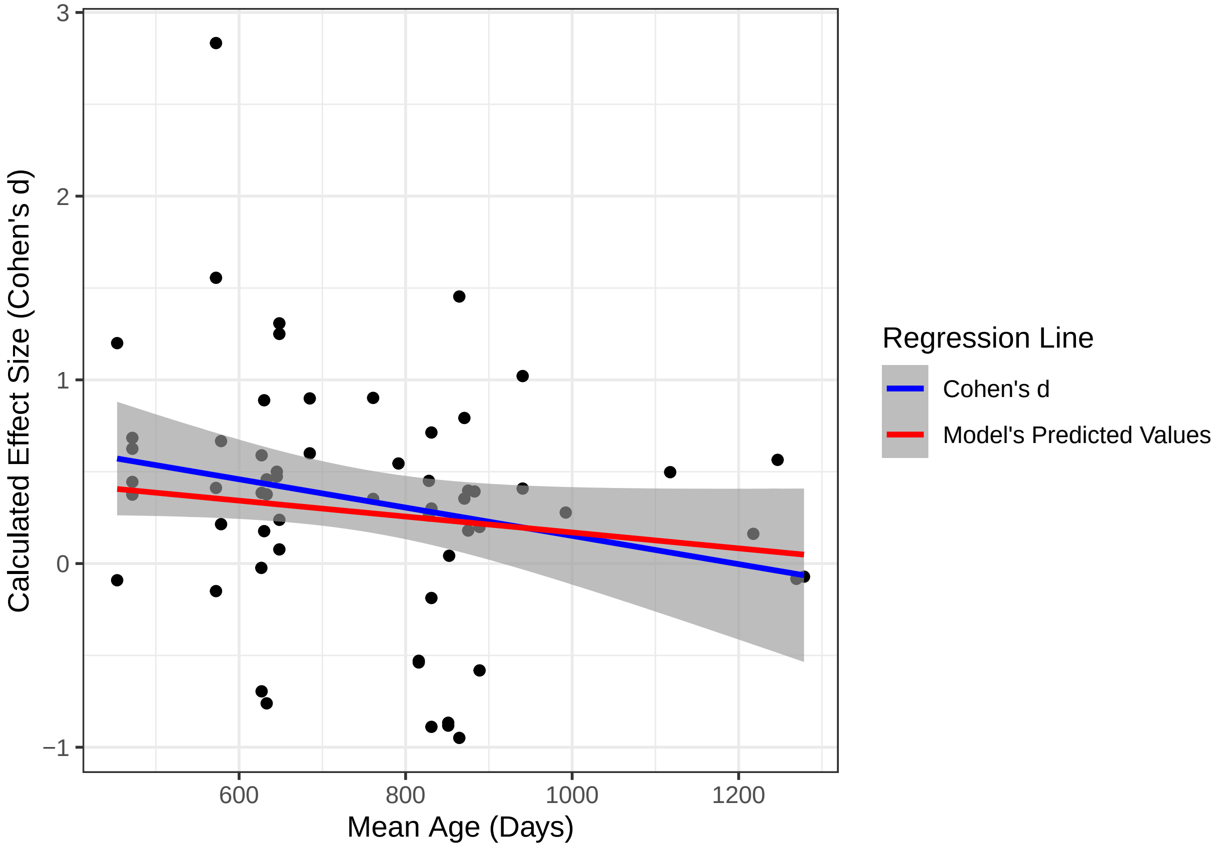
In conclusion, across two analyses we find some evidence for publication bias, but the bias alone is not sufficient to explain away the observed effect. Some of the observed bias using the classical methods might be attributed to the heterogeneity in the data. In the following sections, we analyzed theoretical factors and methodological factors that were contributing to this heterogeneity.

Relating the syntactic bootstrapping effect to other word learning stategies

Theoretical Moderators

There was evidence for considerable hetergenity in effect sizes across our sample (Q = 197.75; p <.001). We next explored whether this hetergenity could be accounted for by the theoretical moderators of interest.

Experience.

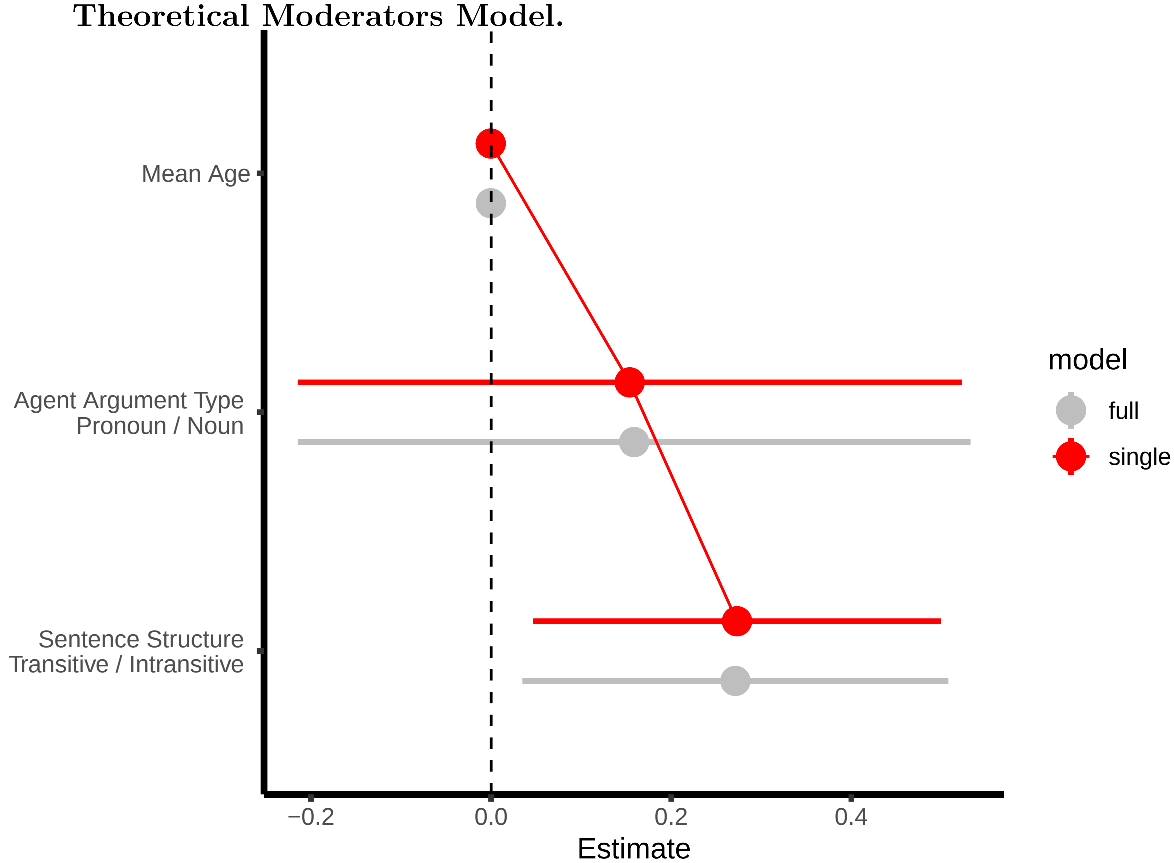


Children do not perform better in the syntactic bootstrapping task as they get more experience. Although age and median productive vocabulary size correlated with each other ($r(30) = 0.85$, p: < 0.0001), neither one was a significant predictor of the effect size in the mixed-effect linear regression model (Age: $\beta = 0$ [0, 0], $SE = 0$, $z =$ -1.40, $p = 0.16$; Vocabulary Size: $\beta =$ -0.01 [-0.02, 0], $SE = 0.01$, $z =$ -1.74, $p = 0.08$).

Sentence structure. One question we were hoping to address is how the verbs' syntactic environment and the semantic environment influence the learning outcome. To answer this question, we considered two moderators: the sentence structure and the types of words in the agent argument. The moderator sentence structure has two levels: transitive sentence and intransitive sentence. We fit a mixed effect model with the sentence structure as the single predictor. Our model suggests that sentence structure is a significant predictor ($\beta = 0.27$ [0.05, 0.5], $SE = 0.12$, $z = 2.36$, $p = 0.02$). Children tested in the transitive conditions (M = 0.50, SD = 0.72) tend to have larger effect size than those tested under the intransitive conditions (M = 0.18, SD = 0.58).

Noun phrase type. Like sentence structure, the moderator agent argument structure also has two levels: pronoun and noun. Using a similar model, we found that the agent argument type is not a significant predictor of the effect size (β = 0.15 [-0.21, 0.52], SE = 0.19, z = 0.82, p = 0.41).

Theoretical Moderators Model.



Finally, we also fit a mixed-effect model that includes all the moderators discussed above. Because there is no a priori reason to believe that these factors would interact with each other, we did not include interaction terms. We also excluded the median vocabulary size because there were only 32 conditions with this information avaialble. In this model, the intercept is no longer significant (β = 0.28 [-0.32, 0.89], SE = 0.31, z = 0.91, p = 0.36). This suggests that the moderators can explain away some observed learning effects. The results for other predictors are consistent with the single-moderator models. Sentence structure is a significant predictor (β = 0.27 [0.03, 0.51], SE = 0.12, z = 0.91, p = 0.36), whereas agent argument type (β = 0.16 [-0.21, 0.53], SE = 0.19, z = 0.83, p = 0.31) and mean age (β = 0 [-0.001, 0], SE = 0, z = -1.01, p = 0.31).

In summary, we found that sentence structure is a significant predictor of the effect size. Children tested with the transitive sentences performed better than those tested with intransitive sentences. The semantic content of the words in agent argument, that is, whether the words are nouns or pronouns, was not found to be a significant predictor. Neither age nor the median productive vocabulary size as measured by CDI was a significant predictor of the effect size.

Methodological Moderators

Motivated by the original Naigles (1990) study, a majority of the research in Syntactic Bootstrapping drew heavily on the Intermodal Preferential Looking Paradigm Golinkoff, Hirsh-Pasek, Cauley, & Gordon (1987). Each of these later study designs often involved some study-specific adaptations of the paradigms. In this section, we consider how the various methodological changes may or may not have moderated the infants' learning outcome.

Role of testing phases. Some studies added additional phases such as character identification phase or practice phase to help infants get used to the testing set-up. We found that neither the presence of the character identification phase (β = 0.19 [-0.24, 0.62], SE = 0.22, z = 0.85, p = 0.39) nor the practice phase (β = -0.21 [-0.5, 0.09], SE = 0.15, z = -1.39, p = 0.17) predicts the effect size.

Role of synchronicity. Studies fall under three categories under the synchronicity between linguistic stimuli and visual stimuli: asynchronous, immediate-after and simultaneous. Asynchronous studies present the linguistic stimuli before the relevant visual stimuli. Immediate-after studies show the linguistic stimuli while the infants are exposed to attention-getter or blank-screen, and the visual stimuli were to follow immediately after.

Simultaneous studies present the visual stimuli and the linguistic stimuli together. We collapsed the latter two levels into one because they contained insufficient number of effect sizes for well-powered analysis. Our model result suggested that infants' learning outcomes were not influenced by this factor. (β = 0.1 [-0.21, 0.41], *SE* = 0.16, z = 0.65, p = 0.52).

Role of the testing procedure structure. Last but not least, the structure of the testing procedure, mass testing or distributed testing, did not predict the effect size in a statistically meaningful way (β = 0.34 [-0.08, 0.76], *SE* = 0.21, z = 1.60, p = 0.11). Infants performed similarly in studies that have multiple train-test pairs and single train-test pair. Furthermore, contrary to common beliefs, the number of exposures per novel verb the infants received prior to testing does not predict the effect sizes either (β = 0.01 [-0.02, 0.03], *SE* = 0.01, z = 0.43, p = 0.67).

Methodological Moderators Model.

```
##
## Multivariate Meta-Analysis Model (k = 60; method: REML)
##
##   logLik  Deviance       AIC       BIC      AICc
## -44.0482   88.0964  106.0964  123.9973  110.1873
##
## Variance Components:
##
##             estim    sqrt  nlvls  fixed                         factor
## sigma^2.1  0.0766  0.2768     18     no                     short_cite
## sigma^2.2  0.1086  0.3295     59     no        short_cite/same_infant
## sigma^2.3  0.0000  0.0000     60     no  short_cite/same_infant/x_1
##
## Test for Residual Heterogeneity:
## QE(df = 54) = 160.1233, p-val < .0001
```

```
##
## Test of Moderators (coefficients 2:6):
## QM(df = 5) = 8.3663, p-val = 0.1372
##
## Model Results:
##
##                                          estimate      se     zval    pval
## intrcpt                                   -0.1796  0.3024  -0.5939  0.5526
## character_identificationyes                0.2127  0.2621   0.8115  0.4171
## practice_phaseyes                         -0.1566  0.1528  -1.0249  0.3054
## presentation_type_collapsedsimultaneous    0.3091  0.2680   1.1536  0.2487
## test_mass_or_distributedmass               0.4671  0.2309   2.0230  0.0431
## n_repetitions_sentence                     0.0211  0.0185   1.1423  0.2533
##                                            ci.lb   ci.ub
## intrcpt                                  -0.7722  0.4131
## character_identificationyes              -0.3010  0.7263
## practice_phaseyes                        -0.4560  0.1429
## presentation_type_collapsedsimultaneous  -0.2161  0.8343
## test_mass_or_distributedmass              0.0145  0.9196  *
## n_repetitions_sentence                   -0.0151  0.0573
##
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
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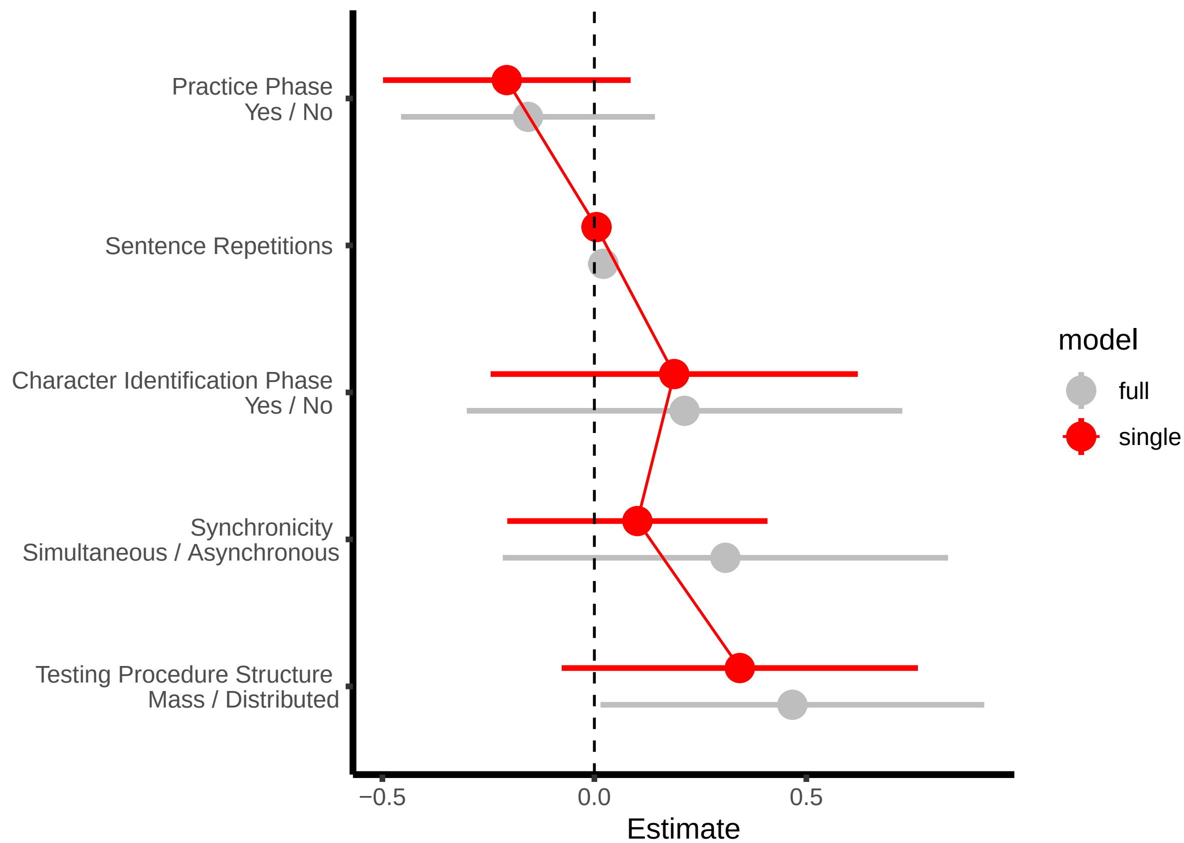

We fit a model that included all the theoretical moderators considered above: the presence of character identification phase, the presence of practice phase, the synchronicity between linguistic stimuli and visual stimuli, the structure of testing procedure and the number of repetitions per novel verb prior to the test. Like the methodological moderators models, the intercept became insignificant (β = -0.18 [-0.77, 0.41], SE = 0.30, z = -0.59, p = 0.55). Most of the moderators were still insignificant, with the exception of testing procedure structure. This moderator became marginally significant in the mega-model, suggesting that children tested in procedure with only one train-test pair performed better than those tested in procedure with multiple train-test pairs (β = 0.47 [0.01, 0.92], SE = 0.23, z = 2.02, p = 0.04). The differences between predictors' performance in single-moderator models and mega-model can be seen in (Figure @ref(fig:methodological_mega_model)).

General Discussion

- Explanations for lack of age effect: variability in design as a function of age, change in input, etc. [Meta point: measuring developmental change requires constancy in task]
- small effect means ma has low power
- Transitivity effect is robust - implications for this? Cross-linguistic implications? Text from old intro about multiple possible explanations of this

Children build up their vocabularies at a dazzling speed. Toward the end of the second year, they were estimated to have a productive vocabulary size of around 300 (Fenson et al., 1994). But children's impressive word-learning abilities do not apply equally to words of all kinds. Verbs, for example, constitute a special challenge for children. Numerous observational studies have shown that verbs are often learned later than nouns (Goldin-Meadow, Seligman, & Gelman, 1976; Lieven, Pine, & Barnes, 1992; Longobardi, Spataro, Putnick, & Bornstein, 2017; Nelson, 1973; Nelson, Hampson, & Shaw, 1993), and laboratory experiments also found that children's verb learning is more slowly and difficult than noun learning(Abbot-Smith, Imai, Durrant, & Nurmsoo, 2017; Childers, Heard, Ring, Pai, & Sallquist, 2012; Childers & Tomasello, 2002, 2006; Gentner, 1978; Imai et al., 2008; Oviatt, 1980; Schwartz & Leonard, 1984). Some scholars have argued that the challenge of verbs is language-dependent (Choi & Gopnik, 1995; Tardif, 1996; Tardif, Gelman, & Xu, 1999). Nevertheless, the cross-linguistic findings are mixed, with others found consistent patterns across languages (Au, Dapretto, & Song, 1994; Bornstein et al., 2004; Kim, McGregor, & Thompson, 2000; Papaeliou & Rescorla, 2011). A more recent large scale, cross-linguistic corpus analysis has shown that across 23 different languages, verbs and other predicates, when compared with nouns, constitute a smaller proportion of children's early production vocabularies, though there are more cross-linguistic differences in early comprehension vocabularies (Frank et al., 2019). Together, these findings suggest that at least certain aspects of the challenge associated with verb learning are universal across languages. Some have hypothesized that it is due to the nature of verbs' references: Unlike nouns, the references of verbs are ephemeral and ever-changing. As a consequence, to learn verbs, children need to rely less on the unreliable extralinguistic information and rely more on the information within the verbs' linguistic context, such as syntax(Gentner & Boroditsky, 2001, p. Gentner (2006)).

The idea that syntactic information can shape children's interpretations of novel words was not new. As early as the late 1950s, a classic study by Brown (1957) has shown that 3- to 5-year-old children would choose to map a novel word to an action if the word is introduced in a verb context (e.g."Do you know what it means to sib?"), and map to an object if introduced in a noun context (e.g."Do you know what a sib is?"). However, this early finding only provided evidence for older children's abilities to discriminate between syntactic categories. It remained unknown how early the abilities emerge and how detailed the underlying representations for the verbs are. In the late 1980s and early 1990s, a hypothesis known as "Syntactic Bootstrapping" revived the interests in the early interaction between syntax and verbs' semantics during language development (Gleitman, 1990; Landau & Gleitman, 1985). The basic idea of Syntactic Bootstrapping is that the structures of the sentences were potent cues for children to interpret the meanings of the verbs. This idea soon received empirical support from a seminal study by Naigles (1990). By using the Intermodal Preferential Looking Paradigm (Golinkoff et al., 1987), Naigles (1990) provided the first evidence for 25-month-olds children's abilities to incorporate syntactic cues in verbs learning.

In this seminal study, the children were tested on four different novel verbs. For each novel verb, there was a training phase and a testing phase. During the training phase, the children would hear either a series of transitive sentences or intransitive sentences, depending on the conditions they were assigned to. Each sentence grammatically contained the novel verb (e.g., for transitive: "The duck is gorping the bunny"; for intransitive: "The duck and the bunny are gorping".) The children were also exposed to the visual stimuli depicting a two-actor action while listening to these sentences. The two actors, one in a bunny suit and the other in a duck suit, would perform two novel actions simultaneously. They would move their arms synchronously while the one pushed the other bending forward. After the training phase, the children would be prompted to look for the action (e.g. "Where's the gorping now?"). The children faced two screens side-by-side, one would show the bunny and duck performing non-causal synchronous arm movements, while the other would show the causal pushing-and-bending action. The children's fixation time toward each of the screens was recorded. A longer looking time for either of the screen indicated a match between the children's conceptual representations of the novel verbs and the action on the screens. Naigles (1990) found that children assigned to the transitive condition looked longer at the causal action than the non-causal action, whereas the children in the intransitive condition showed the opposite pattern. This indicated that at this age children can interpret the meanings of novel verbs as informed by the syntactic structures in a surprisingly detailed way.

This paradigm soon became a standard in studying Syntactic Bootstrapping in young children. Numerous experiments have adopted and extended this paradigm to explore different facets of Syntactic Bootstrapping. Many variations of this paradigm were developed: using pointing instead of looking as the behavioral responses measured (e.g., Arunachalam & Waxman, 2010; Kline, Snedeker, & Schulz, 2017; Rowland & Noble, 2010); using human actors as the protagonists of the actions instead of the humans in animal suits (e.g., Gertner & Fisher, 2012; Bunger & Lidz, 2006; Messenger, Yuan, & Fisher, 2015); adding a practice phase or a character-identification phase to reduce the task demands for young children (Gertner & Fisher, 2012; Scott, Chu, & Schulz, 2017; Scott & Fisher, 2009). The changes can potentially bring unintended effects on the learning outcomes: studies differ significantly in the amount of training experience provided to the participants. Some studies, similar to the original Naigles (1990) design, distributed the training experience across multiple different novel verbs (e.g., He et al., 2020a; Arunachalam, 2013; Naigles & Kako, 1993; Naigles, 1996). Others, by the contrary, focused on training and testing on one novel verb throughout the experiment (e.g., Jin, 2015; Kline et al., 2017; Messenger et al., 2015). As a result, children may have heard the novel verb repeated from as little as 3 times (e.g. Naigles, 1990, 1996; Naigles & Kako, 1993), to as many as 27 times (e.g., Arunachalam, 2013) before they were tested. There are also changes motivated by theoretical considerations. For instance, whether the syntactic cues alone were sufficient to support verbs learning has been studied by altering the visual stimuli during the training phase. Rather than seeing the visual stimuli representing the relevant actions, the children in some training phases would see two actors talking to each other or one actor talking over the phone (e.g. Yuan & Fisher, 2009). The absence of extralinguistic cues did not prevent the children from interpreting the novel verbs correctly, which further suggests the significance of the syntactic cues in verb learning at an early age.

The changes in paradigms have also led to some inconsistent findings. For example, The results have been mixed on whether the children have a transitivity bias, that is, children are more likely to match the correct scenes when the novel verbs are embedded in the transitive frames. Some experiments found that children who were exposed to the transitive sentences would show a larger preference to the matching scenes, whereas children exposed to the intransitive sentences looked by chance or showed a looking pattern similar to the control group who were not provided with any relevant syntactic cues (Arunachalam & Waxman, 2010; Yuan et al., 2012). This transitivity advantage can be attributed to three factors: the clarity, the experience, and the perceptual saliency of the stimuli. First, under certain contexts, the transitive sentences have less ambiguity than their intransitive counterparts. If one sees two scenes: in one a girl patting a boy, in the other a girl and a boy jumping side-by-side, then upon hearing “the girl is gorping the boy”, only the scene with patting action is a plausible interpretation. In contrast, if one hears the intransitive sentence, “the girl is gorping”, the verb can be interpreted as being consistent with both the causative scene and the non-causative scene. Second, children may have more experience with transitive sentences than intransitive sentences. A corpus analysis on parental utterances for 1- to 6-year-old children found that transitive sentences make up approximately 24.36% of all utterances, whereas intransitive sentences occupy only 17.24% (Laakso & Smith, 2007). Thus the familiarity with transitive sentences can potentially improve children's understanding of transitive sentences in the lab. Last but not least, the perceptual saliency of the visual scenes may have contributed to the asymmetrical performance in the transitive conditions and the transitive conditions. Children were found to have a baseline preference for two actors event over one actor event (e.g., Yuan et al., 2012), and for synchronous movement over causative movement (e.g., Naigles & Kako, 1993). These preferences can make detecting an effect in the transitive condition easier than in the intransitive condition.

However, other studies have found the opposite pattern. In the second and the third experiment in Naigles & Kako (1993), it was children in the transitive conditions who showed no preference for neither of the events, whereas children in the intransitive conditions looked longer at the matching event. Similarly, Bunger & Lidz (2004) also showed that children exposed to the intransitive sentences tend to look longer at the matching scene but those exposed to the transitive sentences look by chance. There were two proposed explanations for this reversed effect. First, transitive verbs can be more ambiguous under certain contexts due to children's sensitivity to the internal structure of the event. Research has shown that children under 1 year of age already possess impressive abilities to detect the internal structure of an event. Following the structure, they can parse the event into subcomponents(Hespos, Grossman, & Saylor, 2010; Hespos, Saylor, & Grossman, 2009; Stahl, Romberg, Roseberry, Golinkoff, & Hirsh-Pasek, 2014; for a recent review, see Levine, Buchsbaum, Hirsh-Pasek, & Golinkoff, 2019). On the one hand, successful parsing underlies successful verb learning (Friend & Pace, 2011). But on the other hand, this sensitivity to the internal structure of the event can also lead to challenges for learning transitive verbs. As Bunger & Lidz (2004) pointed out, the transitive verbs can denote both the means of the action and the results of the action. In comparison, the possible meanings of intransitive verbs are more constrained to the results of the action. The wider range of possible meanings could make it more difficult for the children to correctly match the sentences and the scenes. The second possibility for this asymmetry is the processing demands brought by the words in the argument positions. Lidz et al. (2009) noted that the minimal demand from a simple transitive sentence is for children to map at least two nouns, the subject and the object to the corresponding agent and the patient. But for an intransitive sentence, the demand can be as low as only mapping only the subject of the sentence to the agent of the scene. In consequence, learning the novel verbs in the intransitive sentences can be easier than in the transitive sentences.

Besides the number of words in the verbs' arguments, the semantic content is also considered to be a key moderator for the learning process. Some scholars have proposed that semantically rich contexts are beneficial for verb learning, because the semantic content of the surrounding nouns can scaffold the interpretation of the verbs, together with the syntactic structure (Arunachalam & Waxman, 2011, 2015; Fisher et al., 1994; Gillette et al., 1999; Gleitman et al., 2005; Imai et al., 2008; Piccin & Waxman, 2007). But the empirical support for this view is mixed. In a recent study, He et al. (2020b) manipulated the amount of semantic content in the subject argument. Some preschoolers were provided with more information about the subject ("The tall girl is fezzing"), and others less ("The girl is fezzing"). Contrary to the semantic-scaffolding view, He et al. (2020b) found that the children learned better when the nouns were not modified, indicating that the children's limited information processing abilities may have impeded them from utilizing the semantic content. This pattern also persists when the number of words in the agent argument is controlled for. Pronouns have less semantic content than concrete nouns. Multiple studies have found that preschool children learn verbs better when the verbs co-occur with pronouns instead of nouns. They are not only more likely to correctly identify the scenes corresponding to the linguistic stimuli but also are more likely to generalize the syntactic frames to new verbs (Childers & Tomasello, 2001; Lidz et al., 2009).

To further shed light on these conflicting findings, we decided to conduct a meta-analysis on syntactic bootstrapping literature. Our first goal is to estimate the robustness of this phenomenon by calculating the meta-analytic effect size. Knowing the effect size is consequential to theory building (Bergmann et al., 2018; Lewis, 2016). Many past meta-analyses have tapped into other domains of early language development such as phonotactic learning (Cristia, 2018), word segmentation (Bergmann & Cristia, 2016), and mutual exclusivity (Lewis et al., 2020). To our knowledge, this is the first meta-analysis examining the development of syntactic abilities in early childhood and its influence on word learning. Our second goal is to examine the potential moderators of the effect. Understanding the moderators can be valuable for both theoretical reasons and practical reasons. Due to the limited sample sizes, individual infant experiments often have insufficient statistical power, which can make detecting relevant moderators difficult (Oakes, 2017). The variations among different testing procedures also made it difficult to reconcile the conflicting findings, because the differences in the observed effect can be caused by a combination of methodological factors, rather than reflecting the differences in the measured constructs. The meta-analytic approach has the opportunity to reveal some of the underlying interactions between different factors, which can inform future researchers about their experimental designs. Last but not least, our fourth goal is to evaluate how the effect changes with age. Most of the syntactic-bootstrapping studies used a cross-sectional design. Despite the virtue of being rigorously controlled, the "time-slice" nature of this design made it difficult to reconstruct a continuous developmental trajectory. The meta-analysis can provide unique insights into how children's abilities to incorporate syntactic information into verbs learning to develop in the first three years of life.

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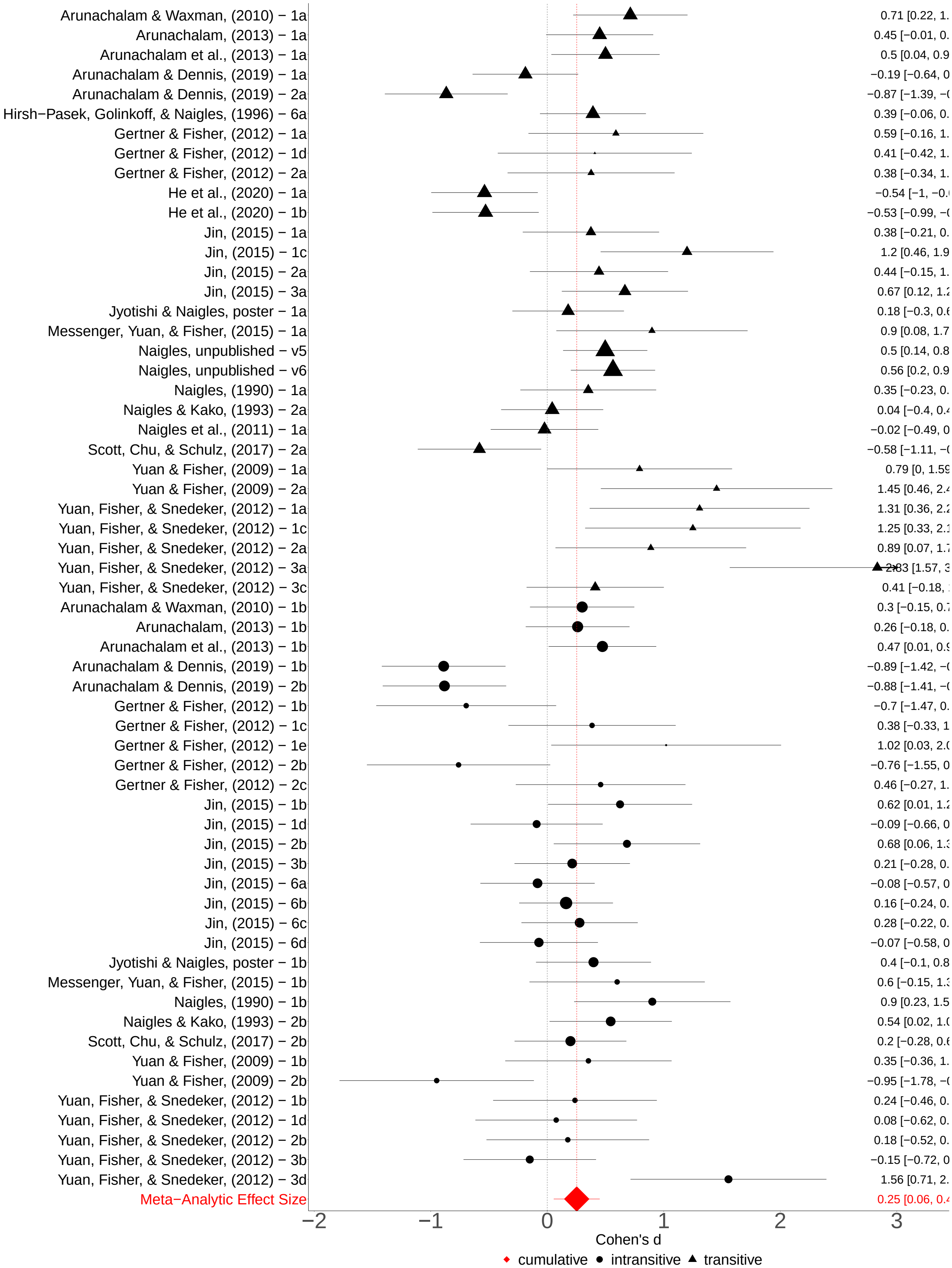
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Hirsh−Pasek, Golinkoff, & Naigles, (1996) − 6a
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Naigles, unpublished − v5
Naigles, unpublished − v6
Naigles, (1990) − 1a
Naigles & Kako, (1993) − 2a
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Jyotishi & Naigles, poster − 1b
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Meta−Analytic Effect Size
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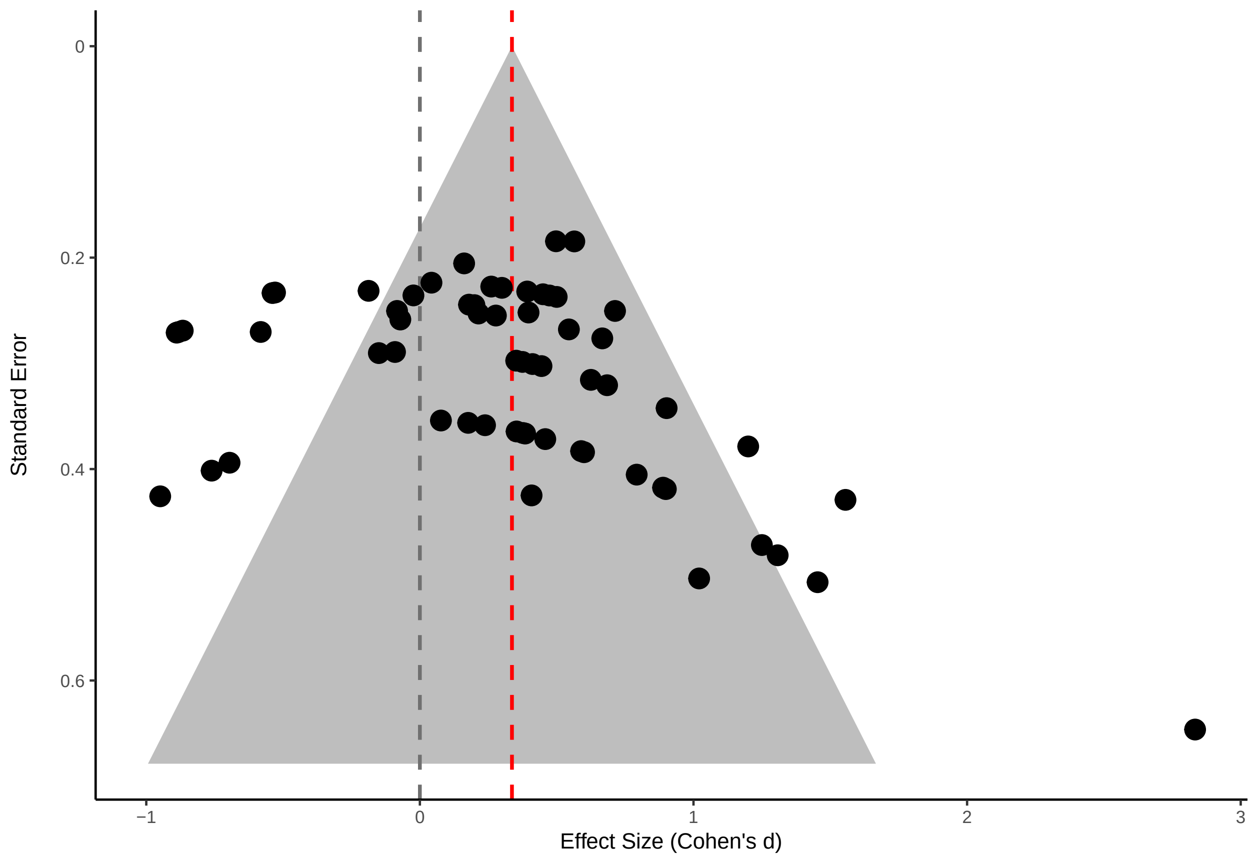

Figure 3. Funnel plots. Each point corresponds to an effect size estimate. The gray dashed line represnets the effect size of zero, the red dash lined represents the mean effect size, and the white funnel represents a 95% confidence interval around this mean.

Appendix