The development of infants' responses to mispronunciations: A Meta-Analysis

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Abstract

As they develop into mature speakers of their native language, infants must not only learn words but also the sounds that make up those words. To do so, they must strike a balance between accepting some variation (e.g. mood, voice, accent), but appropriately rejecting variation when it changes a word's meaning (e.g. cat vs. hat). We focus on studies investigating infants' ability to detect mispronunciations in familiar words, which we refer to as mispronunciation sensitivity. The goal of this meta-analysis was to evaluate the development of mispronunciation sensitivity in infancy, allowing for a test of competing mainstream theoretical frameworks. The results show that although infants are sensitive to mispronunciations, they still accept these altered forms as labels for target objects. Interestingly, this ability is not modulated by age or vocabulary size, challenging existing theories and suggesting that a mature understanding of native language phonology is present in infants from an early age, possibly before the vocabulary explosion. Despite this finding, we discuss potential data analysis choices that may influence different conclusions about mispronunciation sensitivity development as well as offer recommendations to improve best practices in the study of mispronunciation sensitivity.

Keywords: language acquisition; mispronunciation sensitivity; word recognition; meta-analysis; lexicon; infancy

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Introduction

At the turn of the millenium, infant language acquisition researchers had established that during their first two years of life, infants are sensitive to changes in the phonetic detail of newly segmented words (Jusczyk & Aslin, 1995) and learned minimal pairs (Stager & Werker, 1997). Furthermore, when presented with familiar image pairs, children fixate on the referent of a spoken label (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Tincoff & Jusczyk, 1999). Swingley and Aslin (2000) were the first to tie these lines of research together and investigate mispronunciation sensitivity in infant familiar word recognition: Children aged 18 to 23 months learning American English saw pairs of images (e.g. a baby and a dog) and their eye movements to each image were recorded. On "correct" trials, children heard the correct label for one of the images (e.g. "baby"). On "mispronounced" trials, children heard a mispronounced label of one of the images (e.g. "vaby"). The mean proportion of fixations to the target image (here: a baby) was calculated separately for both correct and mispronounced trials by dividing the target looking time by the sum of total looking time to both target and a distractor (proportion of target looking or PTL). Mean fixations in correct trials were significantly greater than in mispronounced trials, and in both conditions looks to the target were significantly greater than chance. We refer to this pattern of a difference between looks to correct and mispronounced words as *mispronunciation sensitivity* and of looks to the target image above chance in each condition as *object identification*. Swingley and Aslin (2000) concluded that already before the second birthday, children represent words with sufficient detail to be sensitive to mispronunciations.

In a mature phono-lexical system, word recognition must balance flexibility to slight variation (e.g., speaker identity, accented speech) while distinguishing between phonological contrasts that differentiate words in a given language (e.g. cat-hat). The study of Swingley and Aslin (2000) as well as subsequent studies examining mispronunciation sensitivity probe this latter distinction. Phonological contrasts relevant for the infant language-learner are determined by their native language. For an infant learning Catalan, the vowel contrast /e/-/E/ signifies a change in meaning, whereas this is not the case for an infant learning Spanish. These contrasts are therefore not inate, but must be learned. In this meta-analysis, we focus on infants' developing ability to correctly apply the phonological distinctions for their native language during word recognition. By aggregating all publicly available evidence using meta-analysis, we can examine developmental trends making use of data from a much larger and diverse sample of infants than is possible in most single studies (see Frank et al. (2017); for a notable exception). Before we outline the meta-analytical approach and its advantages in detail, we first discuss the proposals this study seeks to disentangle and the data supporting each of the accounts.

Research following the seminal study by Swingley and Aslin (2000) has extended mispronunciation sensitivity to infants as young as 8 to 10 months (Bergelson & Swingley, 2017), indicating that from early stages of the developing lexicon onwards, infants can and do detect mispronunciations. Regarding the change in mispronunciation sensitivity over development, however, only about half of studies have compared more than one age group on the same mispronunciation task (see Table 1). Across single studies all possible patterns of development lined out above have been reported, making the current meta-analysis very informative.

Several studies have found evidence for *greater* mispronunciation sensitivity as children develop. More precisely, the difference in target looking for correct and mispronounced trials is reported to be smaller in younger infants and grows as infants develop. Mani and Plunkett (2007) tested 15-, 18-, and 24-month-olds learning British English; although all three groups were sensitive to mispronunciations, 15-month-olds showed a less robust sensitivity. An increase in sensitivity to mispronunciations has also been found from 20 to 24 months (Feest

& Fikkert, 2015) and 15 to 18 months (Altvater-Mackensen, Feest, & Fikkert, 2014) in Dutch infants, as well as German infants from 22 to 25 months (Altvater-Mackensen, 2010). Furthermore, Feest and Fikkert (2015) found that sensitivity to specific kinds of mispronunciations develop at different ages depending on language infants are learning. In other words, the native language constraints which *kinds* of mispronunciations infants are sensitive to first, and that as infants develop, they become sensitive to other mispronunciations.

Other studies have found no difference in mispronunciation sensitivity at different ages. For example, Swingley and Aslin (2000) tested infants over a wide age range of 5 months (18 to 23 months). They found that age correlated with target fixations for both correct and mispronounced labels, whereas the difference between the two (mispronunciation sensitivity) did not. This suggests that as children develop, they are more likely to look at the target in the presence of a correct or mispronounced label, but that the difference between looks elicited by the two conditions does not change. A similar response pattern has been found for British English learning infants aged between 18 and 24 months (Bailey & Plunkett, 2002) as well as younger French-learning infants at 12 and 17 months (Zesiger, Lozeron, Levy, & Frauenfelder, 2012).

One study has found evidence for infants to become *less* sensitive to mispronunciations as they develop. Mani and Plunkett (2011) presented 18- and 24-month-olds with mispronunciations varying in the number of phonological features changed (e.g., changing an p into a b, a 1-feature change, versus changing a p into a g, a 2-feature change). 18-month-olds were sensitive to mispronunciations, regardless of the number of features changed. 24-month-olds, in contrast, fixated the target image equally for both correct and 1-feature mispronounced trials, although they were sensitive to larger mispronunciations. In other words, for 1-feature mispronunciations at least, sensitivity decreased from 18 to 24 months.

Why would mispronunciation sensitivity change as infants develop? Typically, a change in mispronunciation sensitivity is thought to occur along with an increase in vocabulary size, particularly with the vocabulary spurt at about 18 months. As infants learn more words, their focus shifts to the relevant phonetic dimensions needed for word recognition. For example, an infant who knows a handful of words with few phonological neighbors would not need to have fully specified phonological representations in order to differentiate between these words. As more phonologically similar words are learned, however, the need for fully detailed phonological representations increases (Charles-Luce & Luce, 1995). Furthermore, a growing vocabulary also reflects increased experience or familiarity with words, which may sharpen the detail of their phonological representation (Barton, Miller, & Macken, 1980). If vocabulary growth leads to an increase in the phonological specificity of infants' word representation, we should find a relationship between vocabulary size and mispronunciation sensitivity.

Yet, the majority of studies examining a potential association between mispronunciation sensitivity and vocabulary size have concluded that there is no relationship (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Mani & Plunkett, 2007; Mani, Coleman, & Plunkett, 2008; Swingley, 2009; Swingley & Aslin, 2000, 2002; Zesiger et al., 2012). One notable exception comes from Mani and Plunkett (2010). Here, 12-month-old infants were divided into a low and high vocabulary group based on median vocabulary size. High vocabulary infants showed greater sensitivity to vowel mispronunciations than low vocabulary infants, although this was not the case for consonant mispronunciations. Taken together, there is very little evidence for a role of vocabulary size in mispronunciation sensitivity. In our current meta-analysis, we include the relationship between mispronunciation sensitivity and vocabulary size to better understand the variation in experimental results.

Although all mispronunciation sensitivity studies are generally interested in the the phonological detail with which infants represent familiar words, many studies pose more nuanced questions. These questions concern issues at the intersection of phonological development and lexical processing and often result in manipulations of the stimuli and experimental procedure. These manipulations may impact our overall estimate of the effect size of mispronunciation sensitivity. Next to the core investigation of the shape of development of infants' mispronunciation sensitivity, we take the opportunity of a systematic aggregation of data to address these questions and the influence of these manipulations on infants' ability to detect mispronunciations and how this may change with development.

In designing their mispronunciation stimuli, Swingley and Aslin (2000) chose consonant mispronunciations that were likely to confuse adults (Miller & Nicely, 1955). Subsequent research has settled on systematically modulating phonemic features to achieve mispronunciations of familiar words. By utilizing mispronunciations consisting of phonemic changes, these experiments examine infants' sensitivity to factors that change the identity of a word on a measurable level (i.e. 1-feature, 2-features, 3-features, etc.). The importance of controlling for the degree of phonological mismatch, as measured by number of features changed, is further highlighted by studies that find graded sensitivity to both consonant (White & Morgan, 2008) and vowel (Mani & Plunkett, 2011) feature changes. The greater the number of features changed, or *mispronunciation size*, the easier it may be to detect a mispronunciation, whereas more similar mispronunciations may be more difficult to detect.

Although most research examining sensitivity to mispronunciations follows a similar design, there are some notable differences. For example, Swingley and Aslin (2000) presented infants with pairs of familiar images, one serving as the labeled target and one as the unlabeled distractor. In contrast, White and Morgan (2008; see also Mani & Plunkett, 2011; Skoruppa et al., 2013; Swingley, 2016) presented infants with pairs of familiar (labeled target) and unfamiliar (unlabeled distractor) objects. By using an unfamiliar object as a distractor, the infant is presented with a viable option onto which the mispronounced label can be applied (Halberda, 2003; Markman, Wasow, & Hansen, 2003). Infants ages 24 and 30 months associate a novel label with an unfamiliar object, although only 30-month-olds retained this label-object pairing (Bion, Borovsky, and Fernald, 2013). In contrast, 18-month-olds did not learn to associate a novel label with an unfamiliar object, providing evidence that this ability is developing from 18 to 30 months. We may find that if mispronunciation sensitivity changes as children develop, that this change is modulated by *distractor familiarity*: whether the distractor used is familiar or unfamiliar. Although mispronunciation sensitivity in the presence of a familiar compared to unfamiliar distractor has not been directly compared, the baseline preference for familiar compared to novel stimuli is also thought to change as infants develop (Hunter & Ames, 1988). Furthermore, young children have been found to look longer at objects for which they know the name, compared to objects of an unknown name (Schafer & Plukett, 1998). In other words, in absentia of a label, infants may be more or less likely to fixate on an unfamiliar object. To account for inherent preferences to the target or distractor image, mispronunciation experiments typically compare the increase in fixations to the target image from a silent baseline to post-labeling or present the same yoked pairs of target and distractor images in in both a correct and mispronounced labelling context. Considering this evidence, we may expect that in older, but not younger, children, the presence of an unfamiliar distractor may lead to greater mispronunciation sensitivity than in the presence of a familiar distractor.

Furthermore, when presenting infants with a familiar distractor image, some studies control the *phonological overlap between target and distractor labels*. For example, when examining sensitivity to a mispronunciation of the target word “dog”, the vowel mispronunciation “dag” would be paired with a distractor image that shares onset overlap, such as “duck”. This ensures that infants can not use the onset of the word to differentiate between the target and distractor images (Fernald, Swingley, & Pinto, 2001). Instead, infants must pay attention to the mispronounced phoneme in order to successfully detect the change. The influence of distractor overlap also depends on the *position of mispronunciation* in the word, which can be at word onset, medial, or final positions. Models of spoken word processing place more or less importance on the position of a phoneme in a word. The COHORT model (Marslen-Wilson & Zwitserlood, 1989) describes lexical access in one direction, with the importance of each phoneme decreasing as its position comes later in the word. In contrast, the TRACE model (McClelland & Elman, 1986) describes lexical access as constantly updating and reevaluating the incoming speech input in the search for the correct lexical entry, and therefore can recover from word onset and to a lesser extent medial mispronunciations.

TRACE has also been used to model infants' sensitivity to mispronunciation position (Mayor & Plunkett, 2014), finding that as lexicon size increases, so does sensitivity to onset mispronunciations, whereas medial mispronunciations do not experience similar growth. In early language acquisition, infants typically know more consonant compared to vowel onset words. When tested on their recognition of familiar words, therefore, younger infants would show greater sensitivity to onset mispronunciations, which are frequently consonant mispronunciations. The prevalence of consonant onset words may contribute to the finding that consonants carry more weight in lexical processing (C-bias; see Nazzi, Poltrock, & Von Holzen, 2016 for a recent review). In mispronunciation sensitivity, this would translate to consonant mispronunciations impairing word recognition to a greater degree than vowel mispronunciations. Yet, the handful of studies directly comparing sensitivity to consonant and vowel mispronunciations mostly find symmetry as opposed to an asymmetry between consonants and vowels. English-learning 12-, 15-, 18-, and 24-month-olds (Mani & Plunkett, 2007; 2010 keps and tups) and Danish-learning 20-month-olds (Hojen et al., unpublished) demonstrate similar sensitivity to consonant and vowel mispronunciations. One study did find weak evidence for greater sensitivity to consonant compared to vowel mispronunciations (Swingley, 2016). The English-learning infants tested by Swingley were older than previous studies (mean age 28 months). In word learning, the C-bias has been found to develop later in English learning infants (Floccia, Nazzi, Delle Luche, Poltrock, & Goslin, 2014; Nazzi, Floccia, Moquet, & Butler, 2009). In the current meta-analysis, we attempt to synthesize studies examining sensitivity to the *type of mispronunciation*, whether consonant or vowel, across different ages to determine whether infants generally exhibit more sensitivity to consonant compared to vowel mispronunciations in familiar word recognition as predicted by a learned account of C-bias emergence (Floccia et al., 2014; Keidel et al., 2007; Nazzi et al., 2016). We further examine the impact of language family on mispronunciation sensitivity to consonants and vowels, as C-bias emergence has been found to have a different developmental trajectory for Romance (French, Italian) compared to Germanic (British English, Danish) languages (Nazzi et al., 2016).

Finally, mispronunciation sensitivity in infants has been examined in many different languages, such as English, Spanish, French, Dutch, German, Catalan, Danish, and Mandarin Chinese (see Table 1). Infants learning different languages have different ages of acquisition for words in their early lexicon, leaving direct comparisons between languages within the same study difficult and as a result rare. Although we do not explicitly compare overall mispronunciation sensitivity by language (although see previous paragraph for rationale to test by language family), we assess evidence of mispronunciation sensitivity from many different languages using a meta-analytic approach.

In sum, the studies we have reviewed begin to paint a picture of the development of infants' mispronunciation sensitivity. Each study contributes one separate brushstroke and it is only by examining all of them together that we can achieve a better understanding of the big picture of early language development. Meta-analyses can provide unique insights by estimating the population effect, both of infants' responses to correct and mispronounced labels, and of their mispronunciations sensitivity. Because we aggregate data over various age groups, this meta-analysis can also investigate the role of maturation by assessing the impact of age and vocabulary size. We also make hands-on recommendations for experiment planning, for example by providing an effect size estimate for a priori power analyses (Bergmann et al., 2018).

Methods

The present meta-analysis was conducted with maximal transparency and reproducibility in mind. To this end, we provide all data and analysis scripts on the supplementary website (https://osf.io/rvbjs/) and open our meta-analysis up for updates (Tsuji, Bergmann, & Cristia, 2014). The most recent version is available via the website and the interactive platform MetaLab (https://metalab.stanford.edu; Bergmann et al., 2018). Since the present paper was written with embedded analysis scripts in R (R Core Team, 2018) using the papaja package (Aust & Barth, 2018) in R Markdown (Allaire et al., 2018), it is always possible to re-analyze an updated dataset. In addition, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and make the corresponding information available as supplementary materials (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). Figure 1 plots our PRISMA flowchart illustrating the paper selection procedure.

(Insert Figure 1 about here)

Study Selection

We first generated a list of potentially relevant items to be included in our meta-analysis by creating an expert list. This process yielded 110 items. We then used the google scholar search engine to search for papers citing the original Swingley and Aslin (2000) publication. This search was conducted on 22 September, 2017 and yielded 288 results. We removed 99 duplicate items and screened the remaining 299 items for their title and abstract to determine whether each met the following inclusion criteria: (1) original data was reported; (2) the experiment examined familiar word recognition and mispronunciations; (3) infants studied were under 31-months-of-age and typically developing; (4) the dependent variable was derived from proportion of looks to a target image versus a distractor in a eye movement experiment; (5) the stimuli were auditory speech. The final sample (n = *32*) consisted of 27 journal articles, 1 proceedings paper, 2 theses, and 2 unpublished reports. We will refer to these items collectively as papers. Table 1 provides an overview of all papers included in the present meta-analysis.

(Insert Table 1 about here)

Data Entry

The 32 papers we identified as relevant were then coded with as much consistently reported detail as possible (Bergmann et al., 2018; Tsuji et al., 2014). For each experiment (note that a paper typically has multiple experiments), we entered variables describing the publication, population, experiment design and stimuli, and results. For the planned analyses to evaluate the development of mispronunciation sensitivity and modulating factors, we focus on the following characteristics:

1 Condition: Were words mispronounced or not;

2 Mean age reported per group of infants, in days;

3 Vocabulary size, measured by a standardized questionnaire or list;

4 Size of mispronunciation, measured in features changed;

5 Distractor familiarity: familiar or unfamiliar;

6 Phonological overlap between target and distractor: onset, onset/medial, rhyme, none, novel word;

7 Position of mispronunciation: onset, medial, offset, or mixed;

8 Type of mispronunciation: consonant, vowel, or both.

A detailed explanation for moderating factors 3-8 can be found in their respective sections in the Results. We separated conditions according to whether or not the target word was mispronounced to be able to investigate infants' looking to the target picture as well as their mispronunciation sensitivity, which is the difference between looks to the target in correct and mispronounced trials. When the same infants were further exposed to multiple mispronunciation conditions and the results were reported separately in the paper, we also entered each condition as a separate row (e.g., consonant versus vowel mispronunciations; Mani & Plunkett, 2007). The fact that the same infants contributed data to multiple rows (minimally those containing information on correct and mispronounced trials) leads to shared variance across effect sizes, which we account for in our analyses (see next section). We will call each row a record; in total there were 251 records in our data.

Data analysis

Effect sizes are reported for infants' looks to target pictures after hearing a correctly pronounced or a mispronounced label (object identification) as well as the difference between effect sizes for correct and mispronounced trials (i.e. mispronunciation sensitivity). The effect size reported in the present paper is based on comparison of means, standardized by their variance. The most well-known effect size from this group is Cohen's *d* (Cohen, 1988). To correct for the small sample sizes common in infant research, however, we used Hedges' *g* instead of Cohen's *d* (Hedges, 1981; Morris & DeShon, 2002).

We calculated Hedges' *g* using the raw means and standard deviations reported in the paper (n = 177 records from 25 papers) or reported t-values (n = 74 records from 9 papers). Two papers reported raw means and standard deviations for some experimental conditions and just t-values for the remaining experimental conditions (Altvater-Mackensen et al., 2014; Swingley, 2016). Raw means and standard deviations were extracted from figures for 3 papers. In a within-participant design, when two means are compared (i.e. looking during pre- and post-naming) it is necessary to obtain correlations between the two measurements at the participant level to calculate effect sizes and effect size variance. Upon request we were provided with correlation values for one paper (Altvater-Mackensen, 2010); we were able to compute correlations using means, standard deviations, and t-values for 5 papers (following Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016; see also Rabagliati, Ferguson, & Lew-Williams, 2018). Correlations were imputed for the remaining papers (see Black & Bergmann, 2017 for the same procedure). For two papers, we could not derive any effect size (Ballem & Plunkett, 2005; Renner, 2017), and for a third paper, we do not have sufficient information in one record to compute effect sizes (Skoruppa, Mani, Plunkett, Cabrol, & Peperkamp, 2013). We compute a total of 106 effect sizes for correct pronunciations and 150 for mispronunciations. Following standard meta-analytic practice, we remove outliers, i.e. effect sizes more than 3 standard deviations from the respective mean effect size. This leads to the exclusion of 2 records for correct pronunciations and 3 records for mispronunciations.

To take into account the fact that the same infants contributed to multiple datapoints, we analyze our results in a multilevel approach using the R (R Core Team, 2018) package metafor (Viechtbauer, 2010). We use a multilevel random effects model which estimates the mean and variance of effect sizes sampled from an assumed distribution of effect sizes. In the random effect structure we take into account the shared variance of effect sizes drawn from the same paper, and nested therein that the same infants might contribute to multiple effect sizes.

Mispronunciation sensitivity studies typically examine infants' proportion of target looks (PTL) in comparison to some baseline measurement. PTL is calculated by dividing the percentage of looks to the target by the total percentage of looks to both the target and distractor images. Across papers the baseline comparison varied; since other options were not available to us, we used the baseline reported by the authors of each paper. Most papers (n = 52 records from 13 papers) subtracted the PTL score for a pre-naming baseline phase from the PTL score for a post-naming phase and report a difference score.

Other papers either compared post- and pre-naming PTL with one another ($n = 29$ records from 10 papers), thus reporting two variables, or compared post-naming PTL with a chance level of 50% ($n = 23$ records from 9 papers). For all these comparisons, positive values (either as reported or after subtraction of chance level or a pre-naming baseline PTL) indicate target looks towards the target object after hearing the label, i.e. a recognition effect. Standardized effect sizes based on mean differences, as calculated here, preserve the sign. Consequently, positive effect sizes reflect more looks to the target picture after naming, and larger positive effect sizes indicate comparatively more looks to the target.

Publication Bias

In the psychological sciences, there is a documented reluctance to publish null results. As a result, significant results tend to be over-reported and thus might be over-represented in our meta-analyses (see C. J. Ferguson & Heene, 2012). To examine whether this is also the case in the mispronunciation sensitivity literature, which would bias the data analyzed in this meta-analysis, we conducted two tests. We first examined whether effect sizes are distributed as expected based on sampling error using the rank correlation test of funnel plot asymmetry with the R (R Core Team, 2018) package metafor (Viechtbauer, 2010). Effect sizes with low variance were expected to fall closer to the estimated mean, while effect sizes with high variance should show an increased, evenly-distributed spread around the estimated mean. Publication bias would lead to an uneven spread.

Second, we analyze all of the significant results in the dataset using a p-curve from the p-curve app (v4.0, http://p-curve.com; Simonsohn, Nelson, & Simmons, 2014). This p-curve tests for evidential value by examining whether the p-values follow the expected distribution of a right skew in case the alternative hypothesis is true, versus a flat distribution that speaks for no effect being present in the population and all observed significant effects being spurious.

Responses to correctly pronounced and mispronounced labels were predicted to show different patterns of looking behavior. In other words, there is an expectation that infants should look to the target when hearing a correct pronunciation, but studies vary in their report of significant looks to the target when hearing a mispronounced label (i.e. there might be no effect present in the population); as a result, we conducted these two analyses to assess publication bias separately for both conditions.

Meta-analysis

The models reported here are multilevel random-effects models of variance-weighted effect sizes, which we computed with the R (R Core Team, 2018) package metafor (Viechtbauer, 2010). To investigate how development impacts mispronunciation sensitivity, our core theoretical question, we first introduced age (centered; continuous and measured in days but transformed into months for ease of interpreting estimates by dividing by 30.44) as a moderator to our main model. Second, we analyzed the correlation between reported vocabulary size and mispronunciation sensitivity using the R (R Core Team, 2018) package meta (Schwarzer, 2007). Finally, for a subsequent exploratory investigation of experimental characteristics, we introduced each characteristic as a moderator (more detail below).

Results

Publication Bias

Figure 2 shows the funnel plots for both correct pronunciations and mispronunciations (code adapted from Sakaluk, 2016). Funnel plot asymmetry was significant for both correct pronunciations (Kendall's τ = 0.53, p < .001) and mispronunciations (Kendall's τ = 0.16, p = 0.004). These results, quantifying the asymmetry in the funnel plots (Figure 2), indicate bias in the literature. This is particularly evident for correct pronunciations, where larger effect sizes have greater variance (bottom right corner) and the more precise effect sizes (i.e. smaller variance) tend to be smaller than expected (top left, outside the triangle).

The stronger publication bias for correct pronunciation might reflect the status of this condition as a control. If infants were not looking to the target picture after hearing the correct label, the overall experiment design is called into question. However, even in a well-powered study one would expect the regular occurrence of null results even though as a population infants would reliably show the expected object identification effect.

We should also point out that funnel plot asymmetry can be caused by multiple factors besides publication bias, such as heterogeneity in the data. There are various possible sources of heterogeneity, which our subsequent moderator analyses will begin to address. Nonetheless, we will remain cautious in our interpretation of our findings and hope that an open dataset which can be expanded by the community will attract previously unpublished null results so we can better understand infants' developing mispronunciation sensitivity.

(Insert Figure 2 about here)

We next examined the p-curves for significant values from the correctly pronounced and mispronounced conditions. The p-curve based on 72 statistically significant values for correct pronunciations indicates that the data contain evidential value (Z = -17.93, $p < .001$) and we find no evidence of a large proportion of p-values just below the typical alpha threshold of .05 that researchers consistently apply in this line of research. The p-curve based on 36 statistically significant values for mispronunciations indicates that the data contain evidential value (Z = -6.81, $p < .001$) and there is again no evidence of a large proportion of p-values just below the typical alpha threshold of .05.

Taken together, the results suggest a tendency in the literature towards publication bias. As a result, our meta-analysis may systematically overestimate effect sizes and we therefore interpret all estimates with caution. Yet, the p-curve analysis suggests that the literature contains evidential value, reflecting a "real" effect. We therefore continue our meta-analysis.

Meta-analysis

Object Identification for Correct and Mispronounced Words. We first calculated the meta-analytic effect for infants' ability to identify objects when hearing correctly pronounced labels. The variance-weighted meta-analytic effect size Hedges' g was 0.908 (SE = 0.12) which was significantly different from zero (CI [0.673, 1.143], $p < .001$). This is a small to medium effect size (according to the criteria set by Mills-Smith, Spangler, Panneton, & Fritz, 2015). That the effect size is significantly above zero suggests that when presented with the correctly pronounced label, infants tended to fixate on the corresponding object. Although the publication bias present in our analysis of funnel plot asymmetry suggests that the effect size Hedges' g may be overestimated for object identification in response to correctly pronounced words, the p-curve results and a CI lower bound of 0.67, which is substantially above zero, together suggest that this result is somewhat robust. In other words, we are confident that the true population mean lies above zero for object recognition of correctly pronounced words.

We then calculated the meta-analytic effect for object identification in response to mispronounced words. In this case, the variance-weighted meta-analytic effect size Hedges' g was 0.25 (SE = 0.06) which was also significantly different from zero (CI [0.133, 0.367], $p < .001$). This is considered a small effect size (Mills-Smith et al., 2015), but significantly above zero, which suggests that even when presented with a mispronounced label, infants fixated the correct object. In other words, infants are able to resolve mispronunciations, a key skill in language processing We again note the publication bias (which was smaller in this condition), and the possibility that the effect size Hedges' g may be overestimated. But, as the p-curve indicated evidential value, we are confident in the overall pattern, namely that infants fixate the target even after hearing a mispronounced label.

Mispronunciation Sensitivity Meta-Analytic Effect. The above two analyses considered the data from mispronounced and correctly pronounced words separately. To evaluate mispronunciation sensitivity, we compared the effect size Hedges' g for correct pronunciations with mispronunciations directly. To this end, we combined the two datasets. When condition was included (correct, mispronounced), the moderator test was significant (QM(1) = 215.761, $p < .001$). The estimate for mispronunciation sensitivity was 0.495 (SE = 0.034), and infants' looking behavior across conditions was significantly different (CI [0.429, 0.561], $p < .001$). This confirms that although infants fixate the correct object for both correct pronunciations and mispronunciations, the observed fixations to target (as measured by the effect sizes) were significantly greater for correct pronunciations. In other words, we observe a significant difference between the two conditions and can now quantify the modulation of fixation behavior in terms of standardized effect sizes and their variance. This first result has both theoretical and practical implications, as we can now reason about the amount of perturbation caused by mispronunciations and can plan future studies to further investigate this effect with suitable power.

Heterogeneity was significant for both correctly pronounced (Q(103) = 625.63, $p < .001$) and mispronounced words, (Q(146) = 462.51, $p < .001$), as well as mispronunciation sensitivity, which included the moderator condition (QE(249) = 1,088.14, $p < .001$). This indicated that the sample contains unexplained variance leading to significant difference between studies beyond what is to be expected based on random sampling error. We therefore continue with our moderator analysis to investigate possible sources of this variance.

Object Recognition and Mispronunciation Sensitivity Modulated by Age. To evaluate the different predictions we laid out in the introduction for how mispronunciation sensitivity will change as infants develop, we next added the moderator age (centered; continuous and measured in days but transformed into months for ease of interpreting estimates by dividing by 30.44 for Figure 3).

In the first analyses, we investigate the impact of age separately on conditions where words were either pronounced correctly or not. Age did not significantly modulate object identification in response to correctly pronounced (QM(1) = 0.678, $p = 0.41$) or mispronounced words (QM(1) = 1.715, $p = 0.19$). The lack of a significant modulation together with the small estimates for age (correct: $\beta = 0.015$, SE = 0.018, 95% CI[-0.02, 0.049], $p = 0.41$; mispronunciation: $\beta = 0.015$, SE = 0.011, 95% CI[-0.007, 0.037], $p = 0.19$) indicates that there might be no relationship between age and target looks in response to a correctly pronounced or mispronounced label. We note that the estimates in both cases are positive, however, which is in line with the general assumption that infants' language processing overall improves as they mature (Fernald et al., 1998). We plot both object recognition and mispronunciation sensitivity as a function of age in Figure 3.

We then examined the interaction between age and mispronunciation sensitivity (correct vs. mispronounced words) in our whole dataset. The moderator test was significant (QM(3) = 218.621, $p < .001$). The interaction between age and mispronunciation sensitivity, however, was not significant ($\beta = 0.003$, SE = 0.008, 95% CI[-0.012, 0.018], $p = 0.731$); the moderator test was mainly driven by the difference between conditions. The small estimate, as well as inspection of Figure 3, suggests that as infants age, their mispronunciation sensitivity neither increases or decreases.

(Insert Figure 3 about here)

Vocabulary Size: Correlation Between Mispronunciation Sensitivity and Vocabulary. Of the 32 papers included in the meta-analysis, 13 analyzed the relationship between vocabulary scores and object recognition for correct pronunciations and mispronunciations (comprehension = 11 papers and 39 records; production = 3 papers and 20 records). There is reason to believe that production data are different from comprehension data. Children comprehend more words than they can produce, leading to different estimates for comprehension and production. Production data is easier to estimate for parents in the typical questionnaire-based assessment and may therefore be more reliable (Tomasello & Mervis, 1994). As a result, we planned to analyze these two types of vocabulary measurement separately. However, because only 3 papers reported correlations with productive vocabulary scores, only limited conclusions can be drawn. We also note that because individual effect sizes in our analysis were related to object recognition and not mispronunciation sensitivity, we were only able to calculate the relationship between vocabulary scores and the former. In our vocabulary analysis, we therefore focus exclusively on the relationship between comprehension and object recognition for correct pronunciations and mispronunciations.

We first considered the relationship between vocabulary and object recognition for correct pronunciations. Higher comprehension scores were associated with greater object recognition in response to correct pronunciations for 9 of 10 experimental conditions, with correlation values ranging from -0.16 to 0.48. The weighted mean effect size Pearson's r of 0.14 was small but did differ significantly from zero (CI [0.03; 0.25] $p = 0.012$). As a result, we can draw a tentative conclusion that there is a positive relationship between comprehension scores and object recognition in response to correct pronunciations.

We next considered the relationship between vocabulary and object recognition for mispronunciations. Higher comprehension scores were associated with greater object recognition in response to mispronunciations for 17 of 29 experimental conditions, with correlation values ranging from -0.35 to 0.57. The weighted mean effect size Pearson's r of 0.05 was small and did not differ significantly from zero (CI [-0.01; 0.12] $p = 0.119$). The small correlation suggests either a very small positive or no relationship between vocabulary and object recognition for mispronunciations. We again emphasize that we cannot draw a firm conclusion due to the small number of studies we were able to include here.

Figure 4 plots the year of publication for all the mispronunciation sensitivity studies included in this meta-analysis. This figure illustrates two things: the increasing number of mispronunciation sensitivity studies and the decreasing number of mispronunciation studies measuring vocabulary. The lack of evidence for a relationship between mispronunciation sensitivity and vocabulary size in some early studies may have contributed to increasingly fewer researchers including vocabulary measurements in their mispronunciation sensitivity experimental design. This may explain our underpowered analysis of the relationship between object recognition for correct pronunciations and mispronunciations and vocabulary size.

(Insert Figure 4 about here)

Interim Discussion: Meta-Analysis. The main goal of this paper was to assess mispronunciation sensitivity and its maturation with age and increased vocabulary size. The results seem clear: Although infants consider a mispronunciation to be a better match to the target image than to a distractor image, there was a constant and stable effect of mispronunciation sensitivity. This did not change with development, and we might consider age a proxy for vocabulary size. We observe that the data for directly reported vocabulary size were too sparse to draw strong conclusions. In the literature, evidence for all possible developmental trajectories has been found, including mispronunciation sensitivity that increases, decreases, or does not change with age or vocabulary size. The present results do lend some support for the proposal that mispronunciation sensitivity stays consistent as infants develop. Furthermore, although we found a relationship between vocabulary size (comprehension) and target looking for correct pronunciations, we found no relationship between vocabulary and target looking for mispronunciations. This may be due to too few studies including reports of vocabulary size and more investigation is needed to draw a firm conclusion.

Alternatively, the lack of developmental change in mispronunciation sensitivity could be due to differences in the types of tasks given to infants of different ages. If infants' word recognition skills are generally thought to improve with age and vocabulary size, research questions that tap more complex processes may be more likely to be investigated in older infants. In the following section, we investigate the role that different moderators play in mispronunciation sensitivity. To investigate the possibility of systematic differences in the tasks across ages, we additionally include an exploratory analysis of whether different moderators and experimental design features were included at different ages.

Moderator Analyses

In this section, we consider each moderator individually and investigate its influence on mispronunciation sensitivity. For most moderators (except Number of features changed), we combine the correct and mispronounced datasets and include the moderator of condition, to study mispronunciation sensitivity as opposed to object recognition. To better understand the impact of these moderators on developmental change, we include age as subsequent moderator as well as an exploratory analysis of the age of infants tested with each type of moderator. The latter analysis is included to explore whether the lack of developmental change in mispronunciation sensitivity in the overall dataset is due to more complex moderator tasks being given to older infants, which may lower the overall effect size of mispronunciation sensitivity at older ages and dampen any evidence of change.

Number of features changed. To assess whether the number of features changed modulates mispronunciation sensitivity, we calculated the meta-analytic effect for object identification in response to words that were pronounced correctly and mispronounced using 1-, 2-, and 3-feature changes. We did not include data for which the number of features changed in a mispronunciation was not specified or the number of features changed was not consistent (e.g., one mispronunciation included a 2-feature change whereas another only a 1-feature change). This analysis was therefore based on a subset of the overall dataset, with 81 experimental conditions for correct pronunciations, 108 for 1-feature mispronunciations, 16 for 2-feature mispronunciations, and 6 for 3-feature mispronunciations. Each feature change (from 0 to 3; 0 representing correct pronunciations) was considered to have an equal impact on mispronunciation sensitivity, following the argument of graded sensitivity (White & Aslin, 2008; Mani & Plunkett 2011), and this modertor was coded as a continuous variable.

To understand the relationship between number of features changed and mispronunciation sensitivity, we evaluated the effect size Hedges' g with number of features changed as a moderator. The moderator test was significant, QM(1) = 137.214, $p < .001$. Hedges' g for number of features changed was -0.306 (SE = 0.026), which indicated that as the number of features changed increased, the effect size Hedges' g significantly decreased (CI [-0.357, -0.255], $p < .001$). We plot this relationship in Figure **??**. This confirms previous findings of a graded sensitivity to the number of features changed for both consonant (White & Morgan, 2008) and vowel (Mani & Plunkett, 2011) mispronunciations as well as the importance of controlling for the degree of phonological mismatch in experimental design.

(Insert Figure ?? about here)

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Alternatively, an effect of maturation might have been masked by other factors we have not yet captured in our analyses. A strong candidate that emerged during the construction of the present dataset and careful reading of the original papers was the analysis approach. We observed, as mentioned in the Methods section, large variation in the dependent variable reported, and additionally noted that the size of the chosen post-naming analysis window varied substantially across papers. Researchers might adapt their analysis strategy to infants' age or they might be influenced by having observed the data. For example, consider the possibility that there is a true increase in mispronunciation sensitivity over development. In this scenario, younger infants should show no or only little sensitivity to mispronunciations while older infants would show a large sensitivity to mispronunciations. This lack of or small mispronunciation sensitivity in younger infants is likely to lead to non-significant results, which would be more difficult to publish (C. J. Ferguson & Heene, 2012). In order to have publishable results, adjustments to the analysis approach could be made until a significant, but spurious, effect of mispronunciation sensitivity is found. This would lead to an increase in significant results and alter the observed developmental trajectory of mispronunciation sensitivity. Such a scenario is in line with the publication bias we observe (Simmons, Nelson, & Simonsohn, 2011). We examine whether variation in the approach to data analysis may be have an influence on our conclusions regarding infants' developing mispronunciation sensitivity.

We included details related to timing and type of dependent variable in our coding of the dataset because they are consistently reported and might be useful for experiment design in the future by highlighting typical choices and helping establish field standards. In the following section, we include an exploratory analysis to investigate the possibility of systematic differences in the approach to analysis in general and across infant age. The purpose of this analysis was to better understand the influence of choices made in analyzing mispronunciation sensitivity studies as well as the influence these choices may have on our understanding of mispronunciation sensitivity development.

Exploratory Analyses

We identified two sets of variables which varied across papers to assess the influence of data analysis choices on resulting effect size: timing (post-naming analysis window; offset time) and which dependent variable(s) were reported. In the following, we discuss the possible theoretical motivation for these data analysis choices, the variation present in the current meta-analysis dataset, and the influence these analysis choices may have on measurements of mispronunciation sensitivity development. We focus specifically on the size of the mispronunciation sensitivity effect, considering the whole dataset and including condition (correct pronunciation, mispronunciation) as moderator.

Timing. In a typical trial in a mispronunciation sensitivity study, the target-distractor image pairs are first presented in silence, followed by auditory presentation of a carrier phrase or isolated presentation of the target word (correctly pronounced or mispronounced). When designing mispronunciation sensitivity studies, experimenters can choose the length of time each trial is presented. This includes both the length of time before the target object is named (pre-naming phase) as well as after (post-naming phase) and is determined prior to data collection. To examine the size of the time window analyzed in the post-naming phase (post-naming analysis window), we must first consider overall length of time in post-naming (post-naming time window), because it limits the overall time window available to analyze and might thus predict the post-naming analysis window. Across papers, the length of the post-naming time window varied from 2000 to 9000 ms, with a median value of 3500 ms. The most popular post-naming time window length was 4000 ms, used in 74 experimental conditions. There was no apparent relation between infant age and post-naming time window length (r = 0.01, 95% CI[-0.11, 0.13], p = 0.882).

Unlike the post-naming time window, the post-naming analysis window can be chosen after the experimental data is collected. Interestingly, half of the experimental conditions were analyzed using the whole post-naming time window of the trial presented to the infant (n = 124), while the other half were analyzed using a shorter portion of the post-naming time window, usually excluding later portions (n = 127). Across papers, the length of the post-naming analysis window varied from 1510 to 4000 ms, with a median value of 2500 ms. The most popular post-naming analysis window length was 2000 ms, used in 97 experimental conditions. There was an inverse relationship between infant age and post-naming analysis window length, such that younger infants' looking times were analyzed using a longer post-naming analysis window, here the relationship was significant (r = -0.23, 95% CI[-0.35, -0.11], $p < .001$). The choice to use a shorter post-naming analysis window with age is likely related to evidence that speed of processing is slower in younger infants (Fernald et al., 1998). To summarize, we observe variation in time-related analysis decisions related to infants' age.

Another potential source of variation in studies that analyze eye-movements is the amount of time it takes for an eye movement to be initiated in response to a visual stimulus, which we refer to as offset time. Previous studies examining simple stimulus response latencies first determined that infants require at least 233 ms to initiate an eye-movement in response to a stimulus (Canfield & Haith, 1991). In the first infant mispronunciation sensitivity study, Swingley and Aslin (2000) used an offset time of 367 ms, which was "an 'educated guess' based on studies . . . showing that target and distractor fixations tend to diverge at around 400 ms." (Swingley & Aslin, 2000, p. 155). Upon inspecting the offset time values used in the papers in our meta-analysis, the majority used a similar offset time value (between 360 and 370 ms) for analysis (n = 151), but offset values ranged from 0 to 500 ms, and were not reported for 36 experimental conditions. We note that Swingley (2009) also included offset values of 1133 ms to analyze responses to coda mispronunciations. There was an inverse relationship between infant age and size of offset, such that younger infants were given longer offsets, although this correlation was not significant (r = -0.10, 95% CI[-0.23, 0.03], p = 0.13). This lack of a relationship is possibly driven by the field's consensus that an offset of about 367 ms is appropriate for analyzing word recognition with

PTL measures, including studies that evaluate mispronunciation sensitivity.

Although there are a priori reasons to choose the post-naming analysis window (infant age) or offset time (previous studies), these choices may occur after data collection and might therefore lead to a higher rate of false-positives (Gelman & Loken, 2013). Considering that these choices were systematically different across infant ages, at least for the post-naming analysis window, we next explored whether the post-naming analysis window length or the offset time influenced our estimate of infants' sensitivity to mispronunciations.

Post-naming analysis window length.

We first assessed whether size of the post-naming analysis window had an impact on the overall size of the reported mispronunciation sensitivity. We considered data from both conditions in a joint analysis and included condition (correct pronunciation, mispronunciation) as an additional moderator. The moderator test was significant (QM(3) = 236.958, $p < .001$). The estimate for the interaction between post-naming analysis window and condition was small but significant (β = -0.262, SE = 0.059, 95% CI[-0.377, -0.148], $p < .001$). This relationship is plotted in Figure 6a. The results suggest that the size of the post-naming analysis window significantly impacted our estimate of mispronunciation sensitivity. Specifically, the difference between target fixations for correctly pronounced and mispronounced items (mispronunciation sensitivity) was significantly greater when the post-naming analysis window was shorter.

Considering that we found a significant relationship between the length of the post-naming analysis window and infant age, such that younger ages had a longer window of analysis, we next examined whether the size of the post-naming analysis window modulated the estimated size of mispronunciation sensitivity as infant age changed. We therefore included age as additional moderator of the previous analysis. The moderator test was significant (QM(7) = 247.322, $p < .001$). The estimate for the three-way-interaction between condition, size of the post-naming analysis window, and age was small, but significant (β = -0.04, SE = 0.014, 95% CI[-0.068, -0.012], p = 0.006). As can be seen in Figure 6b, a smaller post-naming analysis window leads to a greater increase in measured mispronunciation sensitivity with development. For example, when experimental conditions were analyzed with a post-naming analysis window of 2000 ms or less, mispronunciation sensitivity seems to increase with infant age. If the post-naming analysis window is greater than 2000 ms, however, there is no or a negative relation of mispronunciation sensitivity and age. In other words, all three possible developmental hypotheses might be supported depending on analysis choices made regarding the size of the post-naming analysis window. This is especially important, considering that our key question is how mispronunciation sensitivity changes with development. These results suggest that conclusions about the relationship between infant age and mispronunciation sensitivity may be mediated by the size of the post-naming analysis window.

(Insert Figure 5 about here)

Onset time after target naming.

We next assessed whether the time between target naming and the start of the analysis, namely offset time, had an impact on the size of the reported mispronunciation sensitivity. When we included both condition and offset time as moderators, the moderator test was significant (QM(3) = 236.958, $p < .001$), but the estimate for the interaction between offset time and condition was zero (β = 0, SE = 0, 95% CI[-0.001, 0], p = 0.505). Although we found no relationship between offset time and infant age, we also examined whether the size of offset time modulated the measure of mispronunciation sensitivity over infant age. When both offset time and condition were included as moderators, the moderator test was significant (QM(7) = 200.867, $p < .001$), but the three-way-interaction between condition, offset time, and age was again zero (β = 0, SE = 0, 95% CI[0, 0], p = 0.605). Taken together, these results suggest that offset time does not modulate measured mispronunciation sensitivity. There is no relationship between offset time and age, and we find no influence of offset time on the estimated size of mispronunciation sensitivity over age. We again point out that there is a substantial field consensus, which might mask any relationship.

Dependent variable-related analyses. Mispronunciation studies evaluate infants' proportion of target looks (PTL) in response to correct and mispronounced words. Experiments typically include a phase where a naming event has not yet occurred, which we refer to as the pre-naming phase. This is followed by a naming event, whether correctly pronounced or mispronounced, and the subsequent phase we refer to as the post-naming phase. The purpose of the pre-naming phase is to ensure that infants do not have systematic preferences for the target or distractor (greater interest in a cat compared to a cup) which may drive PTL scores in the post-naming phase. As described in the Data Analysis sub-section of the Methods, however, there was considerable variation across papers in whether this pre-naming phase was used as a baseline measurement, or whether a different baseline measurement was used. This resulted in different measured outcomes or dependent variables. Over half of the experimental conditions (n = 129) subtracted the PTL score for a pre-naming phase from the PTL score for a post-naming phase, resulting in a Difference Score. The Difference Score is one value, which is then compared with a chance value of 0. When positive, this indicates that infants increased their looks to the target after hearing the naming label (correct or mispronounced) relative to the pre-naming baseline PTL. In contrast, Pre vs. Post (n = 69 experimental conditions), directly compare the post- and pre-naming PTL scores with one another using a statistical test (e.g. t-test, ANOVA). This requires two values, one for the pre-naming phase and one for the post-naming phase. A greater post compared to pre-naming phase PTL indicates that infants increased their target looks after hearing the naming label. The remaining experimental conditions used a Post dependent variable (n = 53 experimental conditions), which compares the post-naming PTL score with a chance value of 50%. Here, the infants' pre-naming phase baseline preferences are not considered and instead target fixations are evaluated based on the likelihood to fixate one of two pictures (50%). As most papers do not specify whether these calculations are made before or after aggregating across trials, we make no assumptions about when this step is taken.

The Difference Score and Pre vs. Post can be considered similar to one another, in that they are calculated on the same type of data and consider pre-naming preferences. It should be noted, however, that the Difference Score may better counteract participant- and item-level differences, whereas Pre vs. Post is a group-level measure. The Post dependent variable, in contrast, does not consider pre-naming baseline preferences. To our knowledge, there is no theory or evidence that explicitly drives choice of dependent variable in analysis of mispronunciation sensitivity, which may explain the wide variation in dependent variable reported in the papers included in this meta-analysis. We next explored whether the type of dependent variable calculated influenced the estimated size of sensitivity to mispronunciations. Considering that the dependent variable Post differs in its consideration of pre-naming baseline preferences, substituting these for a chance value, we directly compared mispronunciation sensitivity between Post as a reference condition and both Difference Score and Pre vs. Post dependent variables.

We first assessed whether the choice of dependent variable had an impact on the size of estimated mispronunciation sensitivity. When we included both condition and dependent variable as moderators, the moderator test was significant (QM(5) = 259.817, $p < .001$). The estimate for the interaction between Pre vs. Post and condition was significantly smaller than that of the Post dependent variable (β = -0.392, SE = 0.101, 95% CI[-0.59, -0.194], $p <$ .001), but the difference between the Difference Score and Post in the interaction with condition was small and not significant (β = -0.01, SE = 0.098, 95% CI[-0.203, 0.183], $p =$ 0.916). This relationship is plotted in Figure 7a. The results suggest that the reported dependent variable significantly impacted the size of the estimated mispronunciation sensitivity effect, such that studies reporting the Post. vs. Pre dependent variable showed a smaller mispronunciation sensitivity effect than those reporting Post, but that there was no difference between the Difference Score and Post dependent variables.

We next examined whether the type of dependent variable calculated modulated the estimated change in mispronunciation sensitivity over infant age. When age was included as an additional moderator, the moderator test was significant (QM(11) = 273.585, $p < .001$). The estimate for the interaction between Pre vs. Post, condition, and age was significantly smaller than that of the Post dependent variable (β = -0.089, SE = 0.03, 95% CI[-0.148, -0.03], $p = 0.003$), but the difference between the Difference Score and Post in the interaction with condition and age was small and not significant (β = -0.036, SE = 0.027, 95% CI[-0.088, 0.016], $p = 0.174$). This relationship is plotted in Figure 7b. When the dependent variable reported was Pre vs. Post, mispronunciation sensitivity was found to decrease with infant age, while in comparison, when the dependent variable was Post, mispronunciation sensitivity was found to increase with infant age. There was no difference in the estimated mispronunciation sensitivity change with infant age between the Post and Difference Score dependent variables.

Similar to the length of the post-naming analysis window, all three possible developmental hypotheses might be supported depending on the dependent variable reported. In other words, choice of dependent variable may influence the conclusion drawn regarding how mispronunciation sensitivity may change with infant age.

(Insert Figure 6 about here)

General Discussion

In this meta-analysis, we set out to quantify and assess the developmental trajectory of infants' sensitivity to mispronunciations. Overall, the results of the meta-analysis showed that infants reliably fixate the target object when hearing both correctly pronounced and mispronounced labels. Infants not only recognize object labels when they were correctly pronounced, but are also likely to accept mispronunciations as labels for targets, in the presence of a distractor image. Nonetheless, there was a considerable difference in target fixations in response to correctly pronounced and mispronounced labels, suggesting that infants show an overall mispronunciation sensitivity based on the current experimental literature. In other words, infants show sensitivity to what constitutes unacceptable, possibly meaning-altering variation in word forms, thereby displaying knowledge of the role of phonemic changes throughout the ages assessed here (6 to 30 months). At the same time, infants, like adults, can recover from mispronunciations, a key skill in language processing.

We next evaluated the developmental trajectory of infants' mispronunciation sensitivity. Based on previous theoretical accounts and existing experimental evidence, we envisioned three possible developmental patterns: increasing, decreasing, and unchanging sensitivity. We observed no influence of age when it was considered as a moderator of mispronunciation sensitivity. Of the two mainstream theories identified in our literature review, neither the Perceptual Attunement account (Best, 1994, 1995) nor PRIMIR (Curtin & Werker, 2007; Curtin, Byers-Heinlein, & Werker, 2011; Werker & Curtin, 2005) account for a lack of developmental change. The results of our meta-analysis are reflecting a pattern previously reported by a handful of studies directly comparing infants over a range of ages (Bailey & Plunkett, 2002; Swingley & Aslin, 2000; Zesiger et al., 2012), which also found no developmental change in mispronunciation sensitivity.

Both the Perceptual Attunement (Best, 1994, 1995) and PRIMIR (Curtin & Werker, 2007; Curtin et al., 2011; Werker & Curtin, 2005) accounts link a change of mispronunciation sensitivity specifically with vocabulary growth, in comparison to development in general. Vocabulary growth is predicted to lead either to an increase (PRIMIR; Curtin & Werker, 2007; Curtin et al., 2011; Werker & Curtin, 2005) or a decrease (Perceptual Attunement;

Best, 1994, 1995) in mispronunciation sensitivity; vocabulary has been shown to grow considerably in the age range considered in the current meta-analysis (see http://wordbank.stanford.edu; Frank et al., 2017). However, there are also substantial individual differences in the trajectory of vocabulary growth. The lack of developmental effects found in our meta-analysis may therefore be due to using age, instead of vocabulary size, as a moderator of mispronunciation sensitivity. We tried to address this issue by conducting an analysis of the subset of studies reporting correlations between infants' vocabulary size and their responses to correct and mispronounced labels. However, this analysis relied on only a few papers. We observed that an increasing vocabulary size lead to increased object recognition for correctly pronounced words; this was not the case for mispronunciations. However, it is difficult to draw any strong conclusions regarding the role of an increasing vocabulary size in mispronunciation sensitivity from this data.

Why did we have so few samples for an analysis on vocabulary size to begin with? Despite the theoretical implications, fewer than half of the papers included in this meta-analysis measured vocabulary (n = 13; out of 32 papers total; see also Figure 4). There are more mispronunciation sensitivity studies published every year, perhaps due to the increased use of eye-trackers, which reduce the need for offline coding and thus make data collection much more efficient, but this has not translated to an increasing number of mispronunciation sensitivity studies also reporting vocabulary scores. We suggest that this may be the result of publication bias favoring significant effects or an overall hesitation to invest in data collection that is not expected to yield significant outcomes.

What do our (tentative) results mean for theories of language development? Evidence that infants accept a mispronunciation (object identification) while simultaneously holding correctly pronounced and mispronounced labels as separate (mispronunciation sensitivity) may indicate an abstract understanding of words' phonological structure being in place early on. It appears that young infants may understand that the phonological form of mispronunciations and correct pronunciations do not match (phonological distinctiveness), but that the mispronunciation is a better label for the target compared to the distractor image (phonological constancy). The lack of age or vocabulary effects in our meta-analysis suggest that this understanding is present from an age when the earliest words are learned and is maintained throughout early lexical development. This implies mastery of the principles of phonological constancy and phonological distinctiveness at an age earlier than previously thought, which we recommend should be further explored experimentally and taken into consideration by future theoretical accounts.

Data Analysis Choices

While creating the dataset on which this meta-analysis was based, we included as many details as possible to describe each study. During the coding of these characteristics, we noted a potential for variation in a handful of variables that relate to data analysis, specifically relating to timing (post-naming analysis window; onset time) and to the calculation of the dependent variable reported. We focused on these variables in particular because their choice can potentially be made after researchers have examined the data, leading to an inflated number of significant results which may also explain the publication bias observed in the funnel plot asymmetry analyses (Simmons et al., 2011). To explore whether this variation contributed to the lack of developmental change observed in the overall meta-analysis, we included these variables as moderators in a set of exploratory analyses. We noted an interesting pattern of results, specifically that different conclusions about mispronunciation sensitivity, but more notably mispronunciation sensitivity development, could be drawn depending on the length of the post-naming analysis window as well as the type of dependent variable calculated in the experiment (see Figures 6 and 7).

Infants recognize words more quickly with age (Fernald et al., 1998), which has the potential to influence decisions for the analysis of the post-naming time window in mispronunciation sensitivity studies, including where to begin the time window (onset time) and how long this analysis window should be (post-naming analysis window). For example, as age increases, reaction time should increase and experimenters may adjust and lower offset times in their analysis as well as shorten the length of the analysis window. Yet, we find no relationship between age and offset times, nor that offset time modulated mispronunciation sensitivity. Indeed, a majority of studies used an offset time between 360 and 370 ms, which follows the “best guess” of Swingley and Aslin (2000) for the amount of time needed for infants to initiate eye movements in response to a spoken target word. Without knowledge of the base reaction time in a given population of infants, use of this best guess offset time reduces the number of free parameters. In contrast, we found a negative correlation between infant age and the length of the post-naming analysis window, and that the length of the analysis window moderated mispronunciation sensitivity, such increasing the length of the analysis windows decreases the size of mispronunciation sensitivity. Given a set of mispronunciation sensitivity data, a conclusion regarding the development of mispronunciation sensitivity would be different depending on the length of the post-naming analysis window. Although we have no direct evidence, an analysis window can be potentially set after collecting data. At worst, this adjustment could be the result of a desire to confirm a hypothesis, increasing the rate of false-positives (Gelman & Loken, 2013): a “significant effect” of mispronunciation sensitivity is found with an analysis window of 2000 but not 3000 ms, therefore 2000 ms is chosen. At best, this variation introduces noise into the study of mispronunciation sensitivity, bluring the true developmental trajectory of mispronunciation sensitivity. In the next section, we highlight some suggestions for how the field can remedy this issue.

Surpisingly, we found that the type of dependent variable calculated moderated mispronunciation sensitivity and conclusions about its developmental trajectory. Unlike the exploratory analyses related to timing (onset and post-naming analysis window), there is not a clear reason for one dependent variable to be chosen over another; the prevelence of each dependent variable appears distributed across ages and some authors always calculate the same dependent variable while others use them interchangeably in different publications. One clear difference is that both the Difference Score and Pre vs. Post dependent variables take into account each infants' actual preference in the pre-naming baseline phase, while the Post dependent variable does not. Without access to the raw data, it is difficult to conclusively determine why different dependent variable calculations influence mispronunciation sensitivity. In the next section, we advocate for the adoption of Open Data practices as one way to address this issue.

Recommendations to Establish Analysis Standards

A lack of a field standard can have serious consequences, as our analyses show. Depending on which analysis time window (see Figure 6) or dependent variable (see Figure 7) we focus on, we find support for any of the three possible trajectories of mispronunciation sensitivity development. On the one hand, this limits the conclusions we can draw regarding our key research question. Without access to the full datasets or analysis code of the studies included in this meta-analysis, it is difficult to pinpoint the exact role played by these data analysis choices. On the other hand, this finding emphasizes that current practices of free, potentially ad hoc choices regarding data analyses are not sustainable if the field wants to move towards quantitative evidence for theories of language development.

We take this opportunity to suggest several recommendations to address the issue of potential posthoc analysis decisions. Preregistration can serve as proof of a priori decisions regarding data analysis, which can also contain a data-dependent description of how data analysis decisions will be made once data is collected. The peer-reviewed form of preregistration, termed Registered Reports, has already been adopted by a large number of developmental journals, and general journals that publish developmental works, showing the field's increasing acceptance of such practices for hypothesis-testing studies. Sharing data

(Open Data) can allow others to re-analyze existing datasets to both examine the impact of analysis decisions and cumulatively analyze different datasets in the same way. Considering the issue of analysis time window, experimenters can opt to analyze the time course as a whole, instead of aggregating the proportion of target looking behavior over the entire trial. This allows for a more detailed assessment of infants' fixations over time and reduces the need to reduce the post-naming analysis window. Both Growth Curve Analysis (Law II & Edwards, 2015; Mirman, Dixon, & Magnuson, 2008) and Permutation Clusters Analysis (Delle Luche, Durrant, Poltrock, & Floccia, 2015; Maris & Oostenveld, 2007; Von Holzen & Mani, 2012) offer potential solutions to analyze the full time course. Furthermore, it may be useful to establish standard analysis pipelines for mispronunciation studies. This would allow for a more uniform analysis of this phenomenon, as well as aid experimenters in future research planning. In general, however, a better understanding of how different levels of linguistic knowledge may drive looking behavior is needed. We hope this understanding can be achieved by applying the above suggestions.

Another aspect of study design, namely sample size planning, shows that best practices and current standards might not always overlap. Indeed, across a set of previous meta-analyses it was shown that particularly infant research does not adjust sample sizes according to the effect in question (Bergmann et al., 2018). A meta-analysis is a first step in improving experiment planning by providing an estimate of the population effect and its variance, which is directly related to the sample needed to achieve satisfactory power in the null hypothesis significance testing framework. Failing to take effect sizes into account can both lead to underpowered research and to testing too many participants, both consequences are undesirable for a number of reasons that have been discussed in depth elsewhere. We will just briefly mention two that we consider most salient for theory building: Underpowered studies will lead to false negatives more frequently than expected, which in turn results in an unpublished body of literature (Bergmann et al., 2018). At the same time, underpowered studies with significant outcomes are likely to overestimate the effect, leading to wrong estimations of the population effect when paired with publication bias (Jennions, Mù, Pierre, Curie, & Cedex, 2002). Overpowered studies mean that participants were tested unnecessarily, which has ethical implications particularly when working with infants and other difficult to recruit and test populations.

The estimated effect for mispronunciation sensitivity in this meta-analysis is 0.50, and the most frequently observed sample size is 24 participants. If we were to assume that researchers assess mispronunciation sensitivity in a simple ANOVA, the resulting power is 0.92. Reversely, to achieve 80% power, one would need to test 17 participants. These calculations suggest that for the comparison of responses for correct pronunciations and mispronunciations, the studies included in this meta-analysis contain well-powered analyses. However, many studies in this meta-analysis included further factors to be tested, leading to two-way interactions (age versus mispronunciation sensitivity is a common example), which by some estimates require four times the sample size to detect an effect of similar magnitude as the main effect for both ANOVA (Fleiss, 1986) and mixed-effect-model (Leon & Heo, 2009) analyses. We thus strongly advocate for a consideration of power and the reported effect sizes to test infants' mispronunciation sensitivity.

Limitations

The current meta-analysis aggregated studies designed to investigate mispronunciation sensitivity, but we note that these studies varied in their approach to study our phenomenon of interest. For example, some studies investigated specific questions which required additional manipulations, such as the impact of the number of phonological features changed in the mispronunciations on mispronunciation sensitivity (e.g. Mani & Plunkett, 2011; White & Morgan, 2008) or sensitivity to consonant and vowel mispronunciations (Højen et al., n.d.; Mani & Plunkett, 2007, 2010; Swingley, 2016). The studies in our sample additionally varied in their experimental design, such as whether infants were familiar with the distractor image

(Mani & Plunkett, 2011; Skoruppa et al., 2013; Swingley, 2016; White & Morgan, 2008) or whether the labels for the target and distractor images contained phonological overlap (Fernald, Swingley, & Pinto, 2001). Futhermore, the infants included in this meta-analysis had a variety of native languages (English, Spanish, French, Dutch, German, Catalan, Danish, and Mandarin Chinese) and language backgrounds (monolingual, bilingual, monodialectal, multidialectal). Taken together, these variables have the potential to modulate infant mispronunciation sensitivity, but an investigation of these variables is out of the scope of the current meta-analysis. However, our dataset includes these variables. We hope that future research will be able to better understand the role that these variables play in infants' sensitivity to mispronunciations.

Conclusion

This meta-analysis comprises an aggregation of almost two decades of research on mispronunciation sensitivity, finding that infants accept both correct pronunciations and mispronunciations as labels for a target image. However, they are more likely to accept correct pronunciations, which indicates sensitivity to mispronunciations in familiar words. Despite the predictions of theories of infant phono-lexical development, this sensitivity was not modulated by infant age or vocabulary. This suggests that from a young age on, before the vocabulary explosion, infants' word representations may be already phonologically well-specified. We recommend future theoretical frameworks take this evidence into account.

Despite this overall finding, however, we note evidence that data analysis choices can modulate conclusions about mispronunciation sensitivity development. Future studies should be carefully planned with this evidence in mind. Ideally, future experimental design and data analysis would become standardized which will be aided by the growing trend of preregistration and open science practices. Our analysis highlights how meta-analyses can aid in identification of issues in a particular field and play a vital role in how the field addresses such issues.

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Table 1

Summary of all studies. Age: truncation of mean age reported in the paper. Vocabulary: Comp = comprehension, Prod = production. Distractor Familiarity: Fam = Familiar Distractor, Unfam = Unfamiliar Distractor. Distractor Target Overlap: position of overlap between target and distractor; O = onset, M = medial, C = coda. Mispronunciation Size: number of features changed; commas indicate when sizes were compared separately (e.g. 1, 2, 3), dashes indicate the range of sizes were aggregated (e.g. 1-3). Mispronunciation Position: O = onset, M = medial, C = coda. Mispronunciation Type: C = consonant, V = vowel, T = tone. For both Mispronunciation Position and Type, a slash separator indicates that is was tested but a distinction was not made in the stimuli. For all categories, unspec. indicates that the value was unspecified in the paper

				Distractor		Mispronunciation			
Paper	Format	Age	Vocabulary	Familiarity	Target Overlap	Size	Position	Type	N Effect Sizes
Altvater-Mackensen (2010)	dissertation	22, 25	None	fam, unfam	O, novel	1	O, O/M	C	13
Altvater-Mackensen et al. (2014)	paper	18, 25	None	fam	O	1	O	C	16
Bailey & Plunkett (2002)	paper	18, 24	Comp	fam	none	1, 2	O	C	12
Bergelson & Swingley (2017)	paper	7, 9, 12, 6	None	fam	none	unspec	O/M	V	9
Bernier & White (2017)	proceedings	21	None	unfam	novel	1, 2, 3	O	C	4
Delle Luche et al. (2015)	paper	20, 19	None	fam	O	1	O	C/V	4
Durrant et al. (2014)	paper	19, 20	None	fam	O	1	O	C/V	4
Höhle et al. (2006)	paper	18	None	fam	none	1	O	C	4
Højen et al. (n.d.)	gray paper	19, 20	Comp/Prod	fam	C, O	2-3	O/M, C/M	C/V, V, C	6
Mani & Plunkett (2007)	paper	15, 18, 24, 14, 20	Comp/Prod	fam	O	1-2, 1	O	V, C/V, C	14
Mani & Plunkett (2010)	paper	12	Comp	fam	O	1	M, O	V, C	8
Mani & Plunkett (2011)	paper	23, 17	None	unfam	novel	1-3, 1, 2, 3	M	V	15
Mani, Coleman, & Plunkett (2008)	paper	18	Comp/Prod	fam	O	1	M	V	4
Ramon-Casas & Bosch (2010)	paper	24, 25	None	fam	none	unspec	M	V	4
Ramon-Casas et al. (2009)	paper	21, 20	Prod	fam	none	unspec	M	V	10
Ren & Morgan (in press)	gray paper	19	None	unfam	none	1	O, C	C	8
Skoruppa et al. (2013)	paper	23	None	unfam	O/M	1	C	C	4
Swingley (2003)	paper	19	Comp/Prod	fam	O	1	O, M	C	6
Swingley (2009)	paper	17	Comp/Prod	fam	none	1	O, C	C	4
Swingley (2016)	paper	27, 28	Prod	unfam	novel	1	O/M	C/V, C, V	9
Swingley & Aslin (2000)	paper	20	Comp	fam	none	1	O	C/V	2
Swingley & Aslin (2002)	paper	15	Comp/Prod	fam	none	1, 2	O/M	C/V	4
Tamasi (2016)	dissertation	30	None	unfam	novel	1, 2, 3	O	C	4
Tao & Qinmei (2013)	paper	12	None	fam	none	unspec	unspec	T	4
Tao et al. (2012)	paper	16	Comp	fam	none	unspec	unspec	T	6
van der Feest & Fikkert, (2015)	paper	24, 20	None	fam	O	1	O	C	16
van der Feest & Johnson (2016)	paper	24	None	fam	O	1	O	C	20

Wewalaarachchi et al. (2017)	paper	24	None	unfam	novel	1	O/M/C	C/V/T, V, C, T	8
White & Aslin (2011)	paper	18	None	unfam	novel	1	M	V	4
White & Morgan (2008)	paper	18, 19	None	unfam	novel	1, 2, 3	O	C	12
Zesiger & Jöhr (2011)	paper	14	None	fam	none	1	O, M	C, V	7
Zesiger et al. (2012)	paper	12, 19	Comp/Prod	fam	none	1, 2	O	C	6

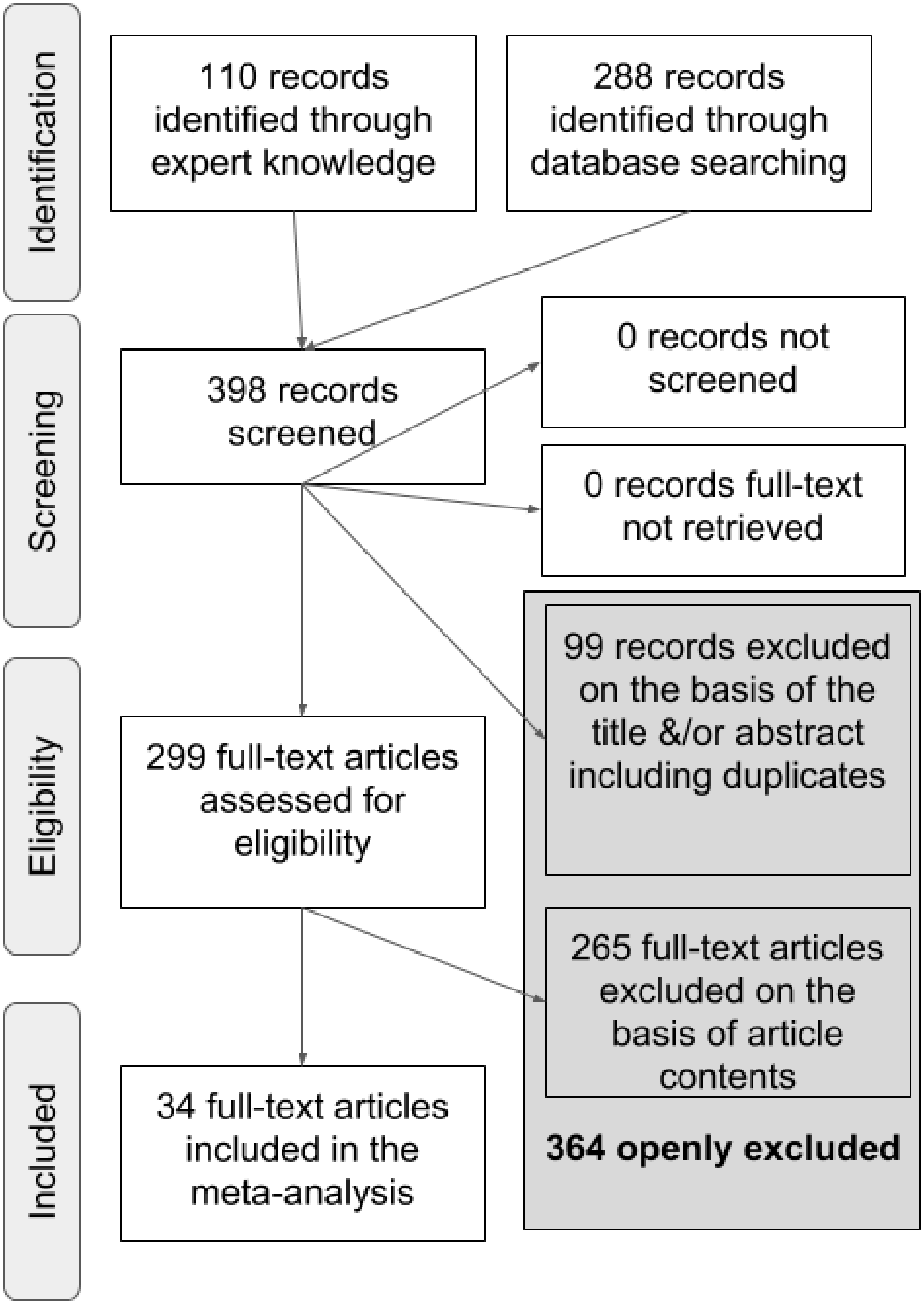

Figure 1. A PRISMA flowchart illustrating the selection procedure used to include studies in the current meta-analysis.

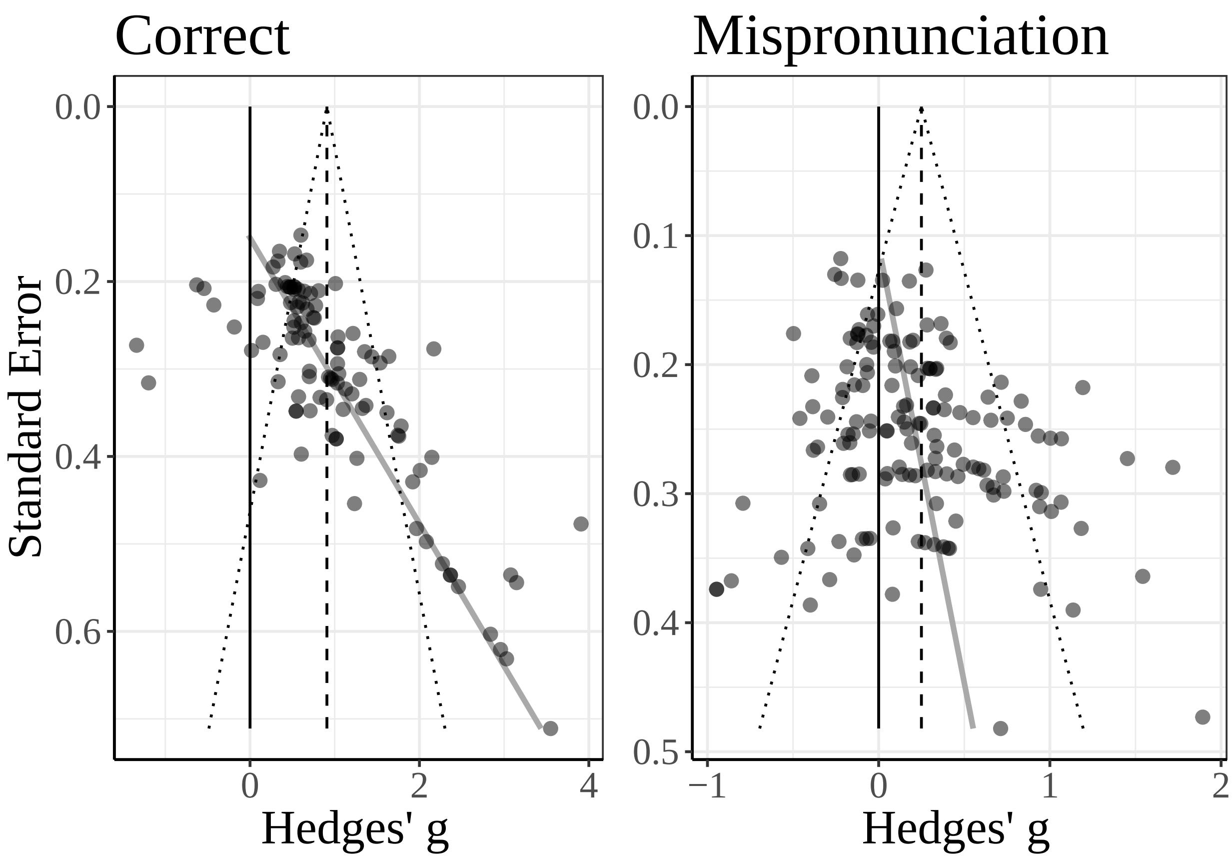

Figure 2. Funnel plots for object identification, plotting the standard error of the effect size in relation to the effect size. The black line marks zero, the dashed grey line marks the effect estimate, and the grey line marks funnel plot asymmetry.

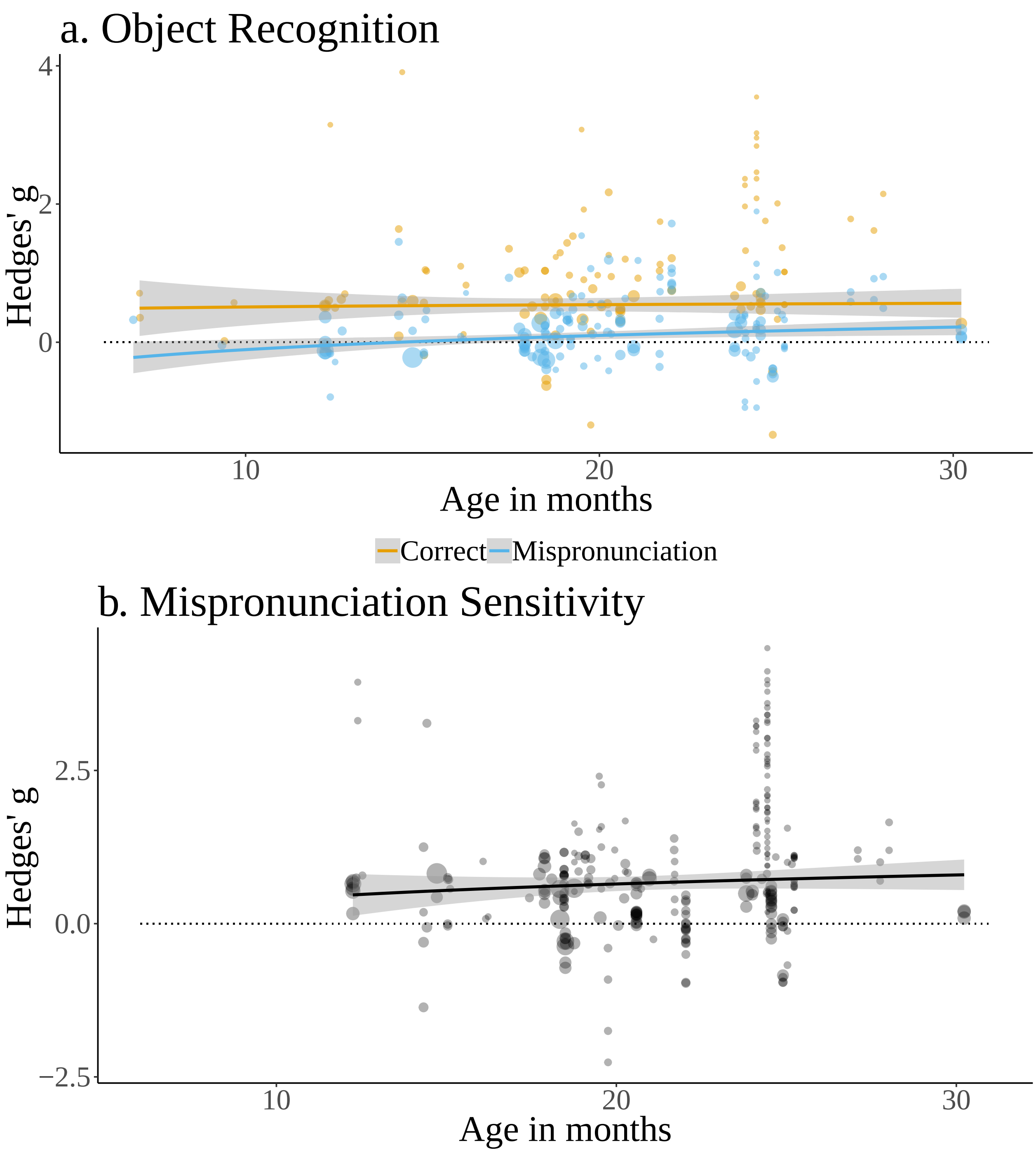

Figure 3. Panel a: Effect sizes for correct pronunciations (orange) and mispronunciations (blue) by participant age. Panel b: Effect sizes for mispronunciation sensitivity (correct - mispronunciations) by participant age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).

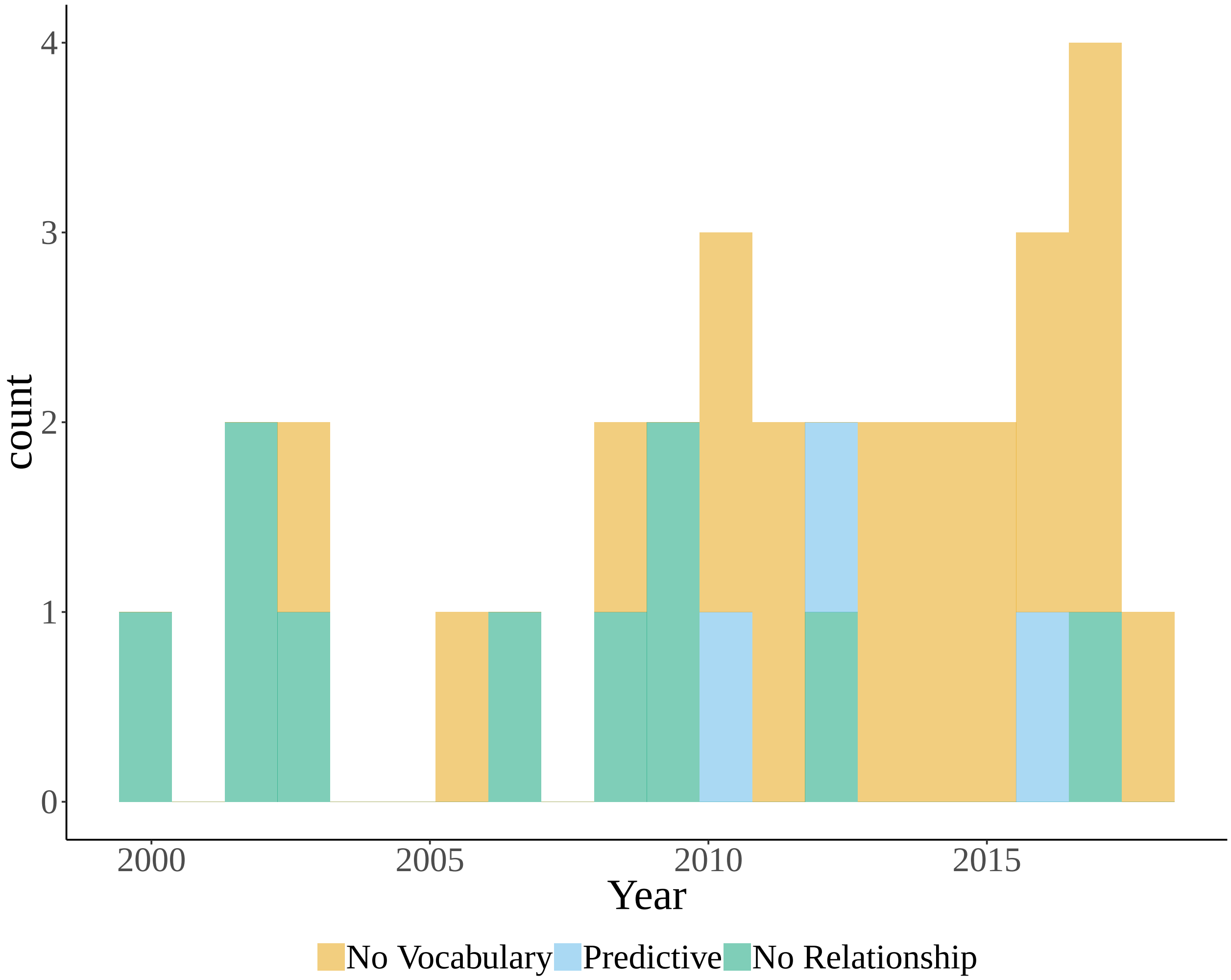

Figure 4. Counts of studies included in the meta-analysis as a function of publication year, representing whether the study did not measure vocabulary (orange), did measure vocabulary and was reported to predict mispronunciation sensitivity (blue), or did measure vocabulary and was reported to not predict mispronunciation sensitivity (green).

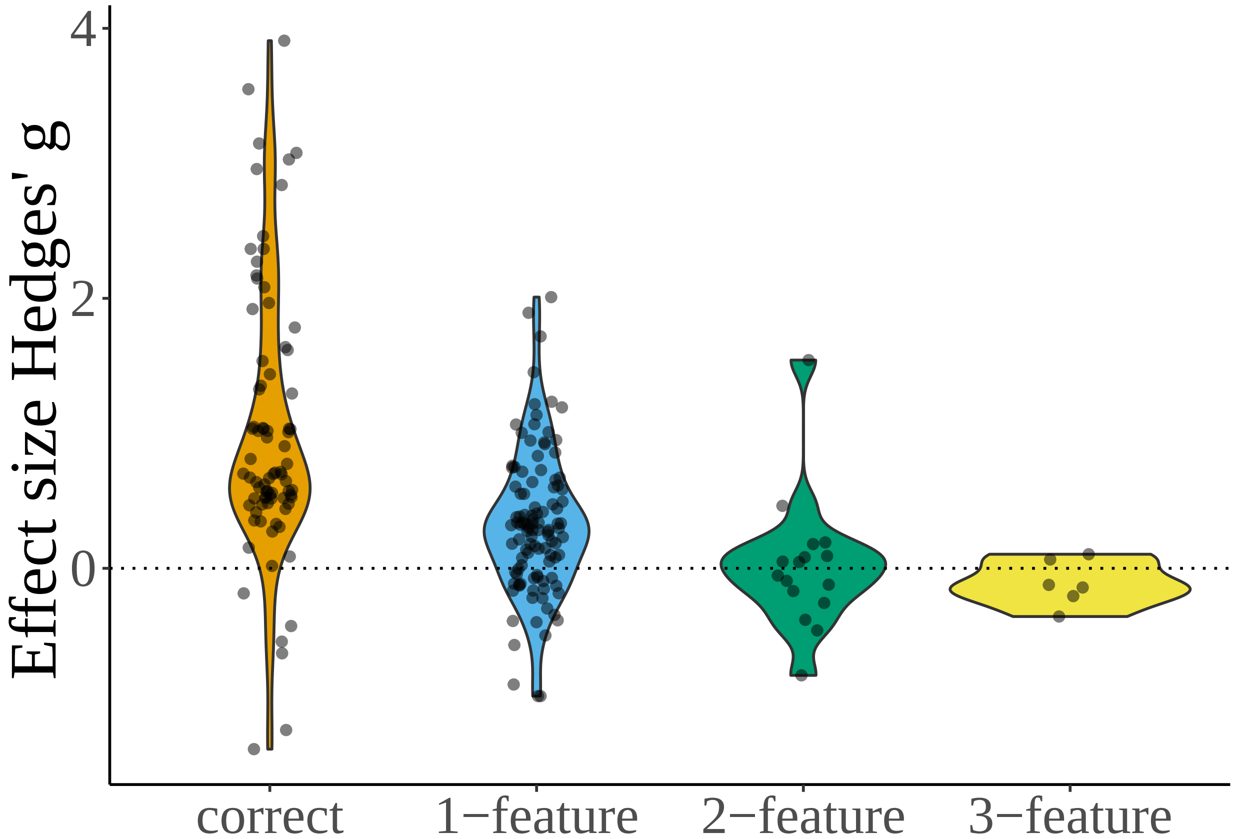
Effect size Hedges' g
4
2
0
correct
1−feature
2−feature
3−feature

Figure 5

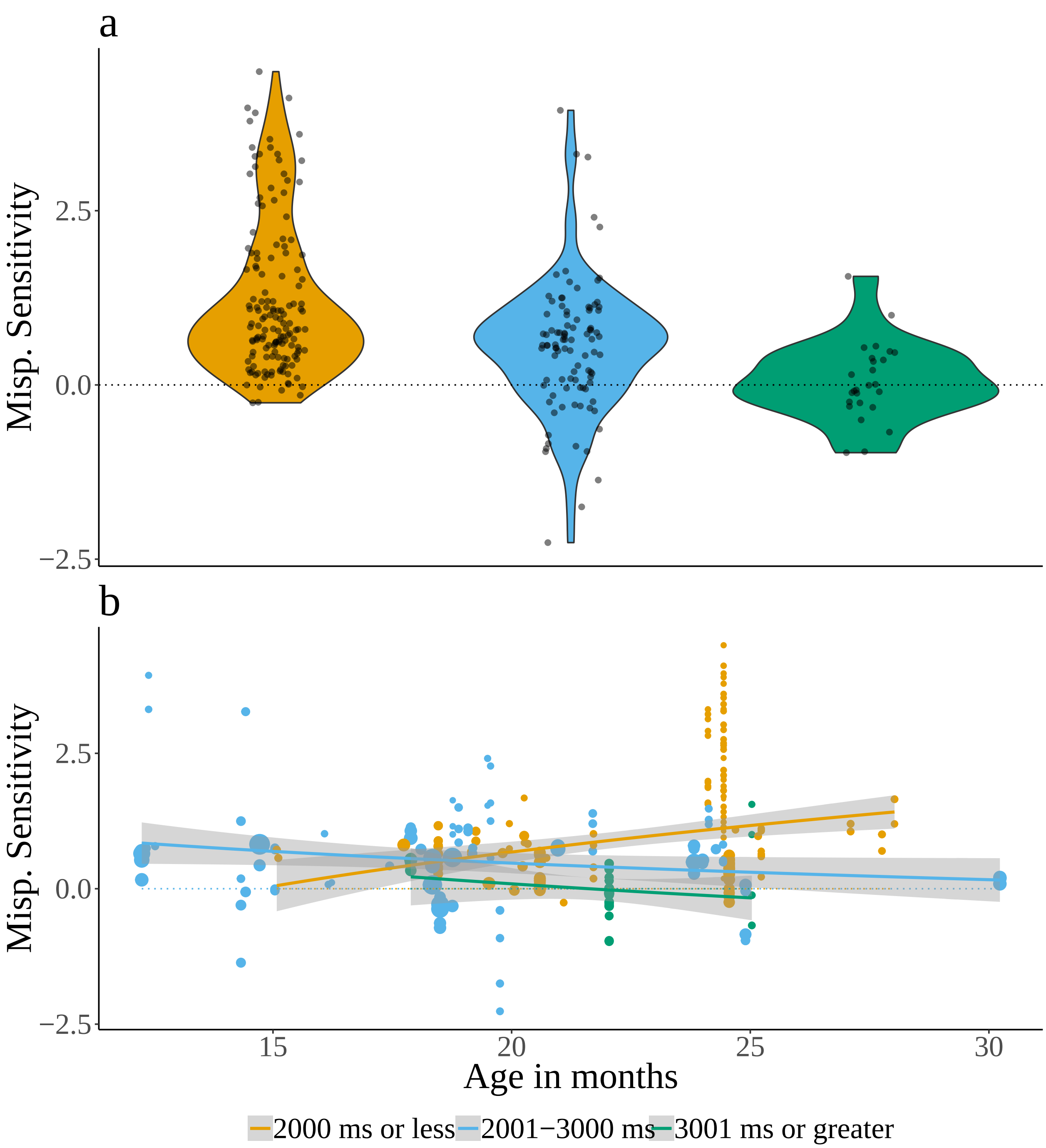

Figure 6. Effect sizes for the different lengths of the post-naming analysis window: 2000 ms or less (orange), 2001 to 3000 ms (blue), and 3001 ms or greater (green). Although length of the post-naming analysis window was included as a continuous variable in the meta-analytic model, it is divided into categories for ease of viewing. Panel a plots mispronunciation sensitivity aggregated over age, while panel b plots mispronunciation sensitivity as a function of age. The lines plot the linear regression and the gray shaded area indicates the standard error.

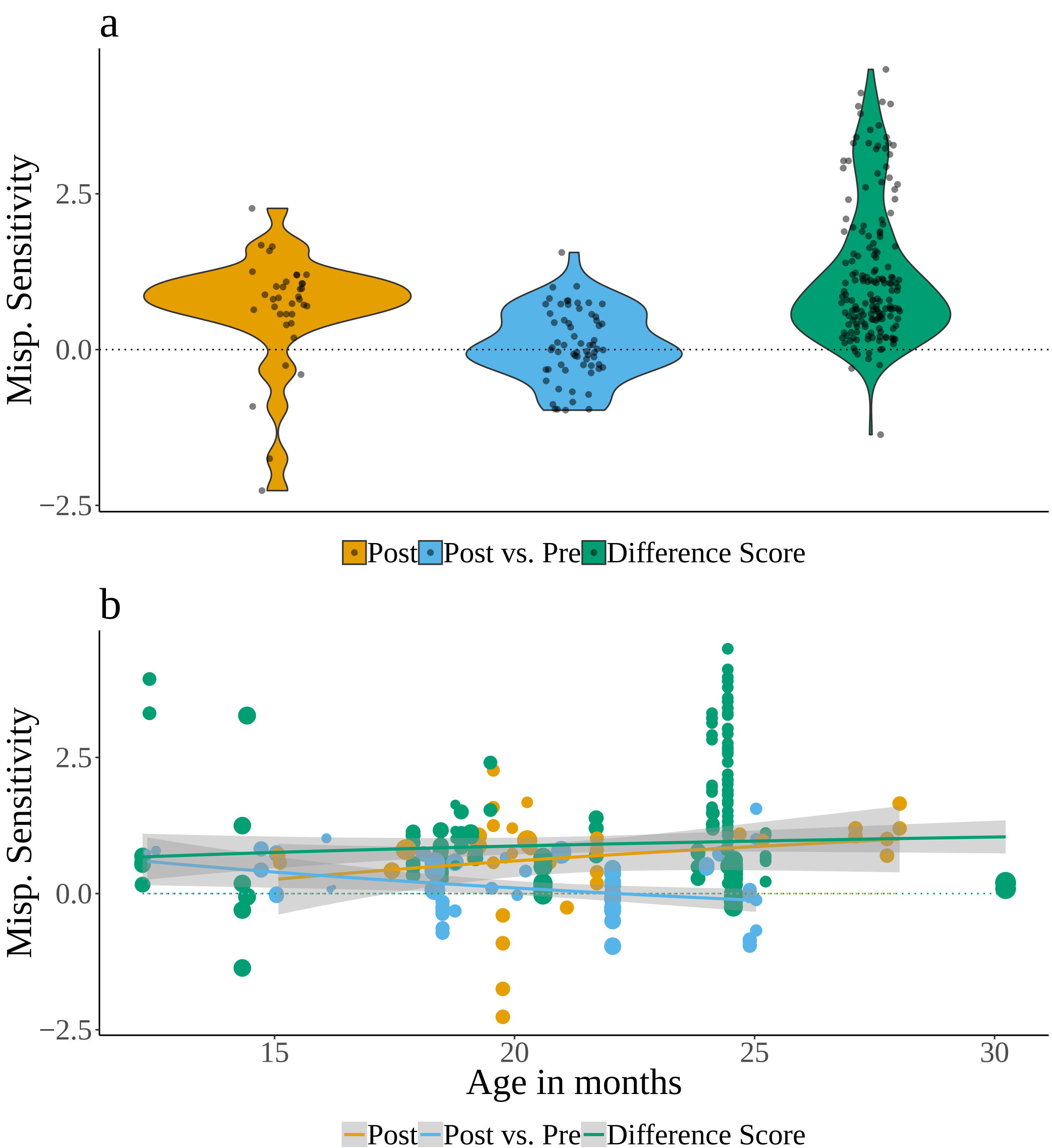

Figure 7. Effect sizes for the different types of dependent variables calculated: Post (orange), Post vs. Pre (blue), and Difference Score (green). Panel a plots mispronunciation sensitivity aggregated over age, while panel b plots mispronunciation sensitivity as a function of age. The lines plot the linear regression and the gray shaded area indicates the standard error.