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

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## Introduction

Acquiring a first language means that young learners are solving a host of tasks in a short amount of time. As infants develop into toddlers during their second and third years they learn new words in earnest while simultaneously refining their knowledge about the sounds that make up these words. Before children can correctly pronounce a word, they already show evidence of sensitivity to slight variations in the phonological form of that word. This mispronunciation sensitivity reflects the specificity with which infants represent the phonological information of familiar words and are sensitive to changes that might signal a change in word meaning. As infants continue to develop into expert language users, their language processing matures and becomes more efficient. In a mature phono-lexical system, word recognition must balance flexibility to slight variation (e.g., speaker identity, accented speech) while distinguishing between phonetic details that differentiate words in their native language (e.g. cat-hat). In this paper, we aggregate and analyze the almost 20 years of literature investigating mispronunciation sensitivity in infants in an attempt to uncover its characteristics and the trajectory of its development.

At the turn of the millenia, infant language acquisition researchers had established that during their first 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 one image upon hearing its label (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998). 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 were presented with pairs of images (e.g. baby, dog) and their eye movements to each image were coded offline. 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). Mean proportion of fixation to the target image (here: a baby) was calculated 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, although looks to the target were significantly greater than chance in both types of trials. 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 as *recognition*. Swingley and Aslin (2000) concluded that already before the second birthday, children represent words with sufficient detail to be sensitive to mispronunciations.

The study of Swingley and Aslin (2000) as well as subsequent studies examining mispronunciation sensitivity address two complementary concepts in early phonological development: *phonological constancy* and *phonological distinctiveness*. Phonological constancy is the ability to accept phonological variation across different instances of a word, as long as the variation does not compromise the overall identity of the word. For example, different speakers - particularly across genders and accents - produce the same word with notable acoustic variation, although the word remains the same. In contrast, phonological distinctiveness describes the ability to differentiate between different words that happen to be phonologically similar, such as bad/bed or cat/hat. To successfully recognize words, infants must therefore simultaneously use both phonological constancy and distinctiveness to determine where phonological variation is appropriate and where it changes a word's meaning.

In the current study, we focus on infants' developing ability to correctly apply the principles of phonological distinctiveness and constancy by using a meta-analytic approach to investigate mispronunciation sensitivity. Considering that infants are sensitive to mispronunciations and that, in general, their processing matures with development, we examine the shape of mispronunciation sensitivity over the course of the second and third year. There are three distinct possibilities how mispronunciation sensitivity might change as infants become native speakers, which are all respectively predicted by theoretical accounts and supported by single studies. 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. 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.

Young infants may begin cautiously in their approach to word recognition, rejecting any phonological variation in familiar words and only later learning to accept appropriate variability. According to the Perceptual Attunement account, this describes a shift away from specific native phonetic patterns to a more mature understanding of the abstract phonological structure of words (Best 1994, 1995). This shift is predicted to coincide with the vocabulary spurt around 18 months, and is therefore related to vocabulary growth. In this case, we would expect the size of mispronunciation sensitivity to be larger at younger ages and *decrease* as the child matures and learn more words, although children continue to detect mispronunciations. Indeed, young infants are less likely than older infants to demonstrate recognition of familiar words (Best, Tyler, Gooding, Orlando, & Quann, 2009; Mulak, Best, & Tyler, 2013) or learn new words (Schmale, Hollich, & Seidl, 2011) from accented speakers.

According to a different theoretical framework, young infants may instead begin with phonologically broad representations for familiar words and only refine their representations as language experience accumulates. PRIMIR (Processing Rich Information from Multidimensional Interactive Representations; Curtin & Werker, 2007; Werker & Curtin, 2005; Curtin, Byers-Heinlein, & Werker, 2011) describes the development of phonemic categories emerging as the number of word form-meaning linkages increases. Vocabulary growth, therefore, promotes more detailed phonological representations in familiar words. Following this account, we predict an *increase* in mispronunciation sensitivity as infants mature and add more words to their growing lexicon.

Finally, sensitivity to mispronunciation may not be modulated by development at all. Infants' overall language processing becomes more efficient, but their sensitivity to mispronunciations may not change. Across infancy and toddlerhood, mispronunciations would thus be detected and lead to less looks at a target than correct pronunciations, but the size of this effect would not change, nor be related to vocabulary size. This pattern is not predicted by any mainstream theory of language acquisition, but for completeness we mention it here.

Research following the seminal study by Swingley and Aslin (2000) has extended mispronunciation sensitivity to infants as young as 12 months (Mani & Plunkett, 2010), 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 a handful of studies have compared more than one age group on the same mispronunciation task (see Table X), making the current meta-analysis very informative. One study has found evidence for infants to become *less* sensitive to mispronunciations as children develop. Mani and Plunkett (2011) presented 18- and 24-month-olds with mispronunciations varying in the number of features changed (see below for a discussion of the role of features). 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, providing support to the prediction that mispronunciation sensitivity may decrease with development.

In contrast, other studies have found evidence for *greater* mispronunciation sensitivity as children develop. More precisely, the difference in target looking for correct and mispronounced trials is 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 (van der Feest & Fikkert, 2015) and 15 to 18 months (Altvater Mackensen et al., 2013) in Dutch infants, as well as German infants from 22 to 25 months (Altvater-Mackensen, 2010). Furthermore, van der 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. These studies award support to the prediction that mispronunciation sensitivity improves with development.

Finally, some studies have found no difference in mispronunciation sensitivity at different ages. 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 effect) did not. This suggests that as children develop, they are more likely to look at the target in the presence of a mispronounced label and that age is not related to mispronunciation sensitivity. 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). These studies award support to the prediction that mispronunciation sensitivity does not change with development.

Why would mispronunciation sensitivity change as infants develop, and would it increase or decrease? The main hypothesis is related to vocabulary growth. Both the Perceptual Attunement (Best, 1994; 1995) and PRIMIR (Curtin & Werker, 2007; Werker & Curtin, 2005; Curtin, Byers-Heinlein, & Werker, 2011) accounts situate a change in mispronunciation sensitivity occurring along with an increase in vocabulary size, particularly with the vocabulary spurt at about 18 months. Knowing more words helps infants shift their focus to the relevant phonetic dimensions needed for word recognition. On the one hand, a smaller lexicon does not require full specification to differentiate between words; as more phonologically similar words are learned, so does the need to have fully detailed representations for those words (Charles-Luce & Luce, 1995). On the other hand, a growing vocabulary is also related to more experience or familiarity with words, which may sharpen the detail of their representation (Barton, 1980).

Yet, the majority of studies examining a potential association between mispronunciation sensitivity and vocabulary size have concluded that there is no relationship (Swingley & Aslin 2000; 2002; Bailey & Plunkett, 2002; Zesiger, Lozeron, Levy, & Frauenfelder, 2012; Swingley, 2009; Ballem & Plunkett, 2005; Mani & Plunkett, 2007; Mani, Coleman, & Plunkett, 2008). One notable exception comes from Mani and Plunkett (2010: keps and tups). Here, 12-month-old infants were divided into a low vocabulary and high vocabulary group based group 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, although receiving considerable support from theories of phono-lexical processing in language acquisition, 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 further disentangle the disconnect between theory and experimental results.

Taken together, the studies we have reviewed begin to paint a picture of the development of 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. Meta-analyses can not only help us summarize the current state of research, but can also help us evaluate theories to drive future research and make hands-on recommendations for experiment planning.

## 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 (metalab.stanford.edu; Bergmann et al., 2018). Since the present paper was written with embedded analysis scripts in R [@R], it is always possible to re-analyze an updated dataset. In addition, we follow 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 & PRISMAGroup, 2009). Figure X plots our PRISMA flowchart.

[Figure X. PRISMA Flowchart.] (figures/PRISMA_MA_Mispronunciation.png)

**Study Selection**

| Paper | Publication format | Age | Vocabulary |
|---|---|---|---|
| Altvater-Mackensen (2010) | dissertation | 22, 25 | None |
| Altvater-Mackensen et al. (2014) | paper | 18, 25 | None |
| Bailey & Plunkett (2002) | paper | 18, 24 | Comprehension |
| Bergelson & Swingley (2017) | paper | 7, 9, 12, 6 | None |
| Bernier & White 2017 | proceedings | 21 | None |
| Delle Luche et al. (2015) | paper | 20, 19 | None |
| Durrant et al. (2014) | paper | 19, 20 | None |
| Hoehle et al. 2006 | paper | 18 | None |
| Hojen et al. | gray paper | 20 | Comprehension/Productio |
| Mani & Plunkett 2007 | paper | 15, 18, 24, 14, 21 | Comprehension/Productio |
| Mani & Plunkett 2010 | paper | 12 | Comprehension |
| Mani & Plunkett 2011 | paper | 23, 17 | None |
| Mani, Coleman, & Plunkett (2008) | paper | 18 | Comprehension/Productio |
| Ramon-Casas & Bosch 2010 | paper | 24, 25 | None |
| Ramon-Casas et al. 2009 | paper | 21, 20 | Production |
| Ren & Morgan, in press | gray paper | 19 | None |
| Skoruppa et al. 2013 | paper | 24 | None |
| Swingley (2009) | paper | 17 | Comprehension/Productio |
| Swingley (2016) | paper | 27, 28 | Production |
| Swingley & Aslin (2000) | paper | 20 | Comprehension |
| Swingley & Aslin (2002) | paper | 15 | Comprehension/Productio |
| Swingley 2003 | paper | 19 | Comprehension/Productio |
| Tamasi (2016) | dissertation | 30 | None |
| Tao & Qinmei 2013 | paper | 12 | None |
| Tao et al. 2012 | paper | 16 | Comprehension |
| van der Feest & Fikkert, 2015 | paper | 24, 20 | None |
| van der Feest & Johnson, 2016 | paper | 24 | None |

[KATIE] THIS TABLE IS DEFINITELY NOT FINISHED! [CHRISTINA suggestions: N features should be a range and exclude 0; we could abbreviate Comperehension/Production to Comp./Prod., etcetc][KATIE] I've reduced the table to be about age and vocabulary, in order to have it more focused for the aim of this paper.

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 & Aslin (2000) publication. This search was conducted on 22 September, 2017 and yielded 288 results. We screened the 398 items, removing 99 duplicate items. We screened remaining 299 items for their title and abstract to determine whether it met the following inclusion criteria: (1) original data was reported; (2) the experiment examined familiar word recognition; (3) infants studied were under 36-months-of-age; (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 thesis, and 2 unpublished reports. We will refer to these items collectively as papers. Table 1 (Summary Table) provides an overview of all papers included in the present meta-analysis.

## Data Entry

The 32 papers we identified as relevant were then coded with as much detail as possible (Tsuji, Bergmann, & Cristia, 2014; Bergmann et al., 2018). 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 present analyses, 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;

We separated out conditions according to whether or not the target word was mispronounced to be able to investigate infants' looking to the target picture separated by whether or not words were mispronounced 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

Mispronunciation sensitivity studies typically examine infants' proportion of target looks (PTL) in comparison to a 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; we used the baseline reported by the authors of each paper. Most papers ($n = 13$) subtracted the PTL score for a pre-naming phase from the PTL score for a post-naming phase. When interpreting this difference score, a positive value indicates that infants increased their looks to the target after hearing the naming label (correct or mispronounced). Other papers either compared post- and pre-naming PTL with one another ($n = 10$) or compared post-naming PTL with a chance level of 50%, ($n = 9$). For all these comparisons, a positive difference score or a post-naming phase PTL score that is greater than the pre-naming phase PTL or chance indicate target looks that indicate object recognition after hearing the naming label.

Consequently, positive effect sizes reflect more looks to the target picture after naming, and larger positive effect sizes indicate comparatively more relative increase in looks to the target.

We report effect sizes 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 we report in the present paper are based on comparison of means, standardized by their variance. The most well-known effect size from this group is Cohen's $d$ [@cohen]. To correct for the small sample sizes common in infant research, however, we use as a dependent variable Hedges' $g$ instead of Cohen's $d$ (Hedges, 1981; Morris, 2000).

We calculated Hedges' $g$ using the raw means and standard deviations reported in the paper ($n = 2$) or using reported t-values ($n = 2$). Raw means and standard deviations were extracted from figures for 3 papers. In a within-participation 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 based on t-values. 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 $n = 4$ (following Csibra, et al. 2016, Appendix B; see also Rabagliati, Ferguson, & Lew-Williams, 2018). Correlations were imputed for the remaining papers (see Black & Bergmann, 2017, for the same procedure). We could compute a total of 104 effect sizes for correct pronunciations and 147 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] package metafor [@metafor]. This means we model as random effect that effect sizes from the same paper share are based on more similar studies than those across papers and that nested therein effects can stem from the same infants.

## Publication Bias

[CHRISTINA: Do you think we have to revise this section? I think it's the same as in the proceedings paper.][KATIE: Are you concerned about the Publication Bias section in particular, or the Methods as a whole? In general, some of the Methods was written before the CogSci paper and in other places to flesh things out I rewrote what we had in the CogSci paper. Its definitely giving the same information and sometimes the wording is close, because there's not too many different ways to explain what a funnel plot is :)]

In the psychological sciences, there is a documented reluctance to publish null results. As a result, there is a potential for significant results to be valued over non-significant results (see 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 conduct two tests. We first examine whether effect sizes are distributed as expected based on sampling error using the rank correlation test of funnel plot asymmetry with the R [@R] package metafor [@metafor]. Effect sizes with low-variance are 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. Second, we analyze all of the significant results in the dataset using a p-curve from the p-curve app (v4.0, p-curve.com; @pcurve). This tests for evidential value by examining whether the p-values have an expected distribution, regardless of whether the null hypothesis is true or not, as well as whether there is a larger proportion of p-values just below the typical alpha threshold of .05, which may indicate questionable research practices. Responses to correctly pronounced and mispronounced labels are predicted to show different patterns of looking behavior; as a result, we conduct these two analyses to assess publication bias separately for both conditions.

## Meta-analysis

The models reported are hierarchical random-effects models (infant groups nested within papers) of variance-weighted effect sizes with the R [@R] package metafor [@metafor]. To investigate how development impacts mispronunciation sensitivity, our core theoretical question, we introduce age (centered; continuous and measured in days but transformed into months for ease of reading by dividing by 30.44) as a moderator to our main model. For the subsequent investigations of experimental characteristics, we introduce each characteristic as a moderator (more detail below).

[CHRISTINA: Let's both reread the full paper once it is ready and check that this is properly motivated and whether we do need to list them all. For now I think the last sentence is fine, but I would tend to prefer a reminder for the forgetful reader.][KATIE: that's reasonable! We had just listed everything 7 paragraphs before, which doesn't seem like a lot of "space". Alternatively, this information could be listed in a table, and then just referred to.]

# Results

## Publication Bias

Figure 1 shows the funnel plots for both correct pronunciations and mispronunciations (code adapted from Sakaluk, 2016). Funnel plot assymmetry was significant for both correct pronunciations (Kendall's $\tau$ = 0.53, $p$ < .001) and mispronunciations (Kendall's $\tau$ = 0.16, $p$ = 0.004). These results, quantifying the assymmetry in the funnel plots (Figure 1), indicate bias in the literature. This is particularly evident for correct pronunciations, where larger effect sizes have greater variance (bottom right corner) and there are a smaller number of more precise effect sizes (i.e. smaller variance) than expected (top left, outside the triangle).

The stronger publication bias for correct pronunciation might reflect the status of this condiction as a control. If infants were not looking to the target picture after hearing the correct label, the overall experiment design is called into questions. However, due to the small effect and sample sizes (which we will discuss in the following sections in more detail) 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 beside publication bias. The funnel plot asymmetry may also reflect heterogeneity in the data, perhaps due to some studies investigating more subtle effects than other studies. [CHRISTINA: I have to add some bits here.]

**(Insert Figure 1 about here)**

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## [1] TRUE
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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 there is no evidence of a large proportion of p-values just below the typical alpha threshold of .05. 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 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 overall, 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 object identification, i.e. looks to the target image in response to correctly pronounced words. The variance-weighted meta-analytic effect size Hedges' $g$ was 0.908 (SE = 0.12) which was significantly different from zero (95% CI[0.673, 1.143], $p <$ .001). This is a rather large effect size (according to the criteria set by Cohen, 1988; see also Bergmann, et al., 2018; for comparative meta-analytic effect sizes in language acquisition research). That the effect size is significantly above zero suggests that when presented with the correctly pronounced label, infants fixated the corresponding object. Our analysis of funnel plot asymmetry, however, found evidence for publication bias, which might lead to an overestimated effect sizes as smaller, non-significant results might not be published. Although 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 suggests that this result is robust even when correcting for publication bias. In other words, we are confident that the true population mean lies above zero for object recognition of correctly pronounced words.

[CHRISTINA: Can you explain what the CI lower bound means here? I don't follow.][KATIE: What do you think about this (last sentence)? The CI lower bound stuff here actually comes from something you wrote, so tell me whether its correct.]

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 (95% CI[0.133, 0.367], $p$ < .001). This is considered a small effect size (Cohen, 1988), 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 patterns, namely that infants fixate the target even after hearing a mispronounced label.

Heterogeneity was significant for both correctly pronounced (Q(103) = 625.63, $p < .001$) and mispronounced words, (Q(146) = 462.51, $p < .001$). This indicated that the sample contains unexplained variance leading to significant difference across our studies beyond what is to be expected based on random sampling error. We therefore continue with our moderator analysis.

**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, merging the two datasets. The moderator test was significant, QM(1) = 215.761, $p < .001$. Hedges' $g$ for mispronunciation sensitivity was 0.495 (SE = 0.034), which indicated that the responses across conditions were significantly different (95% 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.

**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, in days). 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) = 215.761, $p< .001$ or mispronounce words QM(1) = 215.761, $p< .001$. The lack of a significant modulation together with the small estimates indicates that there was no relationship between age and target looks in response to a correctly pronounced or mispronounced label. This relationship is plotted in Figure 2.

We then examined the interaction between age and mispronunciation sensitivity (correct vs. mispronounced words) in our whole dataset. The moderator test was significant QM(1) = 215.761, $p< .001$. This result is in line with the general observation that as infants mature they become better at language processing. 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 small estimate size, as well as inspection of Figure 2 suggests that as infants age, their mispronunciation sensitivity remains the same.

**(Insert Figure 2 about here)**

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**Vocabulary Size: Correlation Between Mispronunciation Sensitivity and Vocabulary.** Of the 32 papers included in the meta-analysis, 8 (comprehension = 7 papers; production = 1) analyzed the relationship between vocabulary scores and mispronunciation sensitivity, specifically object recognition for correct pronunciations and mispronunciations. There is reason to believe that production data are different from comprehension data (the former being easier to estimate for parents in the typical questionnaire-based assessment), so we analyze this data separately.

[CHRISTINA] SO WE DON'T WANT TO INTERPRET THE FIXED EFFECTS MODEL AT ALL, IT IS NOT SUITABLE BECAUSE THERE IS VARIANCE BETWEEN EVERY RECORD (LANGUAGE ETC). I WOULD INTERPRET THE OVERALL CORRELATION AND THE CI, NOT THE P-VALUE (IN GENERAL). I ALSO WONDER WHETHER WE SHOULD MOVE THE SUBSET ANALYSES TO THE SUPPLEMENTARY MATERIALS AND JUST SAY OVERALL WE SEE NO RELATIONSHIPS AND CORRELATION COEFFICIENTS CONSISTENYL BELOW .1 WE THEREFORE MUST CONCLUDE THAT WITHIN NARROW AGE GROUPS VOCABULARY DOES NOT INFLUENCE ANYTHING WE LOOK AT. WE CANNOT DO THIS ANALYSIS FPOR MP SENSITIVITY BECAUSE WE DON'T HAVE THE NECESSARY RAW DATA. [KATIE: Ah, so because for each paper the correlation and CI values straddle 0, this indicates that there really isn't much evidence for a relationship? I've tried to write this out below, let me know what you think. Over the summer, I had also played around with looking at how collection of vocabulary data has dropped off over the years, even though more mispronunciation studies have been published. That might be something interesting to add. If we truly think that this is what is driving the development of mispronunciation sensitivity, then why are people not collecting this data?] (BUT I WONDER WHETHER WECOULD ENCODE THE REPORTED INTERACTION TERMS AND THE CORRELATION AND THEN DO SOMETHING WITH THAT?) [KATIE: I'm not really sure what you mean by this :(]

[Katie: below, I'm using coweeta.uga.edu/publications/10436.pdf, page 80 as a model for writing up these results. I haven't the funniest clue what I'm doing! :p]

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 12 experimental conditions, with correlation values ranging from -0.17 to 0.48. The mean effect size XXX was 0.0897, but did not differ significantly from zero (95% CI[-0.0105; 0.1900] $p$ = .0795). Higher production scores were also associated with greater object recognition in response to correct pronunciations for 9 of 16 experimental conditions, with correlation values ranging from -0.23 to 0.44. The mean effect size XXX was 0.0601, but did not differ significantly from zero (95% CI[-0.0331; 0.1533] $p$ = .2061). For both comprehension and production scores, the small correlation effect sizes and large variances suggest a lack of relationship between vocabulary and object recognition for 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 correct pronunciations for 17 of 31 experimental conditions, with correlation values ranging from -0.35 to 0.57. The mean effect size XXX was 0.0377, but did not differ significantly from zero (95% CI[-0.0260; 0.1014] $p$ = .2465). For production, however, lower production scores were associated with greater object recognition in response to mispronunciations for 16 of 31 experimental conditions, with correlation values ranging from -0.28 to 0.44. The mean effect size XXX was -0.0402, but did not differ significantly from zero (95% CI[-0.1043; 0.0238] $p$ = .2181). For both comprehension and production scores, the small correlation effect sizes and large variances suggest a lack of relationship between vocabulary and object recognition for mispronunciations.

**Interim Discussion.** The main goal of this paper was to assess mispronunciation sensitivity and its maturation with age. The results are clear: Although infants consider a mispronunciation as a better match with the target image than a distractor image, there was a consistent effect of mispronunciation sensitivity. This did not change with development. Of the 3 predictions and assumptions about the development of infants' sensitivity to mispronunciations discussed in the Introduction, the present results lend some support for the argument that mispronunciation sensitivity stays consistent as infants develop. This runs counter to existing theories of phono-lexical development, which predict either an increase (PRIMR ref) or decrease (Assim Model ref) in mispronunciation sensitivity. Furthermore, counter to the predictions for the PRIMR (PRIMR ref) and Assimilation(Assim ref) models, we found no relationship between vocabulary and target looking for correct pronunciations or mispronunciations. In sum, it seems that current theories of infants' phono-lexical development cannot fully capture our results and should be reconsidered with all the evidence in mind.

Alternatively, it is possible that variation in the analysis approach lead to systematic differences in the size of mispronunciation sensitivity. Choices about the approach to data analysis have a higher possibility to be influenced by the shape of the data itself after collection, and are therefore susceptible to a higher rate of false-positives (Simmons, Nelson, & Simonsohn, 2011). Although we did not have specific predictions about these variables, such as size of time window analyzed or dependent variable calculated, we included these variables in our coding scheme for the meta-analysis dataset. As reported in the Methods section (and discussed in detail below), some of these variables varied widely across studies. 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.

[KATIE] I've changed the above paragraph to lead to exploratory analyses, not moderators. Since the fmailiar/unfamiliar analysis doesn't really work out except for if we kind of subset and torture the data, I think its more interesting to talk about how choices of analysis / researcher degrees of freedom may influence the data

## Exploratory Analyses

We identified several variables to assess the influence of data analysis choices. These variables fall into two types of categories: time-related and dependent variable related. In the following analyses, we discuss the theoretical motivation for these data analysis choices, the variation present in the current meta-analysis dataset, and the influence these choices have on mispronunciation sensitivity development.

**Time-related analyses.** When designing mispronunciation sensitivity studies, experimenters 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. Across papers, trial length varied from 2750 to 13000 ms, with a mode of 5000 ms. There was an inverse relationship between infant age and trial length, such that younger infants were given trials of a longer length, although this correlation was not significant ($r$ = -0.11, $p$ = 0.086). Presumably, younger infants may be given longer trials because their word recognition abilities may be slower than older infants (Fernald et al., 1998).

Unlike the length of trial, the length of the post-naming phase analyzed can be chosen after the experimental data is collected. Interestingly, half of the experimental conditions were analyzed using the same length of post-naming phase as the infant heard in the actual experiment 126, while the other half were analyzed using a shorter length of post-naming phase, excluding later portions of the post-naming phase 125. Across papers, the length of the post-naming phase analyzed varied from 1510 to 6000 ms, with a mode of 2000 ms. Similar to trial length, there was an inverse relationship between infant age and length of post-naming phase analyzed, such that younger infants were analyzed using a longer length of post-naming phase, although here the relationship was significant ($r$ = -0.21, $p < .001$). Again, the choice to analyze a shorter post-naming time window is likely related to evidence that speed of processing is slower in younger infants (Fernald et al., 1998). Furthermore, the proportion of post-naming phase time window analyzed in comprison to the total post-naming phase presented to infants significantly decreased with increasing infant age ($r$ = -0.18, $p$ = 0.004). Although trial length did not differ by infant age, the size of the post-naming phase time window analyzed did differ by infant age.

When analyzing eye-movements, it is important to consider the amount of time it takes for an eye movement to be initiated in response to a stimulus. 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 mispronunciation sensitivity studies, however, this has often been extended to 367 ms (e.g. Swingley & Aslin, 2000, 2002, 2007). Across papers, the majority used a similar offset 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, $p$ = 0.13). This lack of a relationship is perhaps 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 time window (infant age) or offset time (previous studies), these choices may occur after data collection and are therefore susceptible to a higher rate of false-positives. Considering that differences in these choice were systematically different across infant ages, at least for the post-naming time window, we next explored whether the size of the analyzed post-naming phase time window or the offset time influenced sensitivity to mispronunciations.

**Length of post time.** We first assessed whether size of post-naming phase analyzed had an impact on the size of mispronunciation sensitivity. First, we calculated the meta-analytic effect for object identification in response to mispronounced target words/images, including post-naming phase size as a moderator. The moderator test was not significant QM(1) = 215.761, $p< .001$ and the estimate for post-naming phase size was relatively small, $\beta$ = 0.121, SE = 0.073, 95% CI[-0.022, 0.264], $p$= 0.097. This suggests that upon hearing a mispronunciation, infants' looks to the target image were similar regardless of the size of the post-naming phase analyzed. We next assessed whether post-naming phase size was related to mispronunciation sensitivity. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as an additional moderator. The moderator test was significant, QM(1) = 215.761, $p< .001$. The estimate for the interaction between post-naming phase size and condition was small but significant $\beta$ = -0.156, SE = 0.051, 95% CI[-0.256, -0.056], $p$= 0.002. This relationship is plotted in Figure 3a. The results suggest that although the size of the post-naming phase analyzed did not impact infants' likelihood to fixate the target upon hearing the mispronunciation, it did significantly impact mispronunciation sensitivity. Specifically, the difference between target fixations for correctly pronounced and mispronounced items (mispronunciation sensitivity) was significantly greater when the post-naming phase that was shorter in length.

Considering that we also found a relationship between the length of the post-naming phase analyzed and infant age, such that younger ages had a longer post-naming phase time window of analysis, we next examined whether the size of post-naming phase analyzed modulated the development of mispronunciation sensitivity. For object recognition in response to a mispronunciation, including age as a moderator resulted in a moderator test that was not significant QM(1) = 215.761, $p< .001$, and a small estimate for the interaction between age and size of post-naming phase ($\beta$ = -0.156, SE = 0.051, 95% CI[-0.256, -0.056], $p$= 0.002. This suggests that upon hearing a mispronunciation, infant measured looks to the target image were similar, regardless of infant age or size of the post-naming phase analyzed.

We next assessed whether the relationship between size of the post-naming phase analyzed and mispronunciation sensitivity was modulated by age. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as well as age as additional moderators. The moderator test was significant QM(1) = 215.761, $p< .001$. The estimate for the three-way-interaction between condition, size of post-naming phase, and age was small, but significant ($\beta = =$ NA, SE = NA, 95% CI[NA, NA], $p$NA. This relationship is plotted in Figure 3b. Smaller post-naming phase size lead to greater increases in mispronunciation sensitivity with development. For example, experimental conditions analyzed with a post-naming phase of 2000 ms or less, mispronunciation sensitivity increases with infant age, whereas a post-naming phase of greater than 2000 ms leads to either no impact of age on mispronunciation sensitivity or a negative relationship between age and mispronunciation sensitivity.

**(Insert Figure 3 about here)**

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**Length of offset time.** We next assessed whether offset time had an impact on the size of mispronunciation sensitivity. First, we calculated the meta-analytic effect for object identification in response to mispronounced target words/images, including offset time as a moderator. The moderator test was not significant QM(1) = 215.761, $p< .001$ and the estimate for offset time was very small, $\beta = 0.001$, SE = 0, 95% CI[0, 0.001], $p= 0.132$. This suggests that upon hearing a mispronunciation, infants' looks to the target image were similar regardless of the offset time used to analyze the data. We next assessed whether offset time was related to mispronunciation sensitivity. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as an additional moderator. The moderator test was significant, QM(1) = 215.761, $p< .001$, but the estimate for the interaction between offset time and condition was very small and not significant $\beta = 0$, SE = 0, 95% CI[-0.001, 0], $p$= 0.505.

We next examined whether offset time modulated the development of mispronunciation sensitivity. For object recognition in response to a mispronunciation, including age as a moderator resulted in a moderator test that was not significant QM(1) = 215.761, $p$< .001, and a very small estimate for the interaction between age and size of post-naming phase ($\beta$ = 0, SE = 0, 95% CI[0, 0], $p$= 0.924. This suggests that upon hearing a mispronunciation, infant measured looks to the target image were similar, regardless of infant age or offset time. We next assessed whether the relationship between offset time and mispronunciation sensitivity was modulated by age. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as well as age as additional moderators. The moderator test was significant QM(1) = 215.761, $p$< .001, but the three-way-interaction between condition, offset time, and age was very small and not significant ($\beta$ = = 0, SE = 0, 95% CI[0, 0], $p$= 0.605.

Taken together, these results suggest that offset time does not modulate mispronunciation sensitivity. There is no relationship between offset time and age, and we find no influence of offset time on the development of mispronunciation sensitivity.

**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 no naming event has occured, whether correctly pronounced or mispronounced, which we refer to as the baseline. The purpose of the baseline is to ensure that infants do not have systematic preferences for the target or distractor (greater interest in a cat compared to cup) which may drive PTL scores in the post-naming phase. As described in the Data Analysis sub-section of the Methods, there was considerable variation across papers in way that baseline was calculated, resulting 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. This results in 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. We will refer to this dependent variable as the Difference Score. Another dependent variable, which was used in 69 experimental conditions, directly compared compared the post- and pre-naming PTL scores with one another. 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 increased their target looks after hearing the naming label. We will refer to this dependent variable as Pre vs. Post. Finally, the remaining 53 experimental conditions compared the post-naming PTL score with a chance value of 50%. Here, the infants' pre-naming phase preferences are not considered and instead target fixations are evaluated based on the likelihood to fixate one of two pictures. We will refer to this dependent variable as Post.

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. The Post dependent variable, in contrast, does not consider pre-naming preferences. To our knowledge, there is no theory or evidence to drive choice of dependent variable, 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 sensitivity to mispronunciations. Considering that the dependent variable Post differs in its consideration of pre-naming preferences, 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 mispronunciation sensitivity. First, we calculated the meta-analytic effect for object identification in response to mispronounced target words/images, including dependent variable as a moderator. The moderator test was significant QM(1) = 215.761, $p$< .001. The estimates for both the Pre vs. Post ($\beta$ = -0.369, SE = 0.143, 95% CI[-0.65, -0.088], $p$= 0.01) and Difference Score ($\beta$ = -0.392, SE = 0.135, 95% CI[-0.656, -0.128], $p$= 0.004) dependent variables were significantly smaller than that of the Post dependent variable. This suggests that reported looks to the target upon hearing a mispronunciation were greatest when the dependent variable was Post. We next assessed whether he dependent variable was related to mispronunciation sensitivity. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as an additional moderator. The moderator test was significant, QM(1) = 215.761, $p$< .001. The estimate for the interaction between Pre vs. Post and condition was significantly smaller than that of the Post dependent variable ($\beta$ = -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 ($\beta$ = -0.01, SE = 0.098, 95% CI[-0.203, 0.183], $p$= 0.916). This relationship is plotted in Figure 4a. The results suggest that dependent variable calculated significantly impacted the size fo the mispronunciation sensitivity effect, such that Post. vs. Pre showed a smaller mispronunciation sensitivity effect than Post, but no difference between the Difference Score and Post.

We next examined whether the type of dependent variable calculated modulated the development of mispronunciation sensitivity. For object recognition in response to a mispronunciation, including age as a moderator resulted in a moderator test that was significant QM(1) = 215.761, $p$< .001, but the estimates for the interaction between Pre vs. Post and age ($\beta$ = -0.011, SE = 0.037, 95% CI[-0.083, 0.061], $p$= 0.766) as well as Difference Score and age ($\beta$ = -0.021, SE = 0.033, 95% CI[-0.085, 0.043], $p$= 0.516) were not different from that of the Post dependent variable. This suggests that upon hearing a mispronunciation, infant measured looks to the target image were similar, regardless of infant age or type of dependent variable. We next assessed whether the relationship between dependent variable and mispronunciation sensitivity was modulated by age. We merged the two datasets and included condition (correct pronunciation, mispronunciation) as well as age as additional moderators. The moderator test was significant QM(1) = 215.761, $p<$ .001. The estimate for the interaction between Pre vs. Post, condition, and age was significantly smaller than that of the Post dependent variable ($\beta$ = -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 ($\beta$ = -0.036, SE = 0.027, 95% CI[-0.088, 0.016], $p$= 0.174). This relationship is plotted in Figure 4b. When the dependent variable was Pre vs. Post, mispronunciation sensitivity decreased with infant development, while in comparison, when the dependent variable was Post, mispronunciation sensitivity increased with infant development. There was no difference in mispronunciation sensitivity change with infant development between the Post and Difference Score dependent variables.

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### Controlling for researcher choice

## Discussion

To Summarize:

** Overall Meta-analytic Effect **

- Accept mispronunciations as labels for targets
- Sensitive to mispronunciations
- lack of change over development

** Vocabulary **

- no relationship?
- talk about how few studies report it

** Data Analysis Choices **

- Post-naming phase size and dependent variable impact misp sensitivity development
- Offset time does not impact misp sensitivity development
- the first two do not have theoretical frameworks to guide researchers, whereas offset time does

When it comes to designing studies, 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., in press). A meta-analysis is a first step in improving experiment planning by measuring the underlying 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 yield 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 (citationcitation). Overpowered studies mean that participants were tested unnecessarily, which has substantial ethical consequences particularly when working with infants and other difficult to recruit and test populations.

From Christina: let's make a note to put sth in the discussion about our curve being surprisingly flat for correctly pronounced words bc people adapt their analysis windows? Bc if you look at Molly's reaction time paper, there is a steep increase.

# References

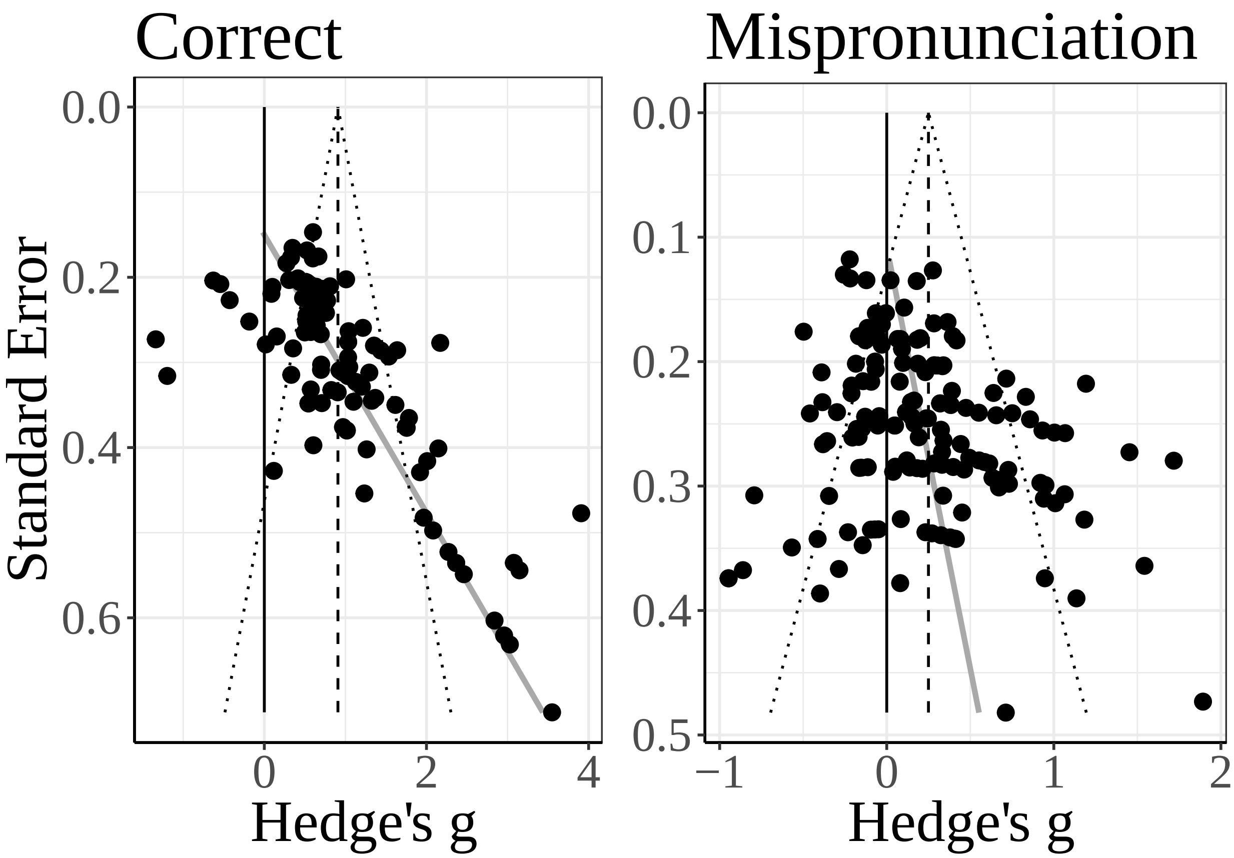

Correct
Mispronunciation
Standard Error
0.0
0.2
0.4
0.6
0
2
4
0.0
0.1
0.2
0.3
0.4
0.5
−1
0
1
2
Hedge's g
Hedge's g

*Figure 1*

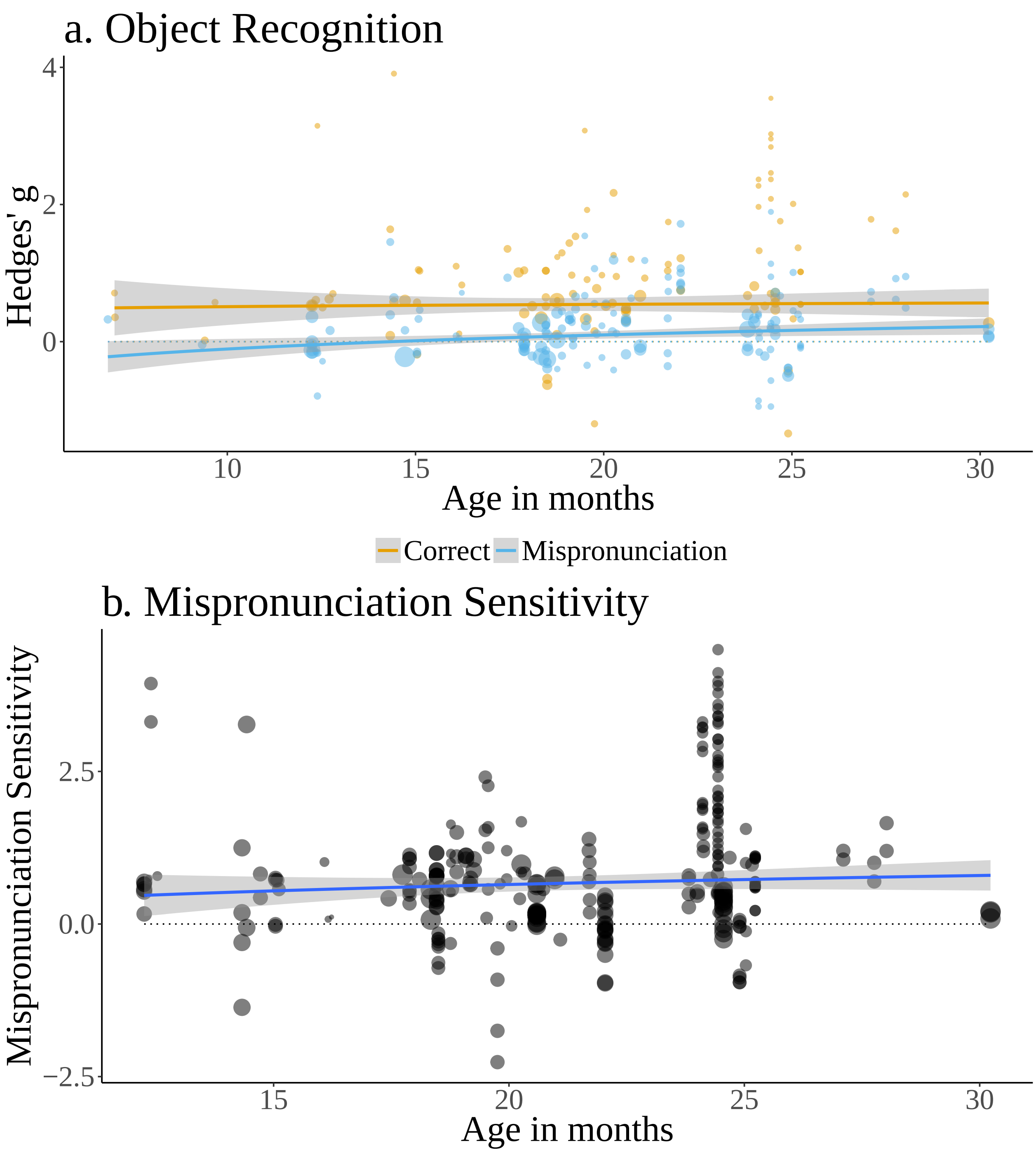
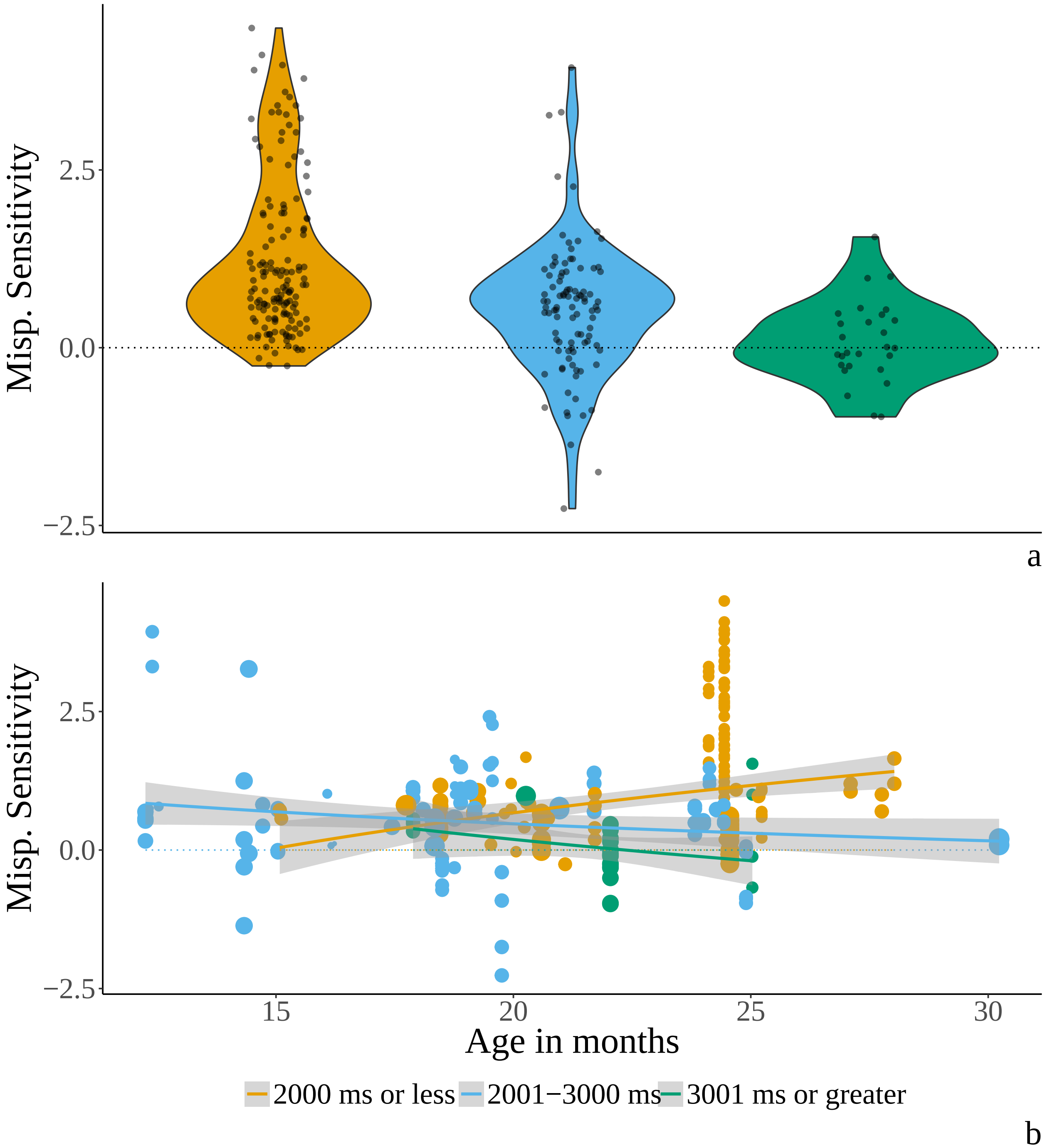

a. Object Recognition
Hedges' g
4
2
0
10
15
20
25
30
Age in months
Correct
Mispronunciation
b. Mispronunciation Sensitivity
Mispronunciation Sensitivity
2.5
0.0
−2.5
15
20
25
30
Age in months

*Figure 2*



Misp. Sensitivity
2.5
0.0
−2.5
a
Misp. Sensitivity
2.5
0.0
−2.5
15
20
25
30
Age in months
2000 ms or less
2001−3000 ms
3001 ms or greater
b


*Figure 3*

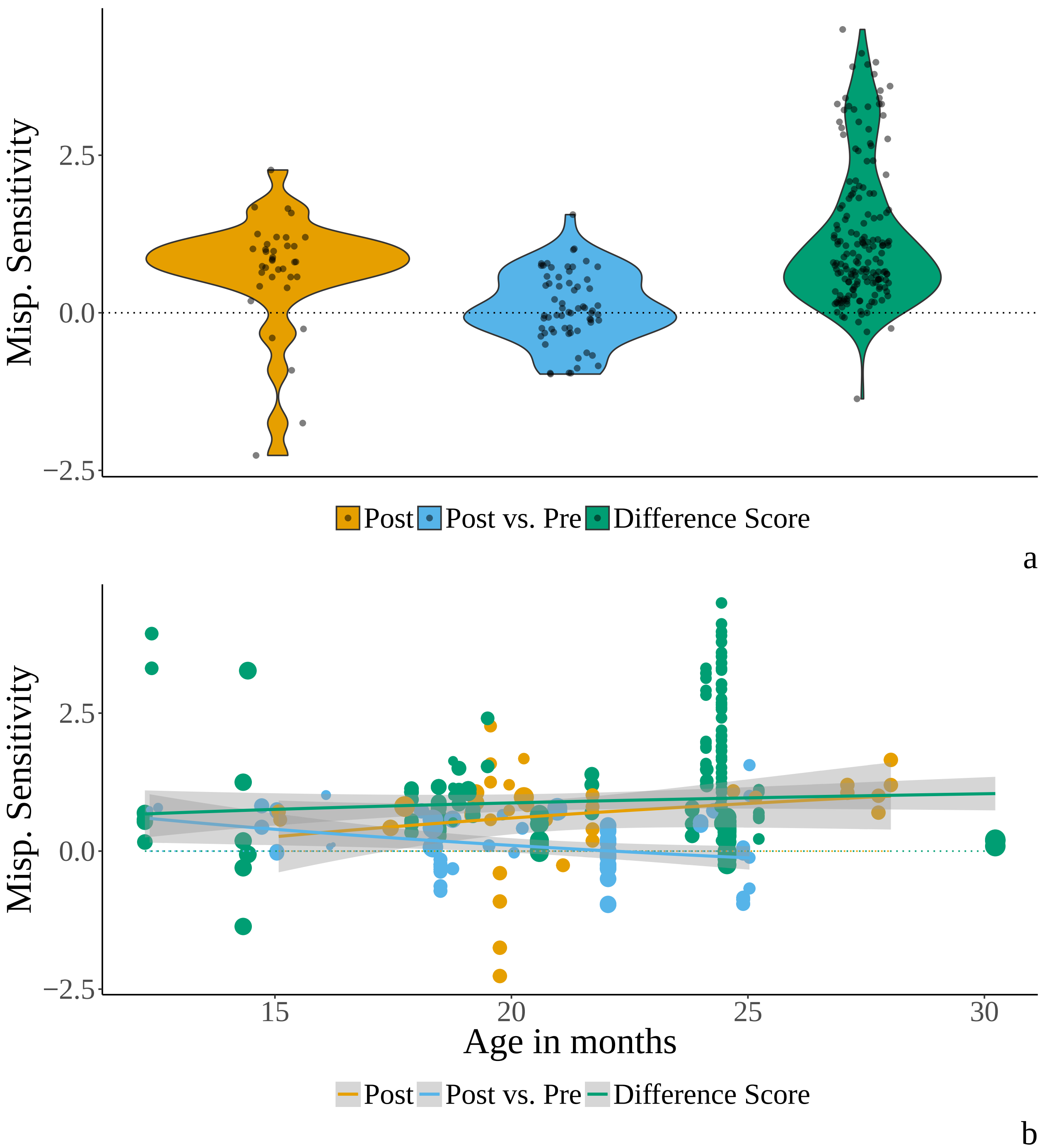

Misp. Sensitivity
2.5
0.0
−2.5
Post
Post vs. Pre
Difference Score
a
Misp. Sensitivity
2.5
0.0
−2.5
15
20
25
30
Age in months
Post
Post vs. Pre
Difference Score
b

*Figure 4*