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

2   Katie Von Holzen[1,2] & Christina Bergmann[3,4]

3   [1] Department of Hearing and Speech Sciences, University of Maryland, USA

4   [2] Laboratoire Psychologie de la Perception, Université Paris Descartes

5   [3] Max Planck Institute for Psycholinguistics, Nijmegen, the Netherlands

6   [4] LSCP, Departement d'Etudes Cognitives, ENS, EHESS, CNRS, PSL Research University

7   Author Note

8   The authors each declare that they have no conflict of interest.

9   Correspondence concerning this article should be addressed to Katie Von Holzen,

10   0221A LeFrak Hall, University of Maryland, College Park, MD 20742. E-mail:

11   katie.m.vonholzen@gmail.com

12   Abstract

13   As they develop into mature speakers of their native language, infants must not only learn

14 words but also the sounds that make up those words. To do so, they must strike a balance

15 between accepting some variation (e.g. mood, voice, accent), but appropriately rejecting

16 variation when it changes a word's meaning (e.g. cat vs. hat). We focus on studies

17 investigating infants' ability to detect mispronunciations in familiar words, which we refer to

18 as mispronunciation sensitivity. The goal of this meta-analysis was to evaluate the

19 development of mispronunciation sensitivity in infancy, allowing for a test of competing

20 mainstream theoretical frameworks. The results show that although infants are sensitive to

21 mispronunciations, they still accept these altered forms as labels for target objects.

22 Interestingly, this ability is not modulated by age or vocabulary size, challenging existing

23 theories and suggesting that a mature understanding of native language phonology is present

24 in infants from an early age, possibly before the vocabulary explosion. Despite this finding,

25 we discuss potential data analysis choices that may influence different conclusions about

26 mispronunciation sensitivity development as well as offer recommendations to improve best

27 practices in the study of mispronunciation sensitivity.

28   *Keywords:* language acquisition; mispronunciation sensitivity; word recognition;

29 meta-analysis; lexicon; infancy

₃₀   The development of infants' responses to mispronunciations: A Meta-Analysis

₃₁   **Introduction**

₃₂   Acquiring a first language means that young learners are solving a host of tasks in a

₃₃ short amount of time. As infants develop into toddlers during their second and third years

₃₄ they learn new words in earnest while simultaneously refining their knowledge about the

₃₅ sounds that make up these words (Best, 1994, 1995; Curtin & Werker, 2007; Kuhl, 2004;

₃₆ Werker & Curtin, 2005). In a mature phono-lexical system, word recognition must balance

₃₇ flexibility to slight variation (e.g., speaker identity, accented speech) while distinguishing

₃₈ between phonetic details that differentiate words in a given language (e.g. cat-hat). To build

₃₉ robust language knowledge, it seems useful to acquire this ability early during development.

₄₀ Indeed, before children can correctly pronounce a word, they already are aware that slight

₄₁ phonological deviations might signal a change in word meaning (H. H. Clark & Clark, 1977).

₄₂ This mispronunciation sensitivity reflects the specificity with which infants represent the

₄₃ phonological information of familiar words. As infants continue to develop into expert

₄₄ language users, their language processing matures and becomes more efficient, including

₄₅ their knowledge of what constitutes a permissible versus word-changing phonological

₄₆ deviation. In this paper, we aggregate and analyze the nearly 20 years of literature

₄₇ investigating mispronunciation sensitivity in infants in an attempt to uncover its

₄₈ characteristics and the trajectory of its development.

₄₉   At the turn of the millenium, infant language acquisition researchers had established

₅₀ that during their first two years of life, infants are sensitive to changes in the phonetic detail

₅₁ of newly segmented words (Jusczyk & Aslin, 1995) and learned minimal pairs (Stager &

₅₂ Werker, 1997). Furthermore, when presented with familiar image pairs, children fixate on the

₅₃ referent of a spoken label (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Tincoff

₅₄ & 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.

The study of Swingley and Aslin (2000) as well as subsequent studies examining mispronunciation sensitivity address two complementary principles that infants must discover in early phonological development in order to form adult-like word representations and processing capabilities: *phonological constancy* and *phonological distinctiveness.* Phonological constancy is the ability to resolve 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, speakers of a given language must therefore simultaneously use both phonological constancy and distinctiveness to determine where phonological variation is appropriate and where it changes a word's meaning. Both abilities have to be acquired, because language

82 systems differ in which sounds signal a meaning change.

83   In the current study, we focus on infants' developing ability to correctly apply the

84 principles of phonological constancy and distinctiveness by using a meta-analytic approach

85 to investigate mispronunciation sensitivity. Considering that infants are sensitive to

86 mispronunciations and that, in general, their processing matures with development, we

87 examine the shape of mispronunciation sensitivity over the course of the second and third

88 year. There are three distinct possibilities how mispronunciation sensitivity might change as

89 infants become native speakers, which are all respectively supported by single studies and

90 additionally two possibilities are predicted by key theoretical accounts. By aggregating all

91 publicly available evidence using meta-analysis, we can examine developmental trends

92 making use of data from a much larger and diverse sample of infants than is possible in most

93 single studies ([see Frank et al. (2017); for a notable exception). Before we outline the

94 meta-analytical approach and its advantages in detail, we first discuss the proposals this

95 study seeks to disentangle and the data supporting each of the accounts.

96   Young infants may begin cautiously in their approach to word recognition, rejecting

97 any phonological variation in familiar words and only later learning to accept appropriate

98 variability. According to the Perceptual Attunement account, this describes a shift away

99 from specific native phonetic patterns to a more mature understanding of the abstract

100 phonological structure of words (Best, 1994, 1995). This shift is predicted to coincide with

101 the vocabulary spurt around 18 months, because it is causally related to vocabulary growth.

102 In this case, we would expect the size of mispronunciation sensitivity to be larger at younger

103 ages and *decrease* as the child matures and learn more words, although children continue to

104 detect mispronunciations. Indeed, young infants are more perturbed by accented speakers

105 than older infants in their recognition of familiar words (Best, Tyler, Gooding, Orlando, &

106 Quann, 2009; Mulak, Best, Tyler, Kitamura, & Irwin, 2014) or learning of new words

107 (Schmale, Hollich, & Seidl, 2011).

108   According to a different theoretical framework, young infants may instead begin with

109 phonologically broad representations for familiar words and only refine their representations

110 as language experience accumulates. PRIMIR (Processing Rich Information from

111 Multidimensional Interactive Representations; Curtin & Werker, 2007; Curtin,

112 Byers-Heinlein, & Werker, 2011; Werker & Curtin, 2005) describes the development of

113 phonemic categories emerging as the number of word form-meaning linkages increases.

114 Vocabulary growth, therefore, promotes more detailed phonological representations in

115 familiar words. Following this account, we predict an *increase* in mispronunciation sensitivity

116 as infants mature and add more words to their growing lexicon.

117   Finally, sensitivity to mispronunciation may not be modulated by development at all.

118 Infants' overall language processing becomes more efficient, but their sensitivity to

119 mispronunciations may not change. Across infancy and toddlerhood, mispronunciations

120 would thus be detected and lead to less looks at a target than correct pronunciations, but

121 the size of this effect would not change, nor be related to vocabulary size. This pattern is not

122 predicted by any mainstream theory of language acquisition, but for completeness we

123 mention it here.

124   Research following the seminal study by Swingley and Aslin (2000) has extended

125 mispronunciation sensitivity to infants as young as 9 months (Bergelson & Swingley, 2017),

126 indicating that from early stages of the developing lexicon onwards, infants can and do

127 detect mispronunciations. Regarding the change in mispronunciation sensitivity over

128 development, however, only about half of studies have compared more than one age group on

129 the same mispronunciation task (see Table 1). In those single studies all possible patterns of

130 development lined out above have been reported, making the current meta-analysis very

131 informative.

132   One study has found evidence for infants to become *less* sensitive to mispronunciations

133 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, 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 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. These studies award support to the

prediction that mispronunciation sensitivity increases 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 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). 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 hypotheses attribute change to vocabulary growth. Both the Perceptual Attunement (Best, 1994, 1995) and PRIMIR (Curtin & Werker, 2007; Curtin et al., 2011; Werker & Curtin, 2005) accounts situate a change in mispronunciation sensitivity occurring 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, 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.

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. As a consequence, our results will be important in evaluating theories and drive future research. 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

211 the interactive platform MetaLab (https://metalab.stanford.edu; Bergmann et al., 2018).

212 Since the present paper was written with embedded analysis scripts in R (R Core Team,

213 2018) using the papaja package (Aust & Barth, 2018) in R Markdown (Allaire et al., 2018),

214 it is always possible to re-analyze an updated dataset. In addition, we followed the Preferred

215 Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and make

216 the corresponding information available as supplementary materials (Moher, Liberati,

217 Tetzlaff, Altman, & Group, 2009). Figure 1 plots our PRISMA flowchart illustrating the

218 paper selection procedure.

219 **(Insert Figure 1 about here)**

220 **Study Selection**

221   We first generated a list of potentially relevant items to be included in our

222 meta-analysis by creating an expert list. This process yielded 110 items. We then used the

223 google scholar search engine to search for papers citing the original Swingley and Aslin

224 (2000) publication. This search was conducted on 22 September, 2017 and yielded 288

225 results. We removed 99 duplicate items and screened the remaining 299 items for their title

226 and abstract to determine whether each met the following inclusion criteria: (1) original data

227 was reported; (2) the experiment examined familiar word recognition and mispronunciations;

228 (3) infants studied were under 31-months-of-age and typically developing; (4) the dependent

229 variable was derived from proportion of looks to a target image versus a distractor in a eye

230 movement experiment; (5) the stimuli were auditory speech. The final sample ($n = 34$)

231 consisted of 28 journal articles, 1 proceedings paper, 3 theses, and 2 unpublished reports. We

232 will refer to these items collectively as papers. Table 1 provides an overview of all papers

233 included in the present meta-analysis.

234 **(Insert Table 1 about here)**

235 **Data Entry**

236 The 34 papers we identified as relevant were then coded with as much consistently
237 reported detail as possible (Bergmann et al., 2018; Tsuji et al., 2014). For each experiment
238 (note that a paper typically has multiple experiments), we entered variables describing the
239 publication, population, experiment design and stimuli, and results. For the planned
240 analyses to evaluate the development of mispronunciation sensitivity, we focus on the
241 following characteristics:

242 1 Condition: Were words mispronounced or not;
243 2 Mean age reported per group of infants, in days;
244 3 Vocabulary size, measured by a standardized questionnaire or list;

245 We separated conditions according to whether or not the target word was
246 mispronounced to be able to investigate infants' looking to the target picture as well as their
247 mispronunciation sensitivity, which is the difference between looks to the target in correct
248 and mispronounced trials. When the same infants were further exposed to multiple
249 mispronunciation conditions and the results were reported separately in the paper, we also
250 entered each condition as a separate row (e.g., consonant versus vowel mispronunciations;
251 Mani & Plunkett, 2007). The fact that the same infants contributed data to multiple rows
252 (minimally those containing information on correct and mispronounced trials) leads to
253 shared variance across effect sizes, which we account for in our analyses (see next section).
254 We will call each row a record; in total there were 271 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 ($n = 186$ records from 26 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 4 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

²⁸¹ leads to the exclusion of 2 records for correct pronunciations and 3 records for

²⁸² mispronunciations.

²⁸³   To take into account the fact that the same infants contributed to multiple datapoints,

²⁸⁴ we analyze our results in a multilevel approach using the R (R Core Team, 2018) package

²⁸⁵ metafor (Viechtbauer, 2010). We use a multilevel random effects model which estimates the

²⁸⁶ mean and variance of effect sizes sampled from an assumed distribution of effect sizes. In the

²⁸⁷ random effect structure we take into account the shared variance of effect sizes drawn from

²⁸⁸ the same paper, and nested therein that the same infants might contribute to multiple effect

²⁸⁹ sizes.

²⁹⁰   Mispronunciation sensitivity studies typically examine infants' proportion of target

²⁹¹ looks (PTL) in comparison to some baseline measurement. PTL is calculated by dividing the

²⁹² percentage of looks to the target by the total percentage of looks to both the target and

²⁹³ distractor images. Across papers the baseline comparison varied; since other options were

²⁹⁴ not available to us, we used the baseline reported by the authors of each paper. Most papers

²⁹⁵ ($n = 52$ records from 13 papers) subtracted the PTL score for a pre-naming baseline phase

²⁹⁶ from the PTL score for a post-naming phase and report a difference score.

²⁹⁷   Other papers either compared post- and pre-naming PTL with one another ($n = 29$

²⁹⁸ records from 10 papers), thus reporting two variables, or compared post-naming PTL with a

²⁹⁹ chance level of 50% ($n = 23$ records from 9 papers). For all these comparisons, positive

³⁰⁰ values (either as reported or after subtraction of chance level or a pre-naming baseline PTL)

³⁰¹ indicate target looks towards the target object after hearing the label, i.e. a recognition

³⁰² effect. Standardized effect sizes based on mean differences, as calculated here, preserve the

³⁰³ sign. Consequently, positive effect sizes reflect more looks to the target picture after naming,

³⁰⁴ 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 $\tau = 0.53$, $p < .001$) and mispronunciations (Kendall's $\tau = 0.16$, $p = 0.004$). 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

351 population infants would reliably show the expected object identification effect.

352   We should also point out that funnel plot asymmetry can be caused by multiple factors

353 besides publication bias, such as heterogeneity in the data. There are various possible

354 sources of heterogeneity, which our subsequent moderator analyses will begin to address.

355 Nonetheless, we will remain cautious in our interpretation of our findings and hope that an

356 open dataset which can be expanded by the community will attract previously unpublished

357 null results so we can better understand infants' developing mispronunciation sensitivity.

358 **(Insert Figure 2 about here)**

359   We next examined the p-curves for significant values from the correctly pronounced

360 and mispronounced conditions. The p-curve based on 72 statistically significant values for

361 correct pronunciations indicates that the data contain evidential value (Z = -17.93, $p < .001$)

362 and we find no evidence of a large proportion of p-values just below the typical alpha

363 threshold of .05 that researchers consistently apply in this line of research. The p-curve

364 based on 36 statistically significant values for mispronunciations indicates that the data

365 contain evidential value (Z = -6.81, $p < .001$) and there is again no evidence of a large

366 proportion of p-values just below the typical alpha threshold of .05.

367   Taken together, the results suggest a tendency in the literature towards publication

368 bias. As a result, our meta-analysis may systematically overestimate effect sizes and we

369 therefore interpret all estimates with caution. Yet, the p-curve analysis suggests that the

370 literature contains evidential value, reflecting a "real" effect. We therefore continue our

371 meta-analysis.

372 **Meta-analysis**

³⁷³ **Object Identification for Correct and Mispronounced Words.** We first

³⁷⁴ calculated the meta-analytic effect for infants' ability to identify objects when hearing

³⁷⁵ correctly pronounced labels. The variance-weighted meta-analytic effect size Hedges' g was

³⁷⁶ 0.908 (SE = 0.12) which was significantly different from zero (CI [0.673, 1.143], $p < .001$).

³⁷⁷ This is a small to medium effect size (according to the criteria set by Mills-Smith, Spangler,

³⁷⁸ Panneton, & Fritz, 2015). That the effect size is significantly above zero suggests that when

³⁷⁹ presented with the correctly pronounced label, infants tended to fixate on the corresponding

³⁸⁰ object. Although the publication bias present in our analysis of funnel plot asymmetry

³⁸¹ suggests that the effect size Hedges' g may be overestimated for object identification in

³⁸² response to correctly pronounced words, the p-curve results and a CI lower bound of 0.67,

³⁸³ which is substantially above zero, together suggest that this result is somewhat robust. In

³⁸⁴ other words, we are confident that the true population mean lies above zero for object

³⁸⁵ recognition of correctly pronounced words.

³⁸⁶ We then calculated the meta-analytic effect for object identification in response to

³⁸⁷ mispronounced words. In this case, the variance-weighted meta-analytic effect size Hedges' g

³⁸⁸ was 0.25 (SE = 0.06) which was also significantly different from zero (CI [0.133, 0.367], $p <$

³⁸⁹ .001). This is considered a small effect size (Mills-Smith et al., 2015), but significantly above

³⁹⁰ zero, which suggests that even when presented with a mispronounced label, infants fixated

³⁹¹ the correct object. In other words, infants are able to resolve mispronunciations, a key skill

³⁹² in language processing We again note the publication bias (which was smaller in this

³⁹³ condition), and the possibility that the effect size Hedges' g may be overestimated. But, as

³⁹⁴ the p-curve indicated evidential value, we are confident in the overall pattern, namely that

³⁹⁵ infants fixate the target even after hearing a mispronounced label.

³⁹⁶ **Mispronunciation Sensitivity Meta-Analytic Effect.** The above two analyses

³⁹⁷ considered the data from mispronounced and correctly pronounced words separately. To

³⁹⁸ 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

425 identification in response to correctly pronounced (QM(1) = 0.678, p = 0.41) or

426 mispronounced words (QM(1) = 1.715, p = 0.19). The lack of a significant modulation

427 together with the small estimates for age (correct: β = 0.015, SE = 0.018, 95% CI[-0.02,

428 0.049], p = 0.41; mispronunciation: β = 0.015, SE = 0.011, 95% CI[-0.007, 0.037], p = 0.19)

429 indicates that there might be no relationship between age and target looks in response to a

430 correctly pronounced or mispronounced label. We note that the estimates in both cases are

431 positive, however, which is in line with the general assumption that infants' language

432 processing overall improves as they mature (Fernald et al., 1998). We plot both object

433 recognition and mispronunciation sensitivity as a function of age in Figure 3.

434   We then examined the interaction between age and mispronunciation sensitivity

435 (correct vs. mispronounced words) in our whole dataset. The moderator test was significant

436 (QM(3) = 218.621, p < .001). The interaction between age and mispronunciation sensitivity,

437 however, was not significant (β = 0.003, SE = 0.008, 95% CI[-0.012, 0.018], p = 0.731); the

438 moderator test was mainly driven by the difference between conditions. The small estimate,

439 as well as inspection of Figure 3, suggests that as infants age, their mispronunciation

440 sensitivity neither increases or decreases.

441 **(Insert Figure 3 about here)**

442   **Vocabulary Size: Correlation Between Mispronunciation Sensitivity and**

443 **Vocabulary.**   Of the 32 papers included in the meta-analysis, 13 analyzed the relationship

444 between vocabulary scores and object recognition for correct pronunciations and

445 mispronunciations (comprehension = 11 papers and 39 records; production = 3 papers and

446 20 records). There is reason to believe that production data are different from

447 comprehension data. Children comprehend more words than they can produce, leading to

448 different estimates for comprehension and production. Production data is easier to estimate

449 for parents in the typical questionnaire-based assessment and may therefore be more reliable

450 (Tomasello & Mervis, 1994). As a result, we planned to analyze these two types of

451 vocabulary measurement separately. However, because only 3 papers reported correlations

452 with productive vocabulary scores, only limited conclusions can be drawn. We also note that

453 because individual effect sizes in our analysis were related to object recognition and not

454 mispronunciation sensitivity, we were only able to calculate the relationship between

455 vocabulary scores and the former. In our vocabulary analysis, we therefore focus exclusively

456 on the relationship between comprehension and object recognition for correct pronunciations

457 and mispronunciations.

458   We first considered the relationship between vocabulary and object recognition for

459 correct pronunciations. Higher comprehension scores were associated with greater object

460 recognition in response to correct pronunciations for 9 of 10 experimental conditions, with

461 correlation values ranging from -0.16 to 0.48. The weighted mean effect size Pearson's r of

462 0.14 was small but did differ significantly from zero (CI [0.03; 0.25] $p = 0.012$). As a result,

463 we can draw a tentative conclusion that there is a positive relationship between

464 comprehension scores and object recognition in response to correct pronunciations.

465   We next considered the relationship between vocabulary and object recognition for

466 mispronunciations. Higher comprehension scores were associated with greater object

467 recognition in response to mispronunciations for 17 of 29 experimental conditions, with

468 correlation values ranging from -0.35 to 0.57. The weighted mean effect size Pearson's r of

469 0.05 was small and did not differ significantly from zero (CI [-0.01; 0.12] $p = 0.119$). The

470 small correlation suggests either a very small positive or no relationship between vocabulary

471 and object recognition for mispronunciations. We again emphasize that we cannot draw a

472 firm conclusion due to the small number of studies we were able to include here.

473   Figure 4 plots the year of publication for all the mispronunciation sensitivity studies

474 included in this meta-analysis. This figure illustrates two things: the increasing number of

475 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.   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. Of the three predictions about the development of infants' sensitivity to mispronunciations discussed in the Introduction, the present results lend some support for the proposal that mispronunciation sensitivity stays consistent as infants develop. This runs counter to existing theories of phono-lexical development, which predict either an increase (Curtin & Werker, 2007; Curtin et al., 2011; Werker & Curtin, 2005) or decrease (Best, 1994, 1995) in mispronunciation sensitivity. 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 also runs counter to the predictions for the PRIMR (Curtin & Werker, 2007; Curtin et al., 2011; Werker & Curtin, 2005) and Assimilation (Best, 1994, 1995) models, but may be due to our analyses being underpowered. In sum, it seems that current theories of infants' phono-lexical development cannot fully capture our results, but that more investigation is

501 needed to draw a firm conclusion.

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

521   We included details related to timing and type of dependent variable in our coding of
522 the dataset because they are consistently reported and might be useful for experiment design
523 in the future by highlighting typical choices and helping establish field standards. In the
524 following section, we include an exploratory analysis to investigate the possibility of
525 systematic differences in the approach to analysis in general and across infant age. The
526 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 5a. 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 5b, 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)

Offset 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

629 significant (QM(7) = 200.867, $p < .001$), but the three-way-interaction between condition,

630 offset time, and age was again zero ($\beta = 0$, SE = 0, 95% CI[0, 0], $p = 0.605$). Taken together,

631 these results suggest that offset time does not modulate measured mispronunciation

632 sensitivity. There is no relationship between offset time and age, and we find no influence of

633 offset time on the estimated size of mispronunciation sensitivity over age. We again point

634 out that there is a substantial field consensus, which might mask any relationship.

635   **Dependent variable-related analyses.**   Mispronunciation studies evaluate infants'

636 proportion of target looks (PTL) in response to correct and mispronounced words.

637 Experiments typically include a phase where no naming event has occurred, whether

638 correctly pronounced or mispronounced, which we refer to as the pre-naming phase The

639 purpose of the pre-naming phase is to ensure that infants do not have systematic preferences

640 for the target or distractor (greater interest in a cat compared to a cup) which may drive

641 PTL scores in the post-naming phase. As described in the Data Analysis sub-section of the

642 Methods, however, there was considerable variation across papers in whether this pre-naming

643 phase was used as a baseline measurement, or whether a different baseline measurement was

644 used. This resulted in different measured outcomes or dependent variables. Over half of the

645 experimental conditions ($n = 129$) subtracted the PTL score for a pre-naming phase from

646 the PTL score for a post-naming phase. This results in one value, which is then compared

647 with a chance value of 0. When positive, this indicates that infants increased their looks to

648 the target after hearing the naming label (correct or mispronounced) relative to the

649 pre-naming baseline PTL. We will refer to this dependent variable as the Difference Score.

650 Another dependent variable, which was used in 69 experimental conditions, directly

651 compared the post- and pre-naming PTL scores with one another. This requires two values,

652 one for the pre-naming phase and one for the post-naming phase. A greater post compared

653 to pre-naming phase PTL indicates that infants increased their target looks after hearing the

654 naming label. We will refer to this dependent variable as Pre vs. Post. Finally, the

655 remaining 53 experimental conditions compared the post-naming PTL score with a chance

656 value of 50%. Here, the infants' pre-naming phase baseline preferences are not considered

657 and instead target fixations are evaluated based on the likelihood to fixate one of two

658 pictures. We will refer to this dependent variable as Post.

659   The Difference Score and Pre vs. Post can be considered similar to one another, in that

660 they are calculated on the same type of data and consider pre-naming preferences. It should

661 be noted, however, that the Difference Score may better counteract participant- and

662 item-level differences, whereas Pre vs. Post is a group-level measure. The Post dependent

663 variable, in contrast, does not consider pre-naming baseline preferences. To our knowledge,

664 there is no theory or evidence that explicitly drives choice of dependent variable in analysis

665 of mispronunciation sensitivity, which may explain the wide variation in dependent variable

666 reported in the papers included in this meta-analysis. We next explored whether the type of

667 dependent variable calculated influenced the estimated size of sensitivity to

668 mispronunciations. Considering that the dependent variable Post differs in its consideration

669 of pre-naming baseline preferences, substituting these for a chance value, we directly

670 compared mispronunciation sensitivity between Post as a reference condition and both

671 Difference Score and Pre vs. Post dependent variables.

672   We first assessed whether the choice of dependent variable had an impact on the size of

673 estimated mispronunciation sensitivity. When we included both condition and dependent

674 variable as moderators, the moderator test was significant (QM(5) = 259.817, $p < .001$).

675 The estimate for the interaction between Pre vs. Post and condition was significantly smaller

676 than that of the Post dependent variable (β = -0.392, SE = 0.101, 95% CI[-0.59, -0.194], $p <$

677 .001), but the difference between the Difference Score and Post in the interaction with

678 condition was small and not significant (β = -0.01, SE = 0.098, 95% CI[-0.203, 0.183], $p =$

679 0.916). This relationship is plotted in Figure 6a. The results suggest that the reported

680 dependent variable significantly impacted the size of the estimated mispronunciation

681 sensitivity effect, such that studies reporting the Post. vs. Pre dependent variable showed a

⁶⁸² smaller mispronunciation sensitivity effect than those reporting Post, but that there was no

⁶⁸³ difference between the Difference Score and Post dependent variables.

⁶⁸⁴ We next examined whether the type of dependent variable calculated modulated the

⁶⁸⁵ estimated change in mispronunciation sensitivity over infant age. When age was included as

⁶⁸⁶ an additional moderator, the moderator test was significant (QM(11) = 273.585, p < .001).

⁶⁸⁷ The estimate for the interaction between Pre vs. Post, condition, and age was significantly

⁶⁸⁸ smaller than that of the Post dependent variable (β = -0.089, SE = 0.03, 95% CI[-0.148,

⁶⁸⁹ -0.03], p = 0.003), but the difference between the Difference Score and Post in the interaction

⁶⁹⁰ with condition and age was small and not significant (β = -0.036, SE = 0.027, 95% CI[-0.088,

⁶⁹¹ 0.016], p = 0.174). This relationship is plotted in Figure 6b. When the dependent variable

⁶⁹² reported was Pre vs. Post, mispronunciation sensitivity was found to decrease with infant

⁶⁹³ age, while in comparison, when the dependent variable was Post, mispronunciation

⁶⁹⁴ sensitivity was found to increase with infant age. There was no difference in the estimated

⁶⁹⁵ mispronunciation sensitivity change with infant age between the Post and Difference Score

⁶⁹⁶ dependent variables.

⁶⁹⁷ Similar to the length of the post-naming analysis window, all three possible

⁶⁹⁸ developmental hypotheses might be supported depending on the dependent variable reported.

⁶⁹⁹ In other words, choice of dependent variable may influence the conclusion drawn regarding

⁷⁰⁰ how mispronunciation sensitivity may change with infant age.

⁷⁰¹ **(Insert Figure 6 about here)**

General Discussion

⁷⁰³ In this meta-analysis, we set out to quantify and assess the developmental trajectory of

⁷⁰⁴ infants' sensitivity to mispronunciations. Overall, the results of the meta-analysis showed

⁷⁰⁵ 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 et al., 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

₇₃₂ considerably in the age range considered in the current meta-analysis (see

₇₃₃ http://wordbank.stanford.edu; Frank et al., 2017). However, there are also substantial

₇₃₄ individual differences in the trajectory of vocabulary growth. The lack of developmental

₇₃₅ effects found in our meta-analysis may therefore be due to using age, instead of vocabulary

₇₃₆ size, as a moderator of mispronunciation sensitivity. We tried to address this issue by

₇₃₇ conducting an analysis of the subset of studies reporting correlations between infants'

₇₃₈ vocabulary size and their responses to correct and mispronounced labels. However, this

₇₃₉ analysis relied on only a few papers. We observed that an increasing vocabulary size lead to

₇₄₀ increased object recognition for correctly pronounced words; this was not the case for

₇₄₁ mispronunciations. However, it is difficult to draw any strong conclusions regarding the role

₇₄₂ of an increasing vocabulary size in mispronunciation sensitivity from this data.

₇₄₃   Why did we have so few samples for an analysis on vocabulary size to begin with?

₇₄₄ Despite the theoretical implications, fewer than half of the papers included in this

₇₄₅ meta-analysis measured vocabulary ($n = 13$; out of 32 papers total; see also Figure 4). There

₇₄₆ are more mispronunciation sensitivity studies published every year, perhaps due to the

₇₄₇ increased use of eye-trackers, which reduce the need for offline coding and thus make data

₇₄₈ collection much more efficient, but this has not translated to an increasing number of

₇₄₉ mispronunciation sensitivity studies also reporting vocabulary scores. We suggest that this

₇₅₀ may be the result of publication bias favoring significant effects or an overall hesitation to

₇₅₁ invest in data collection that is not expected to yield significant outcomes.

₇₅₂   What do our (tentative) results mean for theories of language development? Evidence

₇₅₃ that infants accept a mispronunciation (object identification) while simultaneously holding

₇₅₄ correctly pronounced and mispronounced labels as separate (mispronunciation sensitivity)

₇₅₅ may indicate an abstract understanding of words' phonological structure being in place early

₇₅₆ on. It appears that young infants may understand that the phonological form of

₇₅₇ mispronunciations and correct pronunciations do not match (phonological distinctiveness),

758 but that the mispronunciation is a better label for the target compared to the distractor

759 image (phonological constancy). The lack of age or vocabulary effects in our meta-analysis

760 suggest that this understanding is present from an age when the earliest words are learned

761 and is maintained throughout early lexical development. This implies mastery of the

762 principles of phonological constancy and phonological distinctiveness at an age earlier than

763 previously thought, which we recommend should be further explored experimentally and

764 taken into consideration by future theoretical accounts.

765 **Data Analysis Choices**

766   While creating the dataset on which this meta-analysis was based, we included as

767 many details as possible to describe each study. During the coding of these characteristics,

768 we noted a potential for variation in a handful of variables that relate to data analysis,

769 specifically relating to timing (post-naming analysis window; offset time) and to the

770 calculation of the dependent variable reported. We focused on these variables in particular

771 because their choice can potentially be made after researchers have examined the data,

772 leading to an inflated number of significant results which may also explain the publication

773 bias observed in the funnel plot asymmetry analyses (Simmons et al., 2011). To explore

774 whether this variation contributed to the lack of developmental change observed in the

775 overall meta-analysis, we included these variables as moderators in a set of exploratory

776 analyses. We noted an interesting pattern of results, specifically that different conclusions

777 about mispronunciation sensitivity, but more notably mispronunciation sensitivity

778 development, could be drawn depending on the length of the post-naming analysis window

779 as well as the type of dependent variable calculated in the experiment (see Figures 5 and 6).

780   Infants are expected to recognize words more quickly with age (Fernald et al., 1998).

781 This evidence has often guided decisions for the post-naming time window in

782 mispronunciation sensitivity studies, including where to begin the time window (offset time)

and how long this analysis window should be (post-naming analysis window). Specifically, increasing age should lead to quicker reaction times, and therefore lower offset times. Yet, we found no evidence for a relationship between offset time and infant age 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.

In contrast, both the length of the post-naming analysis window and the type of dependent variable calculated modulated mispronunciation sensitivity. Most critically, however, variation in these variables resulted in changes to the developmental trajectory 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 or the choice of dependent variable.

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 5) or dependent variable (see Figure 6) 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 solutions. 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. Experimenters can also 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 is calculated by truncating the mean age reported in the paper. The abbreviations

Comp and Prod refer to comprehension and production, respectively.

Paper	Publication format	Age	Vocabulary	N Effect Sizes
Altvater-Mackensen (2010)	dissertation	22, 25	None	13
Altvater-Mackensen et al. (2014)	paper	18, 25	None	16
Bailey & Plunkett (2002)	paper	18, 24	Comp	12
Ballem & Plunkett (2005)	paper	14	None	4
Bergelson & Swingley (2017)	paper	6, 7, 9, 12	None	9
Bernier & White (2017)	proceedings	21	None	4
Delle Luche et al. (2015)	paper	20, 19	None	4
Durrant et al. (2014)	paper	19, 20	None	4
Höhle et al. (2006)	paper	18	None	4
Højen et al. (n.d.)	gray paper	19, 20	Comp/Prod	6
Mani & Plunkett (2007)	paper	15, 18, 24, 14, 20	Comp/Prod	14
Mani & Plunkett (2010)	paper	12	Comp	8
Mani & Plunkett (2011)	paper	23, 17	None	15
Mani, Coleman, & Plunkett (2008)	paper	18	Comp/Prod	4
Ramon-Casas & Bosch (2010)	paper	24, 25	None	4
Ramon-Casas et al. (2009)	paper	21, 20, 43, 44	Prod	14
Ren & Morgan (in press)	gray paper	19	None	8
Renner (2017)	dissertation	17, 24	None	6
Skoruppa et al. (2013)	paper	23	None	5
Swingley (2003)	paper	19	Comp/Prod	6
Swingley (2009)	paper	17	Comp/Prod	4
Swingley (2016)	paper	27, 28	Prod	9
Swingley & Aslin (2000)	paper	20	Comp	2
Swingley & Aslin (2002)	paper	15	Comp/Prod	4
Tamasi (2016)	dissertation	30	None	4
Tao & Qinmei (2013)	paper	12	None	4

Tao et al. (2012)	paper	16	Comp	6
van der Feest & Fikkert, (2015)	paper	24, 20	None	16
van der Feest & Johnson (2016)	paper	24	None	24
Wewalaarachchi et al. (2017)	paper	24	None	8
White & Aslin (2011)	paper	18	None	4
White & Morgan (2008)	paper	18, 19	None	12
Zesiger & Jöhr (2011)	paper	14	None	8
Zesiger et al. (2012)	paper	12, 19	Comp/Prod	6
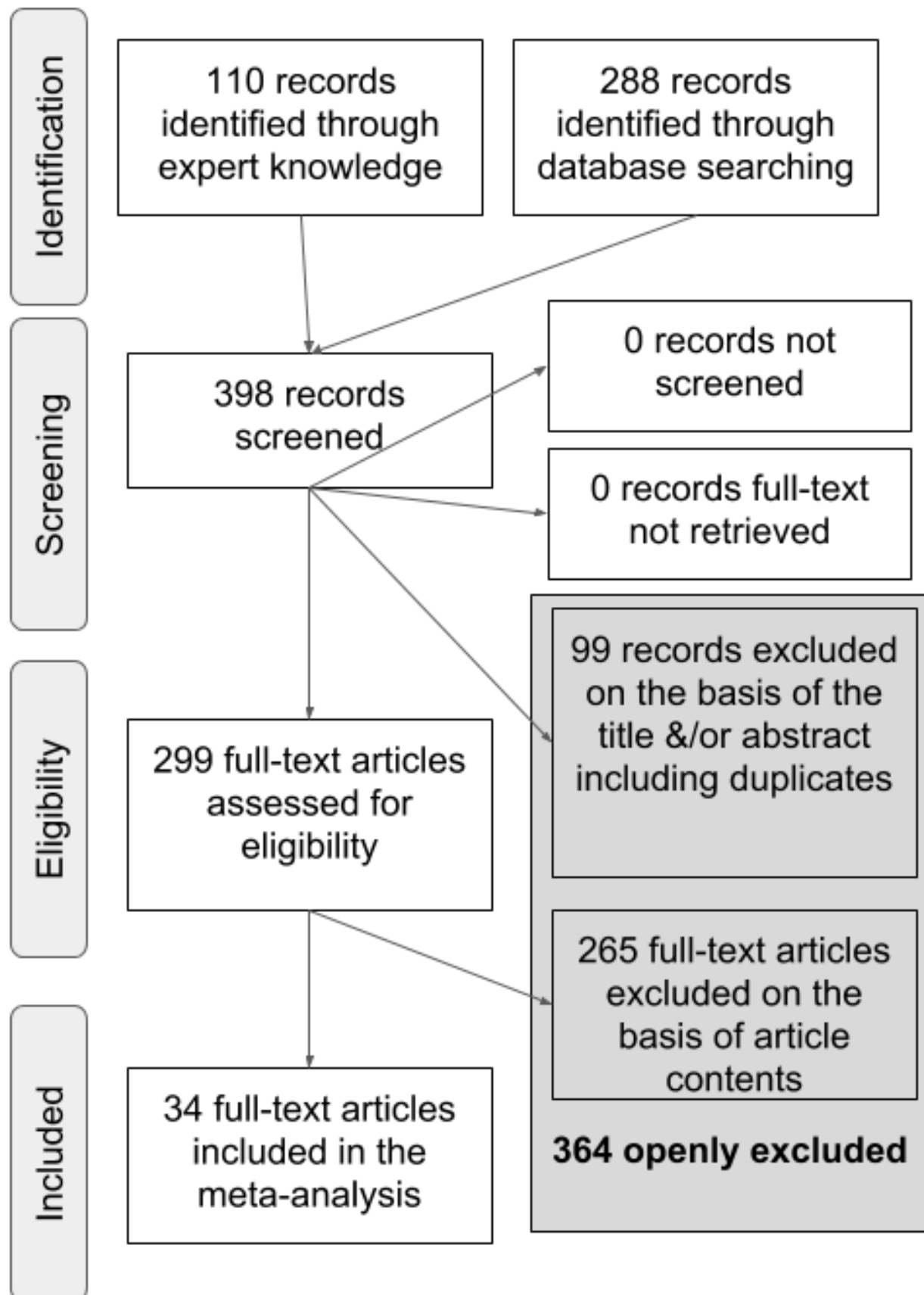
Figure 1. A PRISMA flowchart illustrating the selection procedure used to include studies in the current meta-analysis.
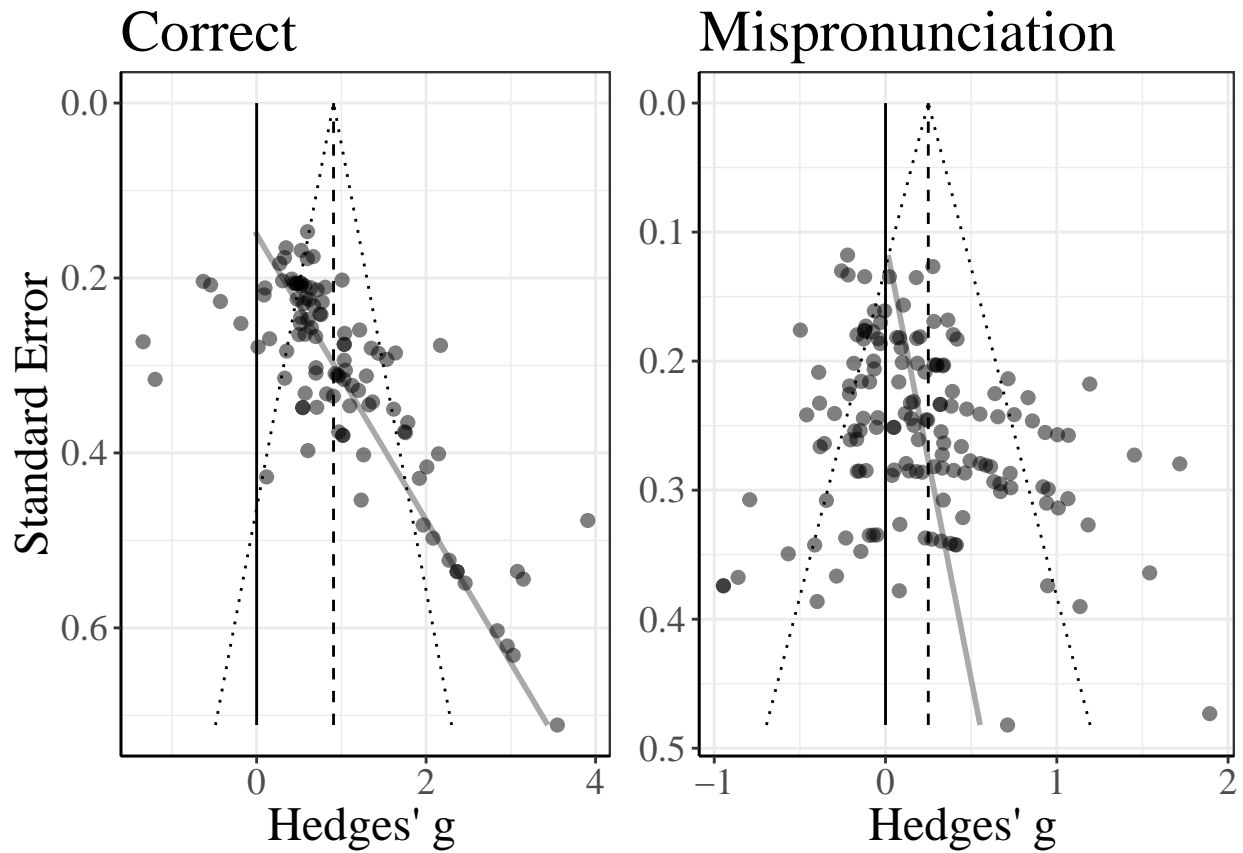
Figure 2. Funnel plots for object identification, plotting the standard error of the effect size in relation to the effect size. The black line marks zero, the dashed grey line marks the effect estimate, and the grey line marks funnel plot asymmetry.
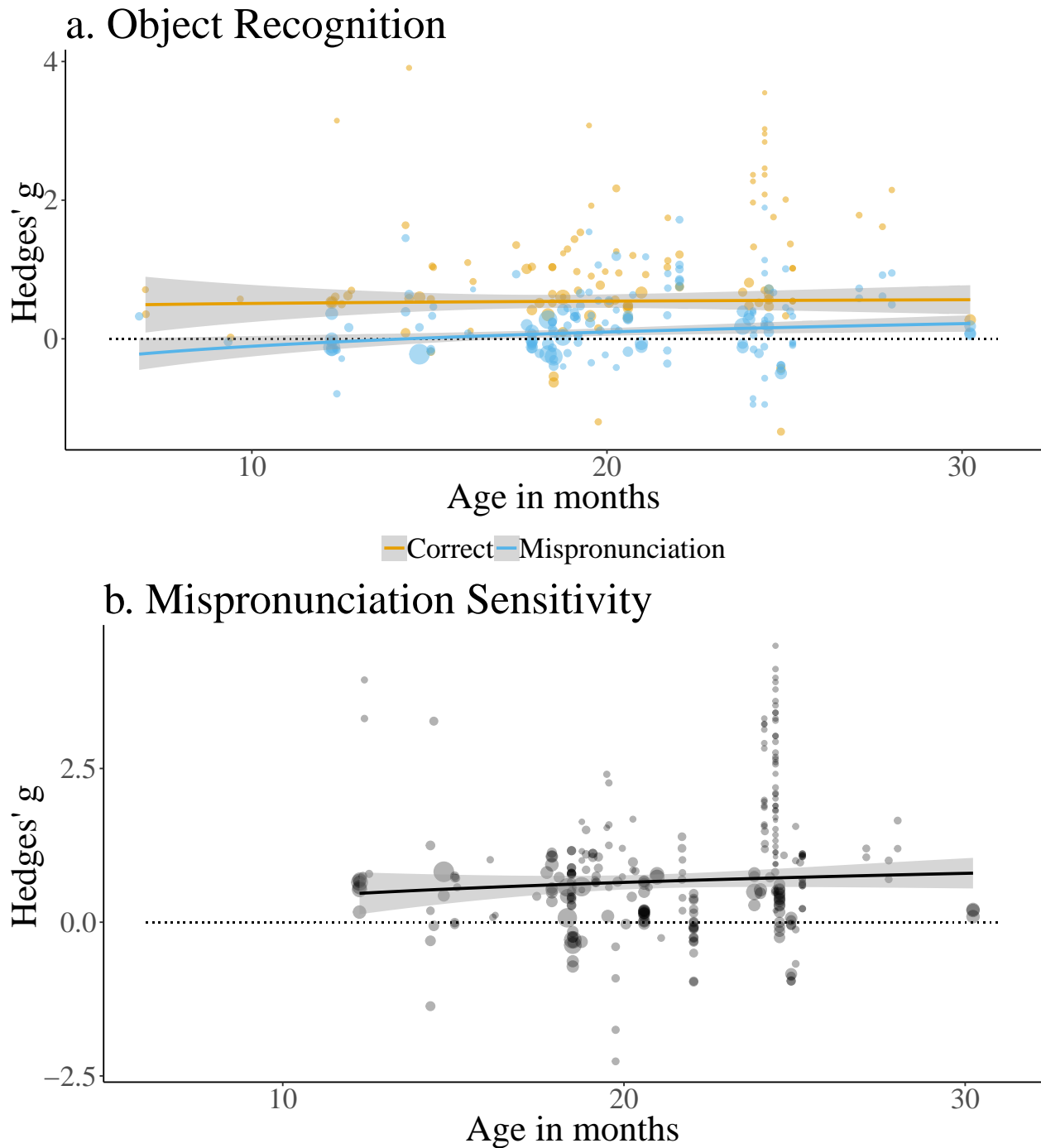
Figure 3. Panel a: Effect sizes for correct pronunciations (orange) and mispronunciations (blue) by participant age. Panel b: Effect sizes for mispronunciation sensitivity (correct - mispronunciations) by participant age. For both panels, point size depicts inverse variance and the dashed line indicates zero (chance).
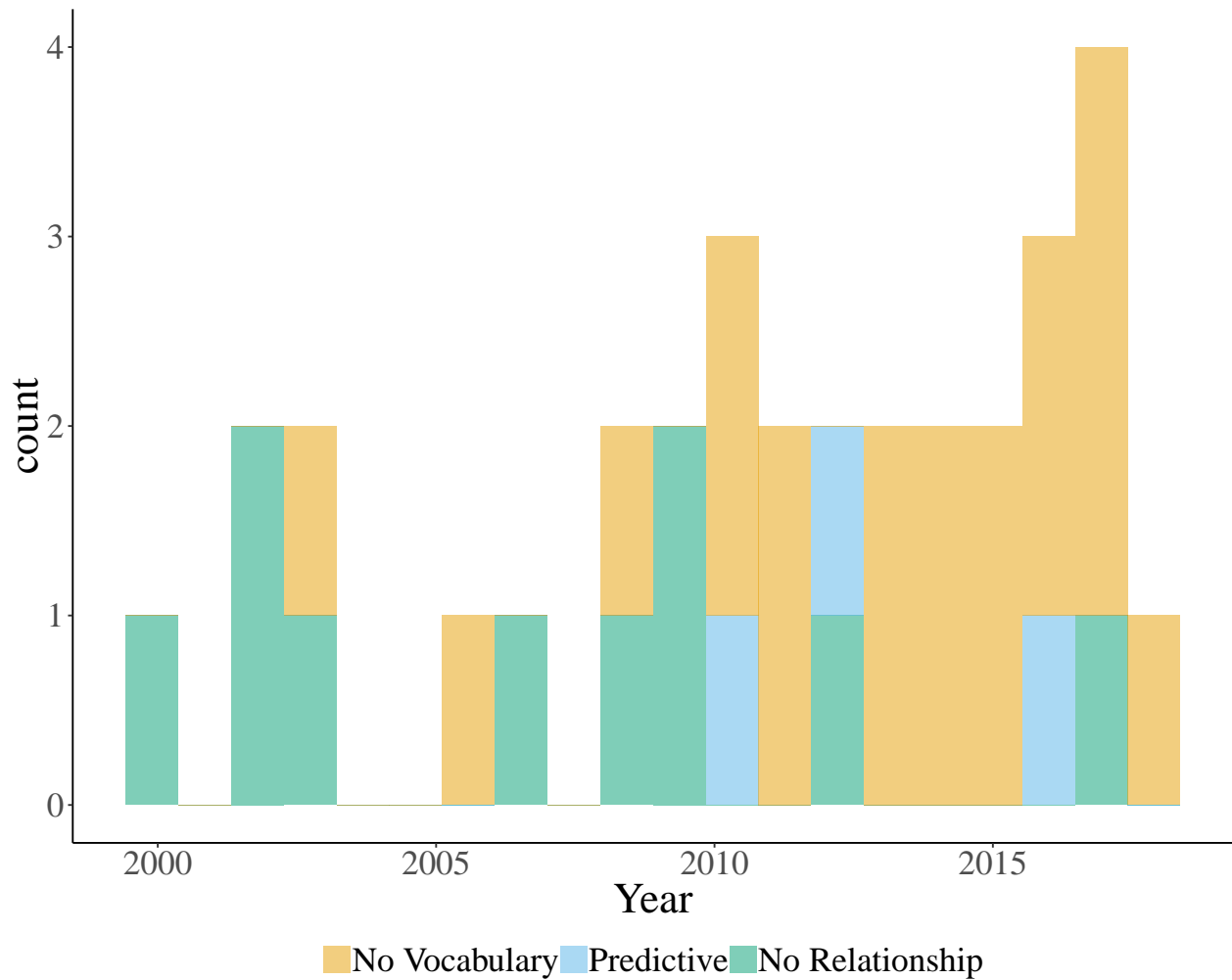
Figure 4. Counts of studies included in the meta-analysis as a function of publication year, representing whether the study did not measure vocabulary (orange), did measure vocabulary and was reported to predict mispronunciation sensitivity (blue), or did measure vocabulary and was reported to not predict mispronunciation sensitivity (green).
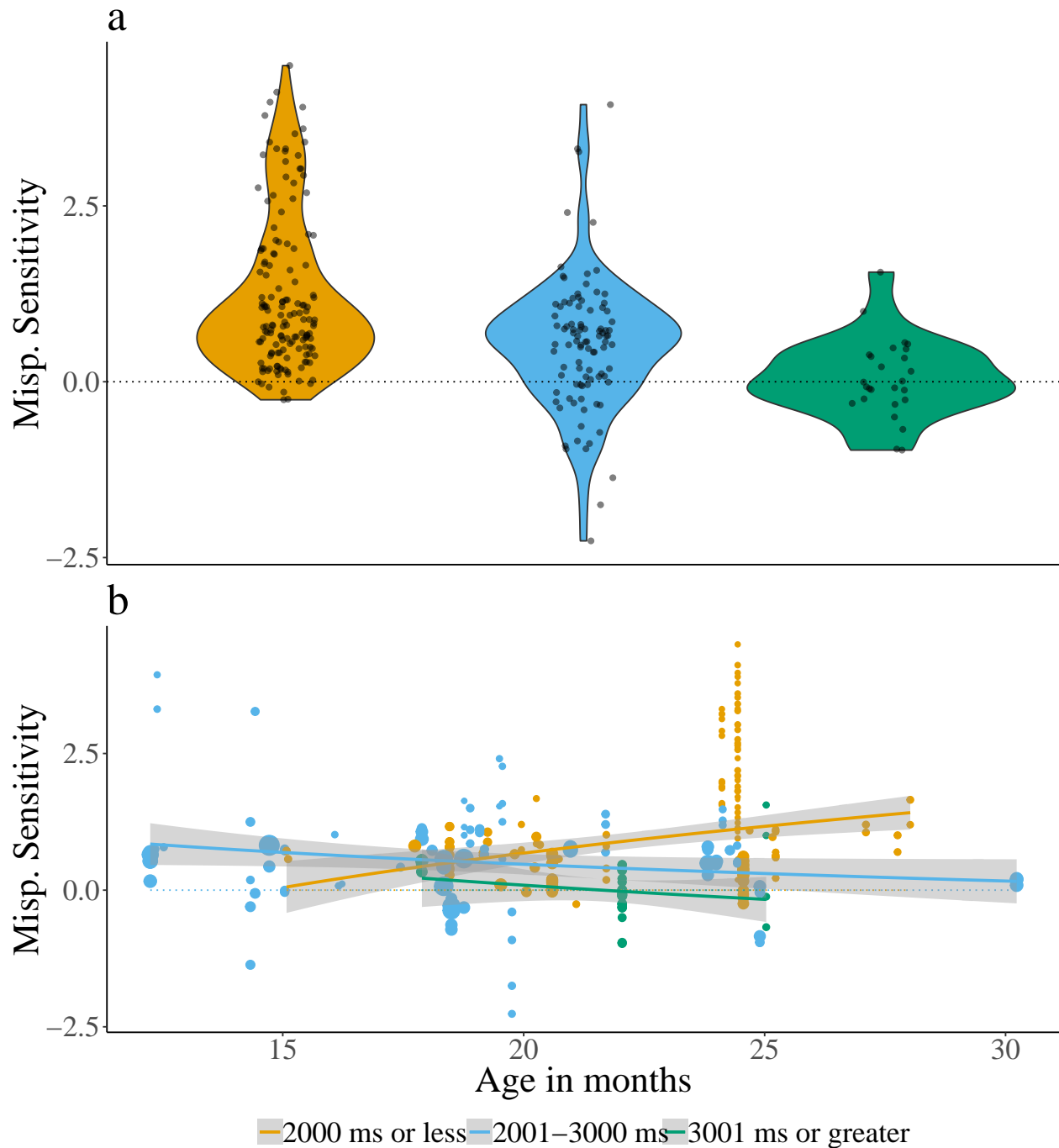
Figure 5. Effect sizes for the different lengths of the post-naming analysis window: 2000 ms or less (orange), 2001 to 3000 ms (blue), and 3001 ms or greater (green). Although length of the post-naming analysis window was included as a continuous variable in the meta-analytic model, it is divided into 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.
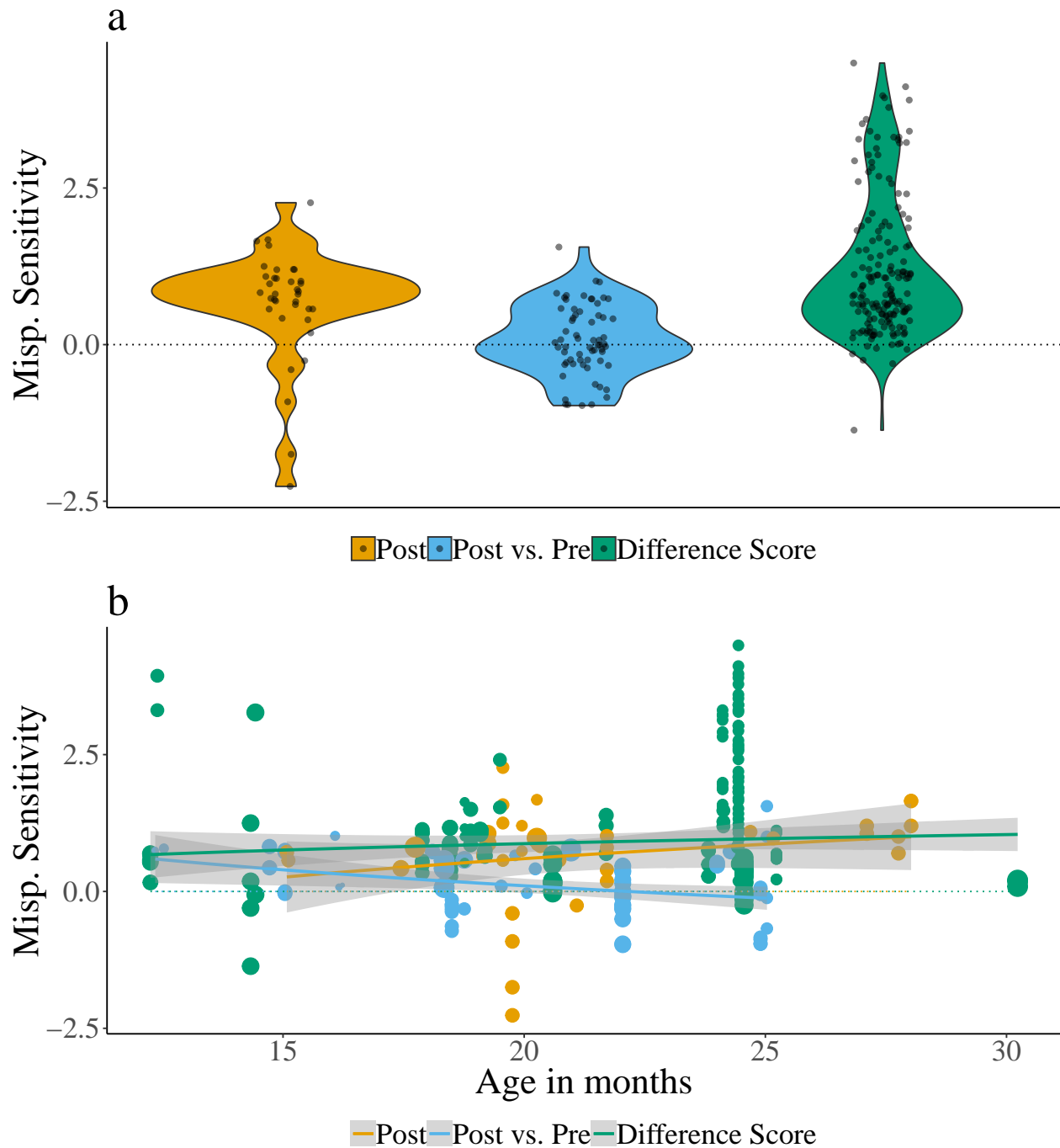
Figure 6. Effect sizes for the different types of dependent variables calculated: Post (orange), Post vs. Pre (blue), and Difference Score (green). Panel a plots mispronunciation sensitivity aggregated over age, while panel b plots mispronunciation sensitivity as a function of age. The lines plot the linear regression and the gray shaded area indicates the standard error.